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# Structure–property relationships and intrinsic antibacterial potential of *Saccharum spontaneum* fibers toward sustainable biomaterial composites

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## Abstract

Natural plant fibers are increasingly explored as sustainable reinforcements for next-generation composite materials. However, the correlation between their structural characteristics and intrinsic bio functional properties remains underexplored. This study systematically investigates *Saccharum spontaneum* stem fibers to establish structure–property–bioactivity relationships relevant to sustainable composite development. X-ray diffraction analysis confirmed a semi-crystalline cellulose I structure with a dominant (002) reflection at  $2\theta \approx 21^\circ$  and a crystallinity index of  $\sim 21\%$ , indicating a predominantly amorphous lignocellulosic framework favorable for matrix interaction and surface functionalization. Fourier transform infrared spectroscopy revealed abundant hydroxyl and aromatic functional groups associated with cellulose, hemicellulose, and lignin, suggesting chemically active interfaces that may influence both mechanical bonding and antimicrobial interactions. Mechanical testing demonstrated a tensile strength of 52.17 MPa with a failure strain of 0.023, indicating suitability for non-structural and hybrid polymer composite systems. Thermogravimetric analysis revealed multi-stage degradation with primary polysaccharide decomposition between 300 and 430 °C and stable char formation temperature beyond 700 °C, confirming compatibility with thermoplastic processing such as PLA-based composites. Importantly, the lignocellulosic composition contributing to interfacial adhesion also imparted intrinsic antibacterial activity against *Escherichia coli*, producing inhibition zones of  $28 \pm 1$  mm and  $35 \pm 1$  mm at 50 µg and 100 µg, respectively. Confocal microscopy further confirmed antibiofilm disruption, linking chemical functionality to biological response. The findings demonstrate that the physicochemical architecture of *Saccharum spontaneum* fibers simultaneously governs mechanical reinforcement potential and intrinsic antibacterial behavior, supporting their integration into sustainable bio functional composite systems rather than representing independent application domains.

**Keywords** Sustainable development, Natural fibers, Functional materials, Biological activities



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## 1 Introduction

The increasing tendency towards natural fiber reinforcement in composite materials is mainly due to environmental, economic and regulatory factors as well as changing performance needs [1]. Natural fibers from renewable plant sources have a much lower environmental footprint than synthetic reinforcements since they are biodegradable, carbon neutral throughout their life cycle and require less energy for their manufacture [2]. The growing focus on sustainability, the principles of circular bioeconomy and adherence to stringent environmental requirements has been a key driver for industries to move away from reliance on petroleum-based fibers [3]. Also, natural fibers are available widely, and those fibers are cost-effective and often obtained from agricultural residues or fast-growing plants, which support the valorization of waste and rural economies [4]. Their low density makes them available for the development of lightweight composites, which is especially advantageous in applications in automotive, building and consumer products, where weight saving corresponds to a higher energy efficiency. Furthermore, natural fibers have good acoustic damping, thermal insulation, and vibration absorption properties, which can be used for multifunctional composite applications [5]. Advances in fiber surface modification, chemical treatments and hybridization strategies have also addressed traditional limitations such as moisture sensitivity and interfacial incompatibility, further increasing the transition towards natural fiber reinforced composites as sustainable alternatives to traditional conventional synthetic systems [6].

Natural plant fibers have several differences with other groups of natural fibers, such as animal and mineral-based fibers, in relation to their origin, structure, composition and functional performance, which determines their suitability for different applications [7]. In contrast, plant fibers are mainly made of cellulose, hemicellulose and lignin, which give them a hierarchical, microfibrillar structure with low density, good flexibility and specific properties [8]. In contrast, animal fibres like wool or silk are protein based which provides better elasticity, thermal comfort and biocompatibility leading to more efficient textile, biomedical sutures and wearable applications as opposed to load bearing composites [9]. Mineral natural fibers, represented by basalt, are inorganic in nature, with higher thermal stability, flame resistance and chemical durability, and are suitable for high temperature fire-resistant and infrastructure-related fields [10]. Within plant fibers themselves, there is also a large variability depending on the origin and the extraction process, as fibers from plants like flax and jute tend to have a higher cellulose content and greater stiffness, being well suited for structural and semi-structural elements of composite materials, while leaf fibers, such as sisal and agave, display higher values for toughness and abrasion resistance, more advantageous in applications on packaging, ropes and impact-resistant panels [11]. Seed and fruit fiber e.g. Cotton and coir have higher lumen content and flexibility which provide more insulation for heat, sounds and cushioning applications. Together, plant fibers are most efficient for lightweight, cost-sensitive and environmentally driven applications, such as automotive interiors, building panels, packaging and consumer goods, while animal fibers are ideal for comfort- and biofunction-oriented applications and mineral fibers dominate high-temperature and durability-critical environments [12].

Antibacterial properties have become more important in the development of reinforced composite materials, especially in applications where hygiene, durability and resistance to microbial degradation are important [13]. Natural fibers and bio-based

reinforcements commonly have inherent phytochemicals, including phenolics, flavonoids, tannins and lignin-derived compounds, that may inhibit the growth of bacteria and fungi. When used as additives in polymer matrices, these antimicrobial properties assist in reducing microbial colonization on the surface of the composites, which in turn limits the formation of biofilm, odor, and deterioration of the materials with time [14]. The reinforcement phase can be modified by introducing anti-microbial agents such as metal or metal oxide nanoparticles (e.g. ZnO, Ag, CuO) or plant-derived extracts, in order to provide effective anti-microbial activity in a controlled manner, without any notable effect on the bulk properties of the composite [15]. Such antibacterial reinforced composites are especially useful in biomedical devices, dental materials, food packaging, water treatment components, as well as interior automobile or building applications, where microbial contamination may pose health and performance dangers [16]. Also, the direct inclusion of antibacterial functionality into the reinforcement phase reduces the need for external coatings or chemical additives, improving long-term effectiveness and sustainability. As a result, antibacterial reinforcements do not only enhance the functional lifetime of composites, but also extend their use into high value, hygiene sensitive environments [17].

*Saccharum spontaneum* stem fibers possess a set of physical and morphological properties which make them attractive as sustainable lignocellulosic reinforcements for polymer composites. The fibers are lightweight, whose bulk density ranges from 1.20 to 1.35 g cm<sup>-3</sup>, which is less than the bulk density of conventional synthetic fibers and contributes to result in the better specific performance of composite [18]. Individual fiber diameters are variable because of the natural origin, between 80 and 250 µm. Finer diameters of 20–40 µm can be observed in the case of the extracted elementary fibers according to the type of retting and separation method. The average length of the fiber obtained from the stem extraction often falls in the range of 30–120 mm, which is favorable for the effective stress transfer in short and medium fiber composite systems [19]. Chemically, *Saccharum spontaneum* stem fibres contain high amounts of cellulose (60–70 wt%), hemicelluloses (18–25 wt%) and lignin (10–15 wt%), resulting in a mostly cellulosic structure that is favourable for interfacial bonding after appropriate surface treatment [20]. The moisture content of untreated fibres is typically in the range of 8–12%, which is indicative of the hydrophilic character given by the presence of hydroxyl groups in cellulose and hemicellulose. Water absorption after 24 h immersion is mostly reported to be between 10 and 18%, pointing to the need of chemical modification in moisture sensitive applications. Morphologically, the lumen structure of the fibers is hollow or partially hollow, and the diameter of the lumen reaches about 10 ~ 30 µm, which gives the fibers low density and good damping and thermal insulation effect. It is collectively these physical, chemical and morphological characteristics that make *Saccharum spontaneum* stem fibers a promising renewable reinforcement material for lightweight and environmentally friendly composite materials without the use of strength-dominated performance parameters [21].

