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Extraction and Characterization of Bio-Based Ligno-Cellulosic Fibers for Sustainable Material Applications

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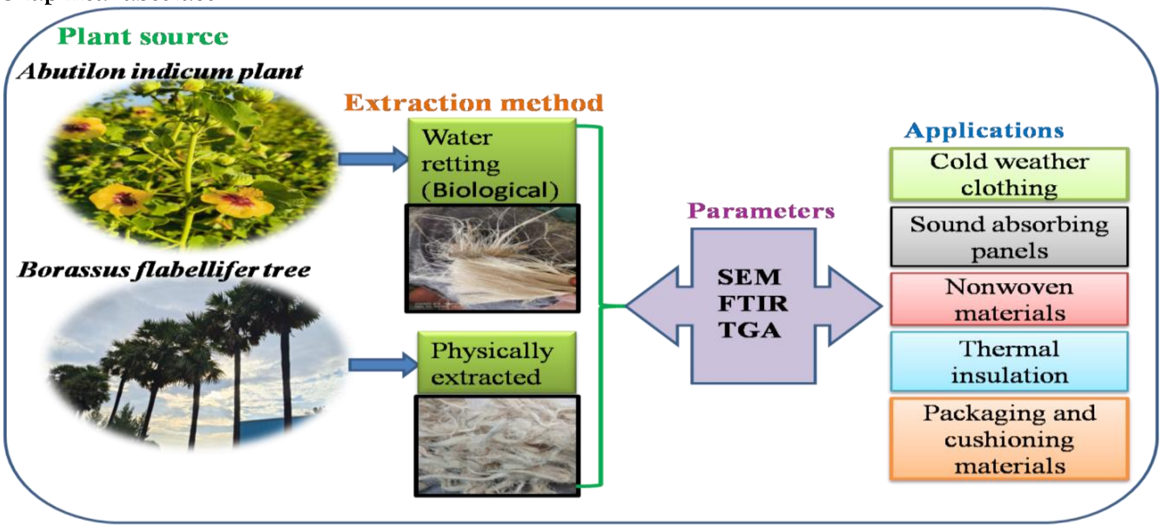
Abstract
Abutilon Indicum stem fiber (AI) and Borassus Flabellifer (Palmyra) fruit fiber (BFF) plant is abundantly available in countries like India, China, Myanmar, Thailand, Indonesia etc. The aim of this study is to investigate the use of AI, BFF as a potential source of natural fibers and the performance properties. The fibers were extracted from the AI plant, BFF fruit by biological retting process, which is a green route for the extraction of natural fibers. To evaluate the properties of two lignocelluloses fibers for eco- friendly nonwoven, composite, and textiles applications through analyzing their morphological, chemical, and thermal properties. The SEM images revealed a rough and uneven surface with longitudinal grooves which highlights the potential for good adhesion with the polymer matrix of AI and a smoother, denser shape with fewer surface striations in BFF. FTIR analysis revealed the presence of major constituents of the natural fiber such as cellulose, hemicelluloses, and lignin. The Thermo Gravimetric Analysis confirms its stability up to 250-390°C, which is higher than the polymerization temperature and sharper degradation peaks. The resulted of surface morphology, functional groups and thermal analysis of the AI and BFF fibers, which would result in production of better biodegradable, cold weather clothing, packaging and cushioning materials, sound absorbing panels, eco-friendly pet animal livestock mat, structurally durable nonwoven materials and eco-composite and thermal insulation applications.
Key words: *Lignocellulosic fiber, Abutilon Indicum, Borassus Flabellifer fiber, Sustainable textiles, SEM, FTIR, TGA.*

Graphical abstract



INTRODUCTION

The plant diversity, whether native or newly introduced, determines a large amount of a nation's wealth. Almost 80 percent of Indians, both in rural and urban regions, depend on plants for their daily necessities. They are essential for food, medicine, clothing, shelter, and farming, among other uses (Kenwat Rameshroo et al 2013; Raghunathan V et al 2024). Because of their ecological principles, economic and social perspectives, sustainability, and environmental concerns, natural fibers are becoming increasingly important. As a consequence of their abundance, biodegradability, recyclable nature, and affordability, natural fibers present a possible substitute for synthetic or petroleum-based fibers (Velmurugan, T et al 2025). Businesses are finding it more and more crucial to use agricultural waste and