The current study fills an obvious research gap in the area of limited scientific characterization and application-based evaluation of *Saccharum spontaneum* stem fibers. While much work has been done on known natural fibers jute, flax, sisal and hemp, it is mainly on the optimization of the mechanical reinforcement properties for structural composites. In contrast, wild grass-derived fibers like *Saccharum spontaneum* despite

their abundance, renewability and low cultivation needs are almost unexplored with respect to systematic structure–property evaluation and functional potential. Existing literature also tends to compartmentalize investigations to either mechanical-thermal characterization or isolated biological activity studies with limited efforts spent correlating intrinsic fiber chemistry, crystallinity, and morphology with both engineering suitability and biological response.

The need to study *Saccharum spontaneum* stems from its ecological importance as a rapid growing, low cost and underutilized biomass resource, especially in areas where it is regarded as agricultural residue. Understanding the physicochemical architecture of is essential to determining the viability of such non-conventional fibers as possible alternatives in sustainable material systems. Rather than presenting new characterization techniques, the innovation of the present work appears to be the establishment of an integrated framework of structure-property-bioactivity for this particular type of fiber, thus providing baseline scientific data that are currently lacking in the literature. Through systematic structural (XRD, FTIR), mechanical (tensile testing), thermal (TGA) and biological (antibacterial and antibiofilm) evaluations, this study is the first comprehensive assessment of the fiber of *Saccharum spontaneum* stem and critically positions the performance of these fibers in relation to commonly studied natural fibers. This integrated evaluation clarifies both the capability and limitations of the material and allow to evidence-based assess the suitability of the material for sustainable and non-structural and bio functional composite applications.

## 2 Materials and experimental process

### 2.1 Plant material compliance statement

*Saccharum spontaneum* L. used in this study was collected from its Venkateshwara Farming in Polur, Tamil Nadu, India, with permission from the landowner Mr. K. Venkatesh. The species is widely distributed and is not classified as endangered or protected. The collection and use of plant material complied with national, and international regulations, including the International Union for Conservation of Nature (IUCN) Policy Statement on Research Involving Species at Risk of Extinction.

### 2.2 Extraction of natural fibers from *Saccharum spontaneum* stem fibers

The plant material used in this study (*Saccharum spontaneum* L.) is a naturally occurring grass species that is neither cultivated nor classified as a protected or endangered plant. The variety used was *Saccharum spontaneum* which grows in the Polur, Tamil Nadu, India and is harvested when the plants are mature and require minimum agro-economic intervention. The *Saccharum spontaneum* stems were extracted under a green water retting process in order to make sure that it was processed sustainably but still the physicochemical characteristics of the fibers were not compromised. The harvesting was done at the physiological maturity of 6 months which was the stage of maximum cellulose deposition and the fairly moderate stage of lignin development. The ratio between structural rigidity and extractability is favorable at this maturity stage to allow an efficient microbial retting without too much fiber loss. After collection, the stems were hand defoliated, rinsed to remove soil and other debris and trimmed to the same length to facilitated equal penetration of water and microbial activity in the retting process.

The retting was done by immersing the stems that had been prepared in fresh water under natural environmental conditions. The incubation time was held 25 days during which naturally available anaerobic and facultative anaerobic microorganisms generated pectinolytic, hemicellulolytic and cellulase regulating enzymes. These enzymes specifically digested the pectin-containing middle lamella and partially solubilized the hemicellulose, thus loosening the bundles of fibres both in relation to the surrounding parenchymatous and vascular tissues and the cellulose microfibril skeleton [22]. Tactile evaluation of the retting process and visual evaluation of the fiber separation were performed to avoid over-retting that will result in surface erosion, micro fibrillation height, and decrease in uniformity of the fiber. The retting temperature controlled by the local climatic conditions 30 °C was a crucial factor in controlling microbial process, where moderated temperatures favoured the controlled microbial action and uniform quality of fibres.

When the retting was complete, the softened stems were beaten lightly and stripped by hand, to recover the bundles of fibers, with as little mechanical handling as possible, to break the fibers. The fibers were then washed again with clean water to wash away residual degraded matrix components, microbial metabolites and soluble impurities to produce cleaner fibers with uncovered hydroxyl functional groups. The drying was performed at ambient temperature by placing the product in the shade to a three-day period to stabilize the moisture level was attained. Shade drying has been selected carefully to prevent the effects of ultraviolet degradation, thermal oxidation, and excessive shrinkage that is caused by direct exposure to the sun. Such controlled drying is also beneficial in retaining the native crystallinity and surface chemistry of the fibers that are of paramount importance in influencing interaction with the polymer matrices. Thus, the green water retting method applied to the *Saccharum spontaneum* stems under scientific control to guarantee minimal environmental impact still provides fibers with constant form, that is, with retained chemical activity and application in high-performance and sustainable composite products. Figure 1 shows the fiber extraction process.



**Fig. 1** Fiber extraction process

### 2.3 Testing process of *Saccharum spontaneum* stem fibers

The stem fibers of *Saccharum spontaneum* were experimentally evaluated by using the combination of biological, chemical, structural, mechanical and thermal characters to provide a thorough evaluation of their aptitude to being utilized in high order materials. The first attempt was to determine the intrinsic bioactive ability of the fibers with regard to the elimination of *Escherichia coli* by the agar well diffusion analysis. Sterilized fiber powders were washed, oven dried (50 °C, 24 h), ground, and sterilized under UV. Aqueous extracts were made by stirring 100 mg fiber powder with 10 mL sterile distilled water over 24 h, centrifuged, and filtered using 0.22 µm. Against *Escherichia coli* ( $\approx 10^8$  CFU mL<sup>-1</sup>, 0.5 McFarland), it was tested on agar wells (6 mm wells) in the agar wells diffusion method at defined concentrations (50 µg and 100 µg per well). *Streptomycin* was used as positive and sterile water as negative control. Plates were incubated at 37 °C during 24 h and triplicate ( $n = 3$ ) data was taken. To gain further insights into the antibiofilm behavior, the inhibitory studies of biofilms were performed with a confocal laser scanning microscopy (CLSM). The biofilms of *E. coli* were grown on sterile glass coverslips with and without fiber extract and then fluorescent staining was done with live/dead viability dyes. The confocal microscope (Leica TCS SP8) was used to perform CLSM imaging, which allowed seeing the coverage of the biofilm surface on two dimensions, and cell viability, which provided qualitative information on biofilm disruption [23].

Fourier Transform Infrared (FTIR) spectroscopy was used to examine chemical functionality of the fibers in order to identify the characteristic functional groups of cellulose, hemicellulose and lignin. The spectra were taken in FTIR between 4000–400 cm<sup>-1</sup> using Bruker Tensor 27 FTIR spectrometer (Bruker Optics, Germany) with a resolution of 4 cm<sup>-1</sup>, in an ATR mode. X-ray diffraction (XRD) was used to analyse structural crystallinity and phase composition using an X-ray diffractometer (PANalytical X'Pert PRO) using an X-ray diffractometer at 40 kV and 30 mA with Cu K $\alpha$  radiation ( $\lambda = 1.5406$  Å). The crystal structure of the fibers was observed using diffraction patterns that are observed over 10–80° C of scanning at 2° min<sup>-1</sup>, in which crystal and amorphous regions in the fiber structure are estimated [24].

The behavior of single-fiber tensile testing was done to assess deformation behavior and mechanical strength. Tests A minimum of five independent specimens ( $n = 5$ ) were run to control statistical reliability to the same conditions. The data are presented in the form of mean standard deviation to indicate variability and repeatability of the samples. The tensile tests were performed as per ASTM D3822 and an Instron 3365 Universal Testing Machine (Instron, USA) was used to conduct tensile tests with a low-capacity load cell. The single fibers were attached to paper frames with a gauge length of 30 mm and experiment conducted at ambient condition with a crosshead speed of 1 mm/min [25]. The thermogravimetric analysis (TGA) as per the ASTM E1131 was used to measure thermal stability and degradation behavior. Using thermogravimetric analyser (e.g., TA Instruments Q50), 10 mg fibers were heated at a rate of 10 °C/minute at room temperature up to 800 °C in the presence of a nitrogen atmosphere. The resultant TGA and derivative thermogravimetric (DTG) curves gave the moisture loss, decomposition of hemicellulose and cellulose, as well as the formation of char [26]. Together with these controlled experiments, these systematically organized experiments provide a strong insight into the antibacterial, physicochemical, structural, mechanical, and thermal

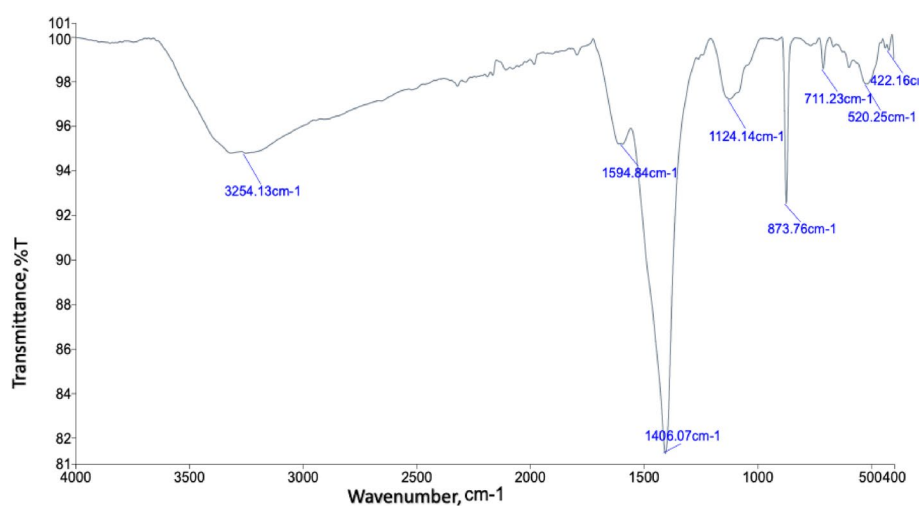
properties of *Saccharum spontaneum* stem fibers, and these findings suggest their application in ecologically sustainable and multifunctional materials systems.

### 3 Results and discussion

#### 3.1 FTIR analysis of *Saccharum spontaneum* stem fibers

The Fourier Transform Infrared spectrum of *Saccharum spontaneum* stem fibers provides a detailed description of the chemical structure, and it is an excellent demonstration of the intricate lignocellulosic structure and the interactions between the elements of cellulose, hemicellulose, and lignin. The wide and high-intensive absorption band galloped at  $3254\text{ cm}^{-1}$  to the vibration of hydroxyl ( $-\text{OH}$ ) groups on cellulose and hemicellulose. This band is very wide and intense, which means that the cellulose microfibrils have a great number of intermolecular and intramolecular hydrogen bonds and some interactions with physically adsorbed moisture [27]. It is this high content of hydroxyl groups that give this hydrophilic property to the fibers and greatly contributed to interfacial adhesion during fabrication of composite especially when suitable surface treatment is performed. Figure 2 shows the FTIR spectrum of *Saccharum spontaneum* fibers.

The observed absorption band at  $1594\text{ cm}^{-1}$  is related to the skeletal vibration of aromatic rings of lignin, which validates the existence of phenylpropanoid structures in the fiber structure. The structural rigidity, thermal stability, as well as natural bioactivity of *Saccharum spontaneum* fibers, are attributed to lignin. The presence of a sharp and powerful peak at around  $1406\text{ cm}^{-1}$  which is attributed to C-H bending and O-H in-plane deformation vibrations of cellulose has been often linked to the crystalline areas of cellulose. Another characteristic of this band is the extent of molecular organization in the fiber structure which can be attributed to the ratio of crystalline and amorphous domains of cellulose. The presence of the band at  $1124\text{ cm}^{-1}$  is assigned to C-O-C asymmetric vibrations of 1,4-glycosidic bonds that identifies the polysaccharide backbone of cellulose. Such peak is an important parameter of cellulose integrity and chain connectivity in the fibers. The absorption maximum of  $873\text{ cm}^{-1}$  is typical of beta-glycosidic linkages of anhydro glucose units in cellulose, which once again confirms the cellulose as the apex structural component. Other bands present in the lower wavenumber like  $711\text{ cm}^{-1}$  and  $520\text{ cm}^{-1}$  are related to out-of-plane C-H bending and skeletal vibration of



**Fig. 2** The FTIR spectrum of *Saccharum spontaneum* fibers

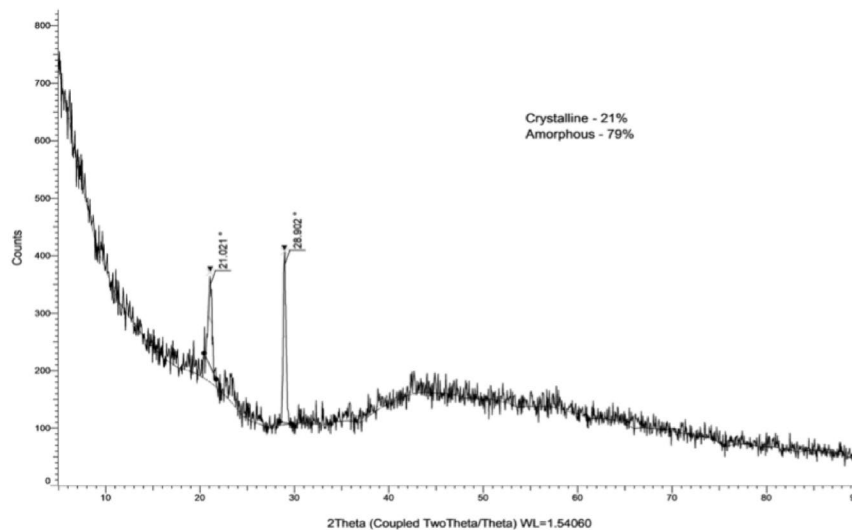
the carbohydrate structure, which is indicative of the cellulose chain organization and the existence of crystalline cellulose I structure [28]. Low-frequency band at  $422\text{ cm}^{-1}$  is associated with the complex deformation of the lignocellulosic network which means that the fiber constituents have strong intermolecular interactions.