Earths resources in order to emphasize sustainability. Few natural fibers perform better than synthetic ones, even though synthetic fibers have mechanical qualities that are comparable to those of natural fibers. In comparison to synthetic fibers, natural fibers are more widely available, lighter, have favorable environmental qualities (biodegradable), as well as performing better. Many parts of plants, including the roots, bark, fruits, stems, and leaves, are easily accessible sources of these fibers (Siva, R et al 2021). It is utilized in place of or in addition to synthetic fibers like glass, carbon, nylon, aramid, etc. because of its intriguing qualities. Depending on their strength, natural fibers have been utilized in a wide range of applications, including flooring, roof ceilings, sporting items, vehicle parts, and aircraft. The chemical composition of natural fibers, the strength of the matrix-fiber interfacial connection, and the environmental and geographic circumstances that prevailed throughout the parent plants growth are the main factors that affect their strength (Sanjay M.R et al 2018; Vinod A et al 2021). In both disposable and long-lasting goods such yarns, textiles, ropes, twines, nets, nonwovens, tissues, paper, packaging, fiberboards, geo textiles, composites, and automotive parts, natural fibers are widely used as fillers or reinforcements, insulating or structural elements. Furthermore, there is potential for sustainable fiber sourcing due to the substantial amount of crop leftovers produced by expanded agricultural productivity. With a variety of agricultural wastes, including straw, stems, stalks, leaves, husks, shells, peels, lint, seeds, stones, pulp, and stubble, India produces more than 500 million tons of crop leftovers per year. The structural and functional characteristics of the fiber are affected by the extraction procedures used to separate the natural fibers from these residues, which include mechanical processing, chemical treatments, retting, and boiling processes (Yamuna Devi S et al 2023).

A fast-growing shrub found across tropical and subtropical climates and a small herb in the Malvaceae family of Abutilon Indicum (also called Thuthi) have lately gained recognition as a potential source of natural cellulose fibers for use in sustainable material applications. This plant is often used as a medicinal plant and is considered invasive on certain tropical islands. The bast fibers that are taken from its stem have good mechanical and physical qualities that make them appropriate for use in the production of textiles and composites, and they have long been prized for their therapeutic qualities. Using renewable and biodegradable materials, like Abutilon Indicum, offers significant ecological and financial advantages in light of growing environmental concerns and the need to lessen dependency on synthetic fibers (Mohana Krishnudu et al 2020).

Although it originated in Africa, the versatile plant Borassus Flabellifer, also called the Palmyra palm, is a member of the Arecaceae family and is grown extensively across Southeast Asia. Often called the Tree of Life, this species is prized for its many uses in lumber, food, drinks, fiber production, and traditional medicine. Approximately 350 fruits may be produced yearly by a single mature tree, which are divided into 6–12 bunches with 50 fruits each. A fruits exterior shell and fibrous parts are usually thrown away as solid trash with little use, while the fruits edible inside pulp is eaten as meals. Environmental contamination results from the frequent open burning or land filling of these wastes. Examining the potential of mature Palmyra fruits for value-added applications in a range of technical areas is essential due to their abundance, affordability, and renewability. Because Palmyra fruit fibers contain a lot of cellulose, there has been about extracting nano cellulose, which has potential use in a variety of industries. In order to provide sustainable and environmentally acceptable substitutes for traditional petroleum-based plastics in packaging and surface protection applications, recent research has concentrated on using cellulose generated from Palmyra to create biodegradable packaging materials and protective coatings (Palanisamy S et al 2025; Raja Rajeshwari et al 2025).