The FTIR spectrum used together confirms that *Saccharum spontaneum* stem fibers have chemically rich surface which is dominated by hydroxyl, ether, and aromatic functional groups. These functional groups not only regulate the absorption of moisture and interaction between fibers and matrices, but also help to explain the antibacterial and antibiofilm activity of organic research because phenolic and aromatic structures obtainable via the lignin are known to destabilize bacterial membranes. The comprehensive FTIR science therefore provides a direct correlation between chemical functionality of the *Saccharum spontaneum* fibers along with their mechanical, thermal and biological capabilities as a rationale to their application as a multifunctional, sustainable, reinforcement in the advanced composite and bioactive material system.

### 3.2 XRD analysis of *Saccharum spontaneum* stem fibers

The X-ray diffraction of *Saccharum spontaneum* stem fibers gives the comprehensive information about the crystallographic structure, level of ordering, and the composition of phases which are directly associated with the material stability and performance in the engineering practice. The diffraction pattern that was obtained with Cu K alpha radiation ( $\lambda = 1.5406\text{ \AA}$ ) has a typical semi-crystalline appearance that is characteristic of fibers of lignocellulosic nature. A clear diffraction peak at a  $2\theta$  value of  $21.0\text{--}21.2^\circ$  corresponds to the (002) cellulose I crystallographic plane which is the natural crystalline form normally reported in the native plant fibers, jute, flax and sisal. This relatively low in intensity and moderately broad peak is a confirmation of the occurrence of ordered cellulose microfibrils in an amorphous matrix [29]. The decreased peak strength against highly crystalline cellulose suggests the small size of crystalline domains and partial disorientation of the long-range order by adjacent hemicellulose and lignin fractions. A secondary, weaker reflection at  $28.8\text{--}29.0^\circ$  ( $2\theta$ ) can be linked to the overlapping cellulose-related reflections or small ordered domains that were formed by re-arranged cellulose chains. The existence of this peak also indicates the existence of partial crystallinity in the fiber structure, which is however low indicating that such domains are not highly developed. Conversely, there is a wide amorphous halo that runs between about  $15^\circ$  and  $35^\circ$  ( $2\theta$ ) which is considered to be a significant contribution by amorphous phases, including hemicellulose, lignin and unordered cellulose regions. The quantitative analysis of the diffractogram shows that the diffractogram is composed of approximately 21% crystalline and 79% amorphous phase, which is consistent with reported values of untreated grass-based and stem-derived natural fibers. Figure 3 shows the XRD curves of *Saccharum spontaneum* stem fibers.

The comparatively large amorphous fraction is extremely important in determining the functional activity of *Saccharum spontaneum* fibers. Amorphous regions also offer superior mobility of molecules and increased access to hydroxyl groups, which increases surface reactivity, moisture absorption, and compatibility with polymer matrices when fabricating composite [30]. Meanwhile, the availability of crystalline cellulose I domains is an aspect that promotes dimensional stability and resists excessive deformation during moderate loading and exposure to heat. The balanced semi-crystalline structure has



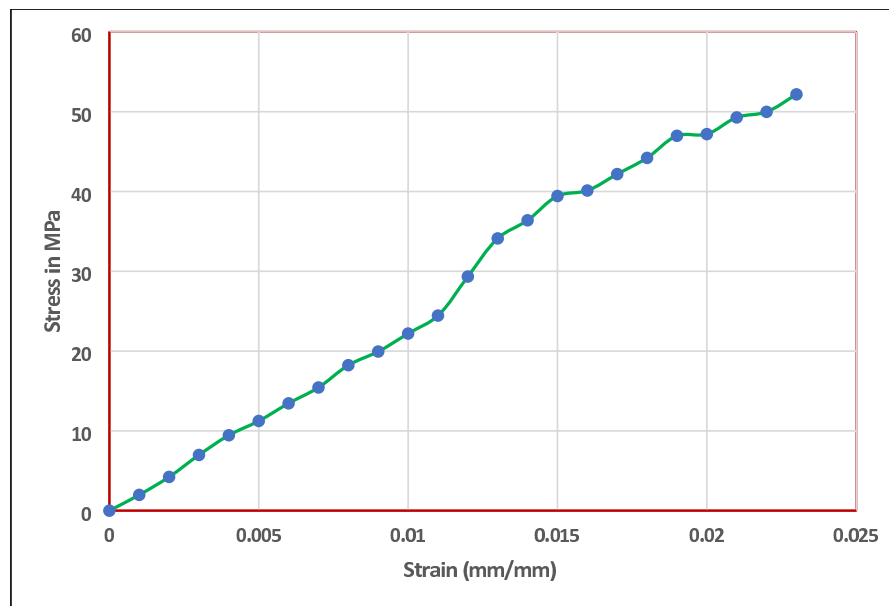
**Fig. 3** The XRD curves of *Saccharum spontaneum* stem fibers

been especially beneficial to composite materials because brittle behavior is reduced and the transfer of stress is easy. Also, the reduced crystal structure facilitates a high alleviation, thermal shock tolerance, and chemical communication with matrix materials, which makes *Saccharum spontaneum* stem fibers applicable to the lightweight and sustainable composites and bio functional material.

### 3.3 Tensile strength of *Saccharum spontaneum* stem fibers

Increase in tensile behavior of *Saccharum spontaneum* stem fibers exhibits a mechanically balanced though brittle predominant response as clearly shown by stress-strain behaviour. The tensile strength of the fibers was  $52.17 \pm 2.59$  MPa and tensile strain at failure was 0.023 which means that its strength is moderate and therefore limited deformation is accompanied by brittle fracture. In the case of the stress strain curve the elasticity between the first loading point and the maximum stress becomes nearly linear and yield point or prolonged plastic deformation region is low. This almost linear relation of the stress to strain followed by a sudden failure at the maximum stress confirms that the fibers are mostly in elastic deformation and then suddenly fail out of the suddenness of the critical stress. This is typical of brittle materials, in which the development and spread of cracks is fast and energy is not lost in plastic deformation. Figure 4 shows the stress vs. strain curve of *Saccharum spontaneum* fibers.

The single fiber tensile strength of *Saccharum spontaneum* is lower than that of flax (50–90 MPa), jute (30–80 MPa) and sisal (40–70 MPa), which are popular in both load-bearing and semi-structural composite applications when compared to the widely used plant fibers [31]. Nevertheless, tensile strength of *Saccharum spontaneum* fibers is near or slightly greater than that of coir fibers with 30–50 MPa [32] as well as a number of untreated fibers of agricultural residues. The observed value of the strain of 0.023 is relatively high but the fact that the stress strain curve does not exhibit an obvious stress strain region means that the strain is built up in the elastic regime instead of ductile yielding. This fracture character may be explained by the prevalence of stiff cellulose microfibrils as the main load-bearing structure and the little ability of the surrounding hemicellulose lignin matrix to promote plastic deformation. When microcracks are



**Fig. 4** The stress vs. strain curve of *Saccharum spontaneum* fibers

started at defects, voids, or weak interfaces, the swiftly expanding crack propagation results in disastrous failure.