This study explores the morphology, substance composition, and thermal behavior of Abutilon Indicum stem fiber (AI) and Borassus Flabellifer fruit fiber (BFF), as well as their extraction, characterization, and possible uses. To evaluate the quality and structure of the fiber, sophisticated analytical methods including Scanning Electron Microscopy (SEM), Thermo Gravimetric Analysis (TGA), and Fourier Transform Infrared Spectroscopy (FTIR) were used. With AI and BFF as an affordable reinforcing fiber for nonwoven and composite products, the findings are intended to aid in the creation of environmentally friendly materials.

MATERIALS AND METHODS

Plants Source and Collection

Stems of Abutilon Indicum, also known as Thuthi, were gathered from bushes and the fruits of Borassus Flabellifer (Palmyra palm) both plants grew naturally were source of the mature plants in Dharmapuri, Tamil Nadu, and India

Fiber Extraction Process

A conventional cement tank water retting technique was used to remove the AI fibers from the stem bast. For 20 days, the stems were immersed in water, which allowed the gums and pectin's that held the fibers together to break down microbiologically. The fibers were hand peeled, cleaned with clean water, are shown by Fig. 1 (A-G) and allowed to air dry after retting.

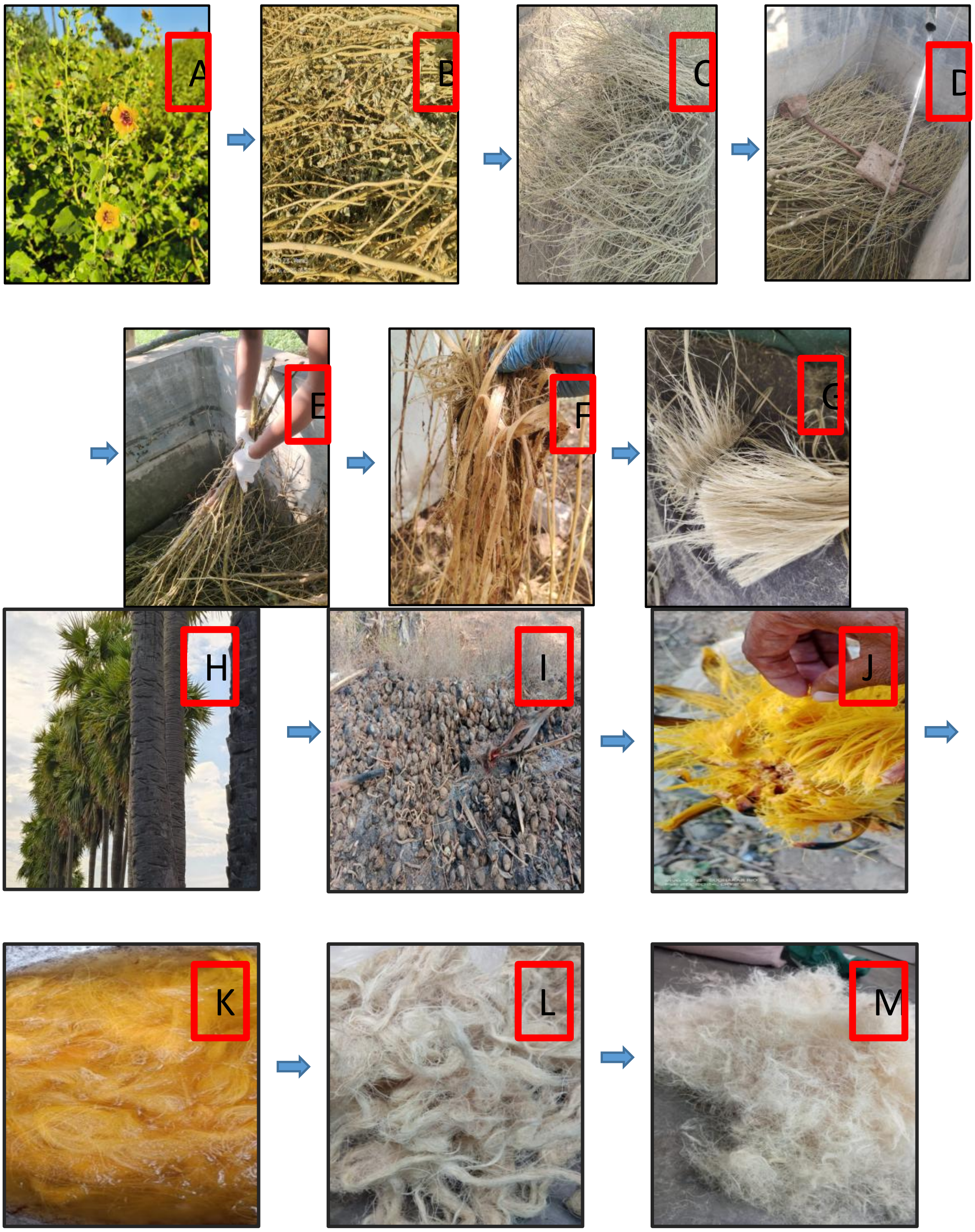


Fig. 1 Isolation and preparation of AIF and BFF fibers

[**A**- AI Plant, **B**- Separation of stem from plant, **C**- Drying of the stem, **D**- Stem soaked in water for retting, **E**- Soaked stem, **F**- Fiber extraction, **G**- AI Fiber.

H- BFF Tree, **I**- BF Fruits, **J**-Fresh fruit of BFF, **K**- Fiber washing, **L**- Drying of fiber, **M**- BFF Fiber.]

Shown by Fig. 1 (H-M) before thoroughly cleaning the fruit to get rid of sugars and other contaminants, the fibrous layer of BFF fruit fiber was physically extracted from the fruit shell. The fibers were washed and then let to dry in the shade. Before undergoing additional processing and characterization, both fibers were kept in closed containers to avoid moisture absorption.

Fiber Characterizations

SEM Analysis