Application wise, the brittle tensile response indicates that *Saccharum spontaneum* fibers is most preferable in non-structural and functional composite parts with elastic stiffness, dimensional stability and light weight properties being more important than the large strain tolerance. Applications Suitable applications are automotive interior panels, door trims, headliners, and dashboard substrates, where applications are mostly low-to-moderate stress, and components are more likely to be stiff than highly deformed. These fibers may also be successfully employed in lightweight board, ceiling panels, insulation layers, and partition walls in the building materials, where brittle failure is not experienced as strongly, and when sudden overloads are not expected. *Saccharum spontaneum* fibers are also of some promise as secondary reinforcements in hybrid composite systems, in which they can be co-assembled with more difficult or more ductile fibers like glass, basalt, or flax. With these hybrids *Saccharum spontaneum* fibers are added to give them stiffness and sustainability, with the associated reinforcements treating the brittle nature by enhancing both crack-bridging ability and damage tolerance [33]. On the whole, the tensile properties point out that even though *Saccharum spontaneum* stem fibers cannot be utilized in the primary load-bearing purposes, it is a sustainable and efficient reinforcement of elastic and light-weight composite systems with multiple functions.

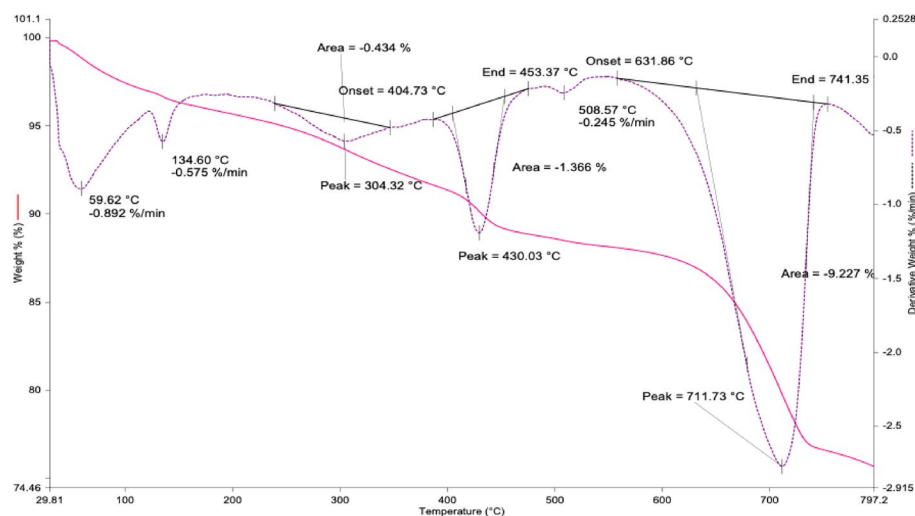
### 3.4 Thermal stability of *Saccharum spontaneum* stem fibers

The thermogravimetric (TG) and derivative thermogravimetric (DTG) curves of *Saccharum spontaneum* stem fibres give a deeper insight into the thermal stability of the materials and their decomposition process as dictated by their inherent lignocellulosic structure. The TG curve shows a small amount of weight loss below 100 °C and a DTG maximum at 59.6 °C that can be considered as a result of a combination of removal of physically absorbed moisture and loosely bound water involving hydroxyl groups in

cellulose and hemicellulose. This is the stage where there is low loss of mass meaning that the fibers are hydrophilic in nature but the inner microfibrillar packing does not allow excessive retention of moisture [34]. A second low-temperature phenomenon observed at 134.6 °C relates to the dislocation of more firmly bound water and the establishment of thermal relaxation of amorphous regions of hemicellulose, as the components are less ordered and more thermally sensitive. Figure 5 shows the thermal stability of *Saccharum spontaneum* fibers.

At a temperature of approximately 404.7 °C the major thermal degradation stage sets in i.e. the stage of breakdown of the polysaccharide structure. A DTG peak at 304.3 °C is related to the degradation of hemicellulose and the first cellulose chain depolymerization in which acetyl and glycosidic bonds break down to give rise to volatile products. This is then succeeded by a higher DTG peak of about 430 °C, which is the main decomposition of cellulose that deals with the scission of 1, 4-glycosidic bonds as well as quick volatilization of organic components [35]. The relatively large onset and peak temperatures of cellulose degradation suggests that there is a stabilizing influence also conferred by the ordered cellulose microfibrils and the partial crystallinity in the fiber structure that slows the thermal degradation relative to highly amorphous biomass materials.

The TG curve exhibits a slower and wider mass-loss region at high temperatures above about 508.6 °C having a low DTG rate, which is type of lignin decomposition. The lignin has a large temperature range of degradation because of its highly intertwined aromatics with complex structures and this slow loss promotes the development of a carbon rich char. The last significant peak in DTG is at around 711.7 °C, which relates to the loss of residual char and degradation of stable aromatic structures, which causes a significant decrease in mass, and a thermally stable residue at temperatures of around 740–800 °C. The existence of this char remains has got a direct relationship with the lignin content and aromatic nature of the fibers which increases the thermal resistance properties [36]. Thus, TG and DTG profiles indicate that the thermal behaviour of *Saccharum spontaneum* fibres is highly affected by their hierarchical structure of crystalline cellulose microfibrils with an amorphous hemicellulose-lignin composite framework. Development of the crystalline regions leads to an increase in thermal stability and slower decomposition of cellulose and the amorphous components dictate the early



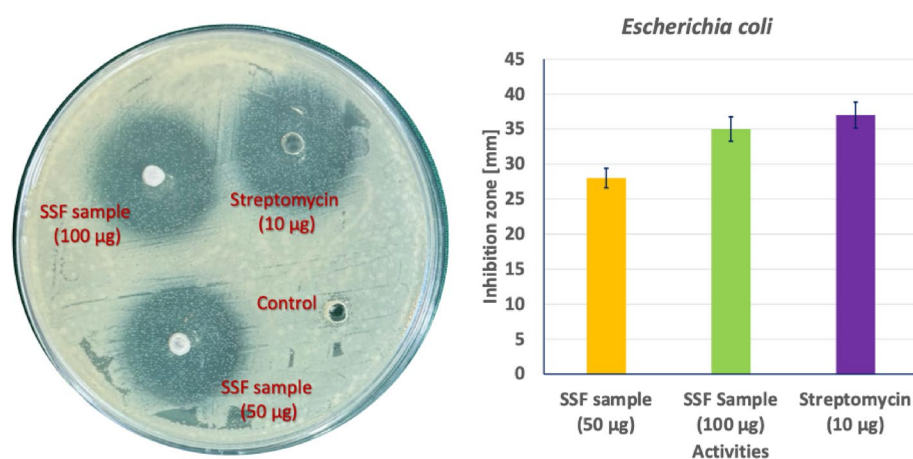
**Fig. 5** The thermal stability of *Saccharum spontaneum* fibers

degradation and loss of weight due to the presence of moisture. This synergistic structural effect leads to a multi-step degradation process and supports the fact that *Saccharum spontaneum* stem fibers have a high thermal stability to be used in the processing and application in polymer composites and bio-based materials that have moderate or high thermal conditions.