For the, evaluation of surface morphology, AIF and PFF samples were prepared for scanning electron microscopy (SEM) analysis. The samples were approximately 5–10 mm length to ensure ease of handling during SEM analysis. These fiber segments were mounted onto aluminum stubs using double-sided carbon adhesive tape to hold them securely in position and the samples were sputter-coated with a thin layer of gold (~10 nm thickness) using a vacuum sputter coater. The prepared samples were then analyzed using a scanning electron microscope under high vacuum at an accelerating voltage suitable for natural fiber imaging 5kV. SEM micrographs were captured at various magnifications to observe and compare the surface texture, cracks, grooves, and general morphology of both AIF and PFF samples.

FTIR Analysis

In working with an infrared spectrometer with a scanning rate of 30 scans min-1 and a resolution of 16 cm-1, Happ-Genzel was able to identify the free functional groups found in the natural fibers as well as their distinct chemical bonds. The 400–4000 cm-1 wavelength range was used to analyze the sample.

TGA Analysis

Determining the notable thermal durability of natural fibers at high temperatures of 220 °C for at least a few minutes is crucial since Thermo Gravimetric Analysis (TGA) uses mass change to measure the thermal stability of natural fibers during the heating process (Selvi S.T et al 2024). A STA Simultaneous Thermal Analyzer was used to perform Thermo Gravimetric Analysis (TGA), Differential Scanning Calorimetric (DSC), and Derivative Thermo gravimetric (DTG). Each fiber samples approximate weights of AI (4.262 mg) and BFF (3.003 mg) were measured and put in an alumina crucible. The analysis was carried out at a steady flow rate of 50 ml/min in an atmosphere of nitrogen that prevents oxidation. The heating procedure took place at a pace of 10°C per minute, ranging from ambient temperature to 1000°C. The heat resistance and weight loss of the fibers under elevated temperatures were examined using thermo gravimetric analysis. The TGA curves for the AI and BFF fiber samples were recorded.