### 3.5 Antibacterial activities of *Saccharum spontaneum* stem fibers

The efficacy of *Saccharum spontaneum* stem fibers (SSF) in *Escherichia coli* as an antibacterial agent was examined in more detail using the agar well diffusion technique to clarify the efficacy of the bioactive constituents derived by the fibers along with its concentration-dependent action against a recognised antibacterial. The outcome of the experiments demonstrated that SSF has a strong antibacterial effect and concentration of extracts in the experiment increased systematically. Within the low concentration (LC, 50  $\mu$ g), the SSF sample resulted in a clear inhibition zone, which was about  $28 \pm 1$  mm, proving that it was able to inhibit the growth of *E. coli* even under a relatively low dosage. When the concentration was further raised to the higher level (HC, 100  $\mu$ g), the size of the inhibition zone was significantly increased to approximately  $35 \pm 1$  mm, which is a significant increase in the antibacterial activity. This dose-sensitive effect implies that the greater the presence of active phytochemicals, the stronger the response is to the bacterial cell envelope resulting in greater growth inhibition. Figure 6 shows the antibacterial inhibition of *Saccharum spontaneum* stem fibers.

To use as a benchmark, streptomycin (10  $\mu$ g), a highly established broad-spectrum antibacterial, had an inhibitory zone of about  $37 \pm 1$  mm; it is important to note that the antibacterial activity of SSF at the concentration of 100  $\mu$ g is very close to the effect of streptomycin and this result suggests a high potential of the natural fiber extract to inhibit bacteria despite its biogenic nature and low chemical ability relative to the synthetic antibacterial. The effect of phenolic compounds, flavonoids, lignin-derived aromatics, and other secondary metabolites naturally present in the fibers are likely related to the antibacterial effect of SSF. These bioactive molecules can adsorb to the bacterial cell surface, destabilize membrane integrity, enhance permeability as well as causing leakage of intracellular components, which ultimately disrupts essential metabolic and replication in *E. coli*, a gram-negative bacterium, with an outer lipopolysaccharide-rich



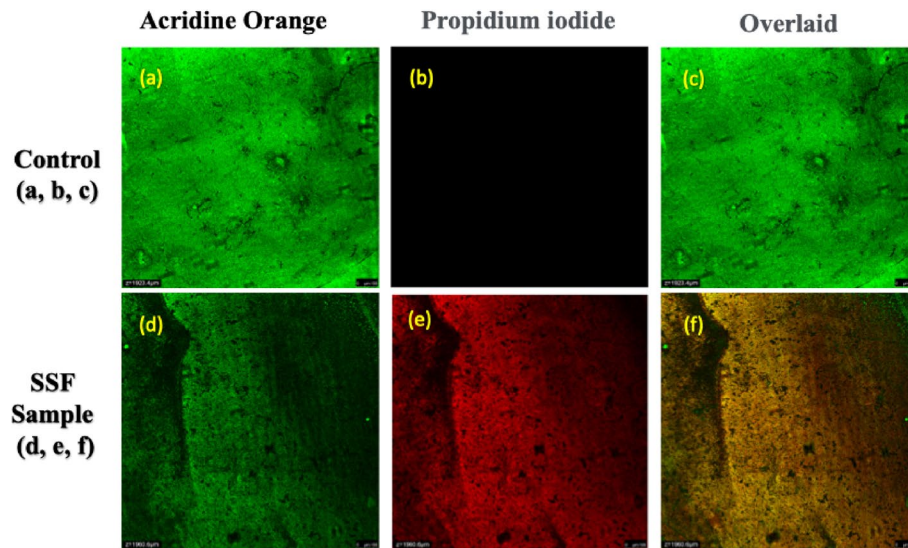
**Fig. 6** The antibacterial inhibition of *Saccharum spontaneum* stem fibers

membrane. Also, the size of the inhibition areas of SSF was relatively large indicating that the active compounds were diffused successfully through the agar medium, a requirement of contact-based antibacterial activity [37]. The similarity in the performance of the SSF high-concentration sample with streptomycin indicates that *Saccharum spontaneum* fibers have the potential to be used as a sustainable antibacterial reinforcement, especially where long-term microbial resistance, environmental considerations, and material-microbe interactions are a concern. The identified antibacterial activity of the fibers of *Saccharum spontaneum* can be explained by the existence of lignocellulosic-derived bioactive compounds. FTIR showed that hydroxyl and aromatic groups were present in large amounts as these classes of phytochemicals are normally linked with these groups. These compounds have been reported to cause disruption of bacterial cell membrane, oxidative stress, and interference with intracellular proteins thus inhibiting growth in microorganisms. Though further quantification of phytochemicals was not carried out in this case, the evidence of the spectroscopy and known literature on lignocellulosic fibers confirm the possibility of its involvement in the observed intrinsic antibacterial behavior. ANOVA (one way) indicated that there was statistically significant difference in the inhibition zones of the treatment groups ( $F(2,6) = 63.00, p < 0.0001$ ). Compared to the 50  $\mu\text{g}$  concentration, the 100  $\mu\text{g}$  SSF sample was very active in antibacterial activity, and streptomycin was the most active in general. Hence, the findings indicate that SSF can be incorporated into environmentally-friendly composite materials, bio-based substrates and antimicrobial surfaces where the desired antibacterial behavior can be controlled and natural when it has a strong and concentration-dependent antibacterial activity against *Escherichia coli*.

### 3.6 Biofilm analysis of *Saccharum spontaneum* stem fibers

The antibiofilm behavior of *Saccharum spontaneum* stem fibers (SSF) using confocal laser scanning microscopy, which in turn can be explained by the intrinsic internal structure and surface chemistry of the fibers and the interactions of these properties with the bacterial cells. Untreated control samples of CLSM images revealed high density green fluorescence following acridine orange staining indicating presence of a compact and metabolically active *Escherichia coli* biofilm with intact cell membranes and an established extracellular polymeric substance (EPS) network. The green signal uniformity and continuous layer of biofilm is a sign of good adhesion and colonization of bacteria without the presence of SSF. Conversely, the samples subjected to SSF showed a significant change in the pattern of fluorescence, the amount of red fluorescence due to propidium iodide staining increased significantly and the amount of green signal decreased significantly indicating widespread destruction of the membrane and death of bacterial cells. The superimposing CLSM images were of yellowish-orange colouring, which indicated the presence of both compromised and non-viable cells with the action of the fibers as being antibiofilm. Figure 7 shows the biofilm images of *Saccharum spontaneum* stem fibers.

Structurally, the antibiofilm-efficacy of SSF can be explained by its hierarchical structure that is composed of compactly packed cellulose microfibrils that are embedded into a matrix of hemicellulose and lignin. This framework is characterized by a coarse, micro- and nano-textured fiber surface with uncovered hydroxyl and phenolic functional groups. This type of topography and chemical functionality of surfaces can interfere with



**Fig. 7** The biofilm images of *Saccharum spontaneum* stem fibers

initial bacterial adhesion by lowering adhesive sites and altering cell-surface interactions. The porous lumen and capillary channels in the fibers could also serve as reservoirs of bioactive phytochemicals that exists naturally in *Saccharum spontaneum* and this would allow continued release of antibacterial compounds at the fiber- biofilm interface. These compounds may leak into the EPS matrix, destabilize its cohesion, as well as disrupt quorum sensing pathways which govern biofilm maturation. Moreover, lignin-rich parts of the fiber are also known to have naturally antimicrobial properties since phenolic groups will be able to create localized oxidative stress and disrupt bacterial membranes [38]. The combination of these lignin developed aromatics with the lipid components of the *E. coli* outer membrane would increase the membrane permeability, which allows entry of propidium iodide to be seen in CLSM images. The microfibrillar structure composed of cellulose also plays an indirect role in offering mechanical rigidity that can physically upset the continuity of biofilms and result in the inability to form a continuous layer of bacteria. Together, the surface roughness, internal porosity, chemical functionality and sustained release of bioactive compounds allow *Saccharum spontaneum* fibers to resist bacterial adhesion, destabilize biofilm structure, and enhance bacterial inactivation. Such CLSM findings that are backed by structural arguments greatly indicate that SSF can be used to prevent biofilm formation by both physicochemical and biochemical pathways, an important fact that warrants its use in antimicrobial composite materials and bioactive surfaces.

#### 4 Conclusion

This study established structure–property–bioactivity relationships for *Saccharum spontaneum* stem fibers relevant to sustainable biomaterial applications. X-ray diffraction confirmed a semi-crystalline cellulose I structure with a crystallinity index of approximately 21%, indicating a relatively amorphous lignocellulosic framework that promotes surface accessibility and potential interfacial compatibility with polymer matrices. Mechanical characterization revealed a tensile strength of 52.17 MPa with limited ductility, suggesting that these fibers are more suitable for non-structural and

hybrid composite reinforcement rather than load-bearing structural applications. Thermogravimetric analysis demonstrated thermal stability up to approximately 300 °C with a residual char yield of about 9%, indicating compatibility with thermoplastic processing systems such as PLA under controlled conditions. The fibers also exhibited intrinsic antibacterial potential against *Escherichia coli*. Quantitative antibacterial activity was confirmed through agar diffusion testing, which showed significant inhibition zones, while confocal laser scanning microscopy was used to qualitatively visualize biofilm disruption on the fiber surface. The CLSM observations served primarily as morphological confirmation of antibiofilm resistance, demonstrating the ability of the fiber surface to limit bacterial attachment rather than performing quantitative live/dead cell analysis. These findings suggest that the lignocellulosic surface chemistry contributes not only to interfacial interactions in composites but also to biologically relevant surface activity.

Despite these promising outcomes, several limitations remain. The present study focuses on single-fiber mechanical characterization and antibacterial evaluation against a single bacterial strain, and does not yet address composite-level performance, long-term durability, moisture sensitivity, cytocompatibility, or large-scale fiber processing. Future work should therefore investigate polymer composite integration, evaluate the stability of the bioactive behavior under service conditions, and conduct broader antimicrobial and biocompatibility studies. Therefore, the results demonstrate that *Saccharum spontaneum* fibers possess moderate mechanical strength, adequate thermal stability, and intrinsic antibacterial functionality, supporting their potential use as sustainable reinforcements in non-structural bio functional composite systems, including hygienic composite panels, antimicrobial packaging materials, interior components, and bio-based surface applications.

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The statement clarifies that the collection and use of plant material were conducted in accordance with national, and international guidelines, including the International Union for Conservation of Nature (IUCN) Policy Statement on Research Involving Species at Risk of Extinction.

#### Author contributions

Raja T- Conceptualization. Yuvarajan Devarajan- Methodology. Kuthalingam Venkadeshwaran - Software. Diksha Nirmalraj Saxena - Validation. Aravinda T – Formal analysis. Dhirendra Nath Thatoi - Investigation. Ganesh Kumar Kantak - Writing - Original Draft; Kulmani Mehar- Writing - Original Draft.

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#### Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

#### Declarations

##### Ethics approval and consent to participate

Not applicable.

##### Consent for publication

Not applicable.

##### Competing interests

The authors declare no competing interests.

##### Conflict of interest

Not applicable.

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## References

1. Liu Y, Huang J, Ou M, Ma Y, Sanjay MR. Application potential of novel natural cellulosic fibers in sustainable composites: a short review of research progress from 2020 to 2024. *J Nat Fibers*. 2025;22(1):2556289.
2. Puttegowda M. Eco-friendly composites: exploring the potential of natural fiber reinforcement. *Discover Appl Sci*. 2025;7(5):1–24.
3. Islam T, Chaion MH, Jalil MA, Rafi AS, Mushtari F, Dhar AK, Hossain S. Advancements and challenges in natural fiber-reinforced hybrid composites: a comprehensive review. *SPE Polym*. 2024;5(4):481–506.
4. Natrayan L, Surakasi R, Kaliappan S, Muthu G, Paramasivam P, Shanmugam K. Effectiveness of natural dye adsorption on ILSS and optical properties of bio synthesised TiO<sub>2</sub> nano particles and reinforced with flax seed fiber/epoxy based hybrid composites. *Discover Appl Sci*. 2024;6(3):125.
5. Abdollahiparsa H, Shahmirzaloo A, Teuffel P, Blok R. A review of recent developments in structural applications of natural fiber-Reinforced composites (NFRs). *Compos Adv Mater*. 2023;32:26349833221147540.
6. Ajithkumar S, Arulmurugan B, Rajeshkumar L. Prospects of natural fiber-reinforced polymer composites in engineering and commercial applications. *Applications of Composite Materials in Engineering*. Elsevier Science Ltd.; 2025. pp. 335–64.
7. Subbiah G, Acharya SK, Reddy MS, Sharma S, Singh BP, Suchithra R, Kumar KP. Roselle plant stem fibers: a sustainable biomaterial for composite reinforcement and antimicrobial applications. *Results Eng*. 2025;26:104852.
8. Murugadoss P, Devakki B, Patel P, Nath JK, Mukherjee J, Manjunath HR, Priya KK. (2025). Sustainable isolation and characterization of natural fibers from *Musa acuminata* stem for green composite development. *Results Chem*, 102735.
9. Lakshmaiya N, Kota SR, Bhaskar K, Palanivel A, Chukka ND K. R., Maranan R. (2025). Sustainable hybrid epoxy composites reinforced with Kenaf Fiber Banana Peel Waste and SiC for multifunctional performance. *Results Eng*, 107558.
10. Aznaw GM. Advances in composite structures: a systematic review of design, performance, and sustainability trends. *Compos Mater*. 2025;9(1):1–17.
11. Ntsie OD, Phiri R, Boonyasopon P, Rangappa SM, Siengchin S. Advancing sustainable infrastructure: natural fiber-reinforced composites in engineering: OD Ntsie. *Discover Appl Sci*. 2025;7(8):884.
12. Seychal G, Perli G, Goldberg A, Sardon H, Aranburu N, Raquez JM. En route to realistic sustainable structural fiber-reinforced polymers in a circular economy. *Adv Compos Hybrid Mater*. 2025;8(6):426.
13. Lakshmaiya N, Karthick M, Bhaskar K, Chukka NDKR, Ross NS, Maranan R. (2025). Development of eco-friendly hybrid nanocomposites with improved antibacterial and mechanical properties through NaOH treated natural fibers. *Results Eng*, 104996.
14. Zhou J, Kamei K, Marin E, Pezzotti G, Ma Y, Li Y, Zhu W. Research on the mechanism of natural antibacterial properties of *Calotropis gigantea* fiber. *Ind Crops Prod*. 2024;221:119447.
15. Prang Rocky B, Thompson AJ. Investigation and comparison of antibacterial property of bamboo plants, natural bamboo fibers and commercial bamboo viscose textiles. *J Text Inst*. 2021;112(7):1159–70.
16. Wei C, Xiong S, Zhang S, Cui Y, Wang S, Lu X, Yang B. A study on the antibacterial property and biocompatibility of ramie fiber. *Biomed Mater*. 2023;18(4):045010.
17. Rahman MM, Das AK, Tabassum S, Das SC, Uddin MA. (2025). Physical and chemical characterization of *Saccharum spontaneum* flower fibre: potential applications in thermal insulation and microbial fuel cells. *arXiv preprint arXiv:2501.05324*.
18. Selvaraj A, Gobikrishnan S. (2020). Physicochemical characterization of native and steam explosion pretreated wild sugarcane (*Saccharum spontaneum*). *Int J Renew Energy Dev*, 9(3).
19. Hassan A, Malik K, Naqvi SAM, Khan K, Sadia H. A comprehensive review of *Saccharum spontaneum*, its traditional uses, phytochemistry and pharmacology. *Ethnobotany Res Appl*. 2024;29:1–13.
20. Pandey VC, Bajpai O, Pandey DN, Singh N. *Saccharum spontaneum*: an underutilized tall grass for revegetation and restoration programs. *Genet Resour Crop Evol*. 2015;62(3):443–50.
21. Thandavamoorthy R, Devarajan Y, Manjunath HR, Tripathy S, Verma L, Sengupta S, Pal Singh D, Mehar K. Comprehensive evaluation of agave cantala fiber: structural robustness, mechanical behavior, and antimicrobial properties for multifunctional bio-material applications. *Mater Technol*. 2025;41(1). <https://doi.org/10.1080/10667857.2025.2606173>
22. Abdelhakeem E, Attia H, Hashem MM, Khalek MAA, Badr-Eldin SM, Adel IM. Innovative antimicrobial nanofibers: natural integrations for enhanced wound healing and biofilm disruption. *AAPS PharmSciTech*. 2025;26(6):181.
23. Thandavamoorthy R, Devarajan Y, Mehar K. Synthesis of ZnO Nanoparticles From *Pergularia daemia* Fibre: Potential for Caries Prevention and Infection Control. *Int Dent J*. 2026;76(2):109396.
24. Debbarma D, Rupa PKP. (2025, November). Processing and investigation on tensile properties of natural fiber reinforced polymer composites. In *AIP Conference Proceedings* (Vol. 3360, No. 1, p. 030003). AIP Publishing LLC.
25. Kumar R, Ganguly A, Purohit R. (2023). Thermogravimetric analysis of natural fiber reinforced hybrid composites—A review. *Materials Today: Proceedings*.
26. El-Bassuony AA, Ibrahim AF, Abdelsalam HK. Using natural products in contemporary fabric design: a critical review of trends, innovations, and future prospects (2019–2024). *Cellulose*. 2025;32(13):7485–99.
27. Raja T. Exploring a natural fiber extracted from henequen plant leaves: a sustainable innovation for reinforcement in composite materials. *Results Eng*. 2025;25:104015.
28. Pattnaik SS, Behera AK, Das N. Spectroscopic analysis of interfacial adhesion in natural fibre polymer composites. interfacial bonding characteristics in natural fiber reinforced polymer composites: fiber-matrix interface in biocomposites. Singapore: Springer Nature Singapore; 2024. pp. 79–96.
29. Albedah A, Abdo HS, Mohammed SM, Bouiadja BAB, Al-Ghurabi EH, Allothman OY. Potential of recycled polypropylene: a study on effect of natural fiber on the morphology and properties of biocomposite. *J King Saud University-Science*. 2024;36(5):103167.
30. Mohanraj, C. M., Rameshkumar, R., Mariappan, M., Mohankumar, A., Rajendran, B., Senthamaraikannan, P., ... Kumar, R. (2025). Recent progress in fiber reinforced polymer hybrid composites and its challenges-A comprehensive review. *Journal of Natural Fibers*, 22(1), 2495911.
31. Chahar M, Kumar R, Habeeb A, Kumar Garg R, Punia U. Factors affecting flexural and impact strength of natural fiber reinforced polymer composites: a review. *Green Mater*. 2025;13(2):76–91.
32. Devarajan Y, Raja T, Kalidhas AM, Patel P, Ramachandra C, Acharya SK, Meena M, Mehar K, Jayabal R. Plant-derived nanobioactive systems from industrial crops: Scalable pathways toward sustainable high-value industrial products. *Ind Crop Prod*. 2026;241:122727. <https://doi.org/10.1016/j.indcrop.2026.122727>

33. Tamat, N. S. M., Rahman, W. M. N. W. A., Ahmad, N., Sarmin, S. N., Hua, L. S., Khalid, M. H., ... Yunus, N. K. M. (2025, November). Thermogravimetric analysis and FTIR of Kenaf eco board properties. In IOP Conference Series: Earth and Environmental Science (Vol. 1553, No. 1, p. 012029). IOP Publishing.
34. Hindi J, Muralishwara K, Gurumurthy BM. Comparative analysis of physical, morphological, tensile and thermal stability characteristics of raw and alkali treated novel *Tinospora cordifolia* natural fiber. *Sci Rep.* 2025;15(1):18596.
35. Vigneshwaran N, Arputharaj A. Enhancing the functionality of natural fiber textiles through in situ nanofinishing techniques: a sustainable and cost-effective approach. *Sustainable Nano Textile Technology: Case Studies*. Cham: Springer Nature Switzerland; 2025. pp. 5–24.
36. Raja T, Devarajan Y, PS RR, Tiwari A, Dash S, Sellamuthu P, Shukla KK, Mehar K. Fabrication and Characterization of ZnO-Enhanced Kevlar Fiber/Epoxy Composites for Advanced Lightweight Structural and Engineering Applications. *J Nat Fibers.* 2026;23(1). <https://doi.org/10.1080/15440478.2026.2635687>
37. Abdullah CK, Khalil HA, Fazita MN, Baharudin MS, Nurazzi NM, Yusra AI, Bairwan RD. (2025). Nanocellulose-reinforced semi-refined carrageenan biofilms: surface modification and characterization for sustainable packaging. *Int J Biol Macromol*, 147319.
38. Zhao, J., Zhu, M., Jin, W., Zhang, J., Fan, G., Feng, Y., ... Li, Y. (2025). A comprehensive review of unlocking the potential of lignin-derived biomaterials: from lignin structure to biomedical application. *Journal of Nanobiotechnology*, 23(1), 538.

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