RESULTS AND DISCUSSIONS

Scanning Electron Microscopy (SEM) Analysis of AIF and BFF fibers

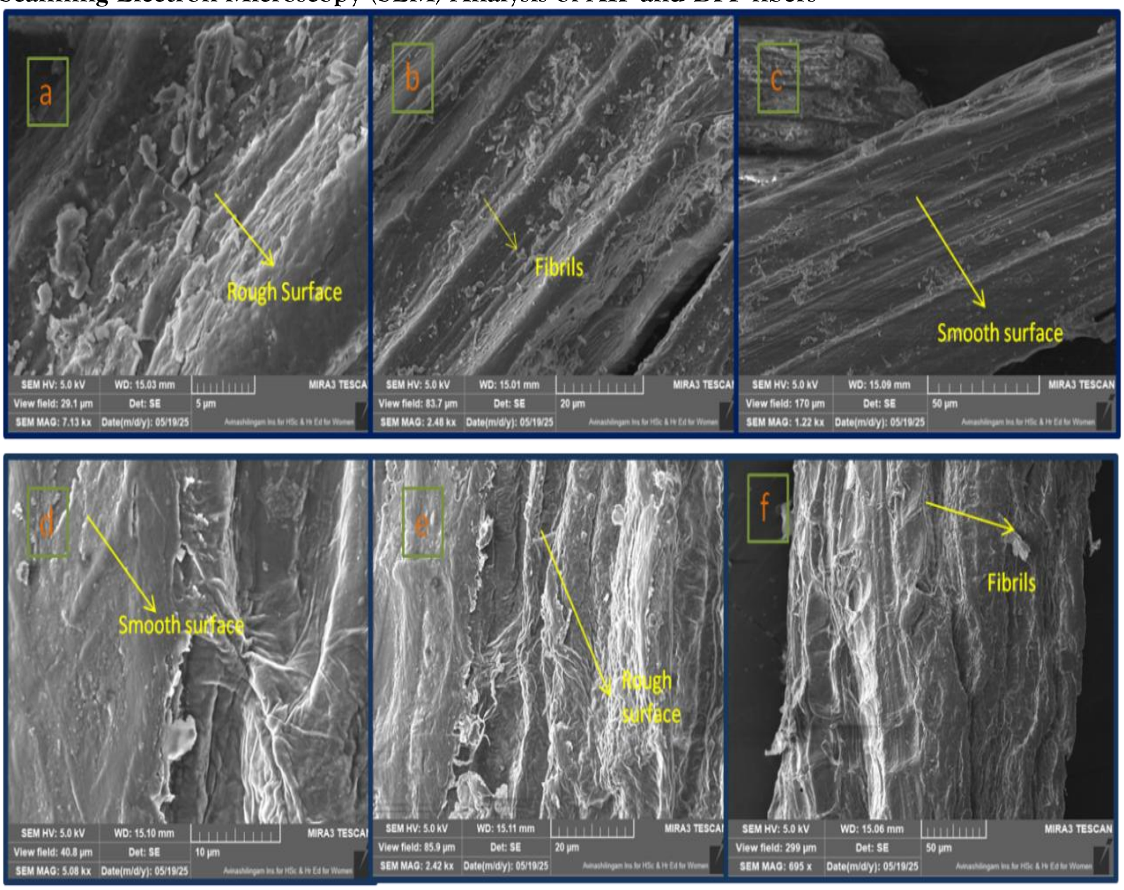


Fig. 2 SEM image of surface view- AI (a-c) and BFF (d-f)

Different morphological characteristics of AI and BFF fibers are shown in Fig. 2, (a-f) the SEM investigation. Longitudinal ridges, grooved surfaces enhance area for improved fiber-matrix attachment and rough surface of the fiber that indicates the possibilities of using AI fibers as reinforcement in a fiber reinforced polymer composites. While small cracks might improve mechanical interlocking without sacrificing fiber integrity, the extraction method worked as clean fiber surface, free from residual impurities, reflects the effectiveness of AI fibers Shown in Fig. 2 (a-c). A denser structure with less moisture absorption and enhanced dimensional stability is indicate a smoother, more compressed surface, which has fewer striations and occasional micro-voids of BFF shown in Fig. 2 (d-f). These variations demonstrate whether the two fibers work together effectively for thermal insulation applications, with AI providing better interfacial bonding and BFF adding bulk and stability.

Functional groups Evaluation of AIF and BFF fibers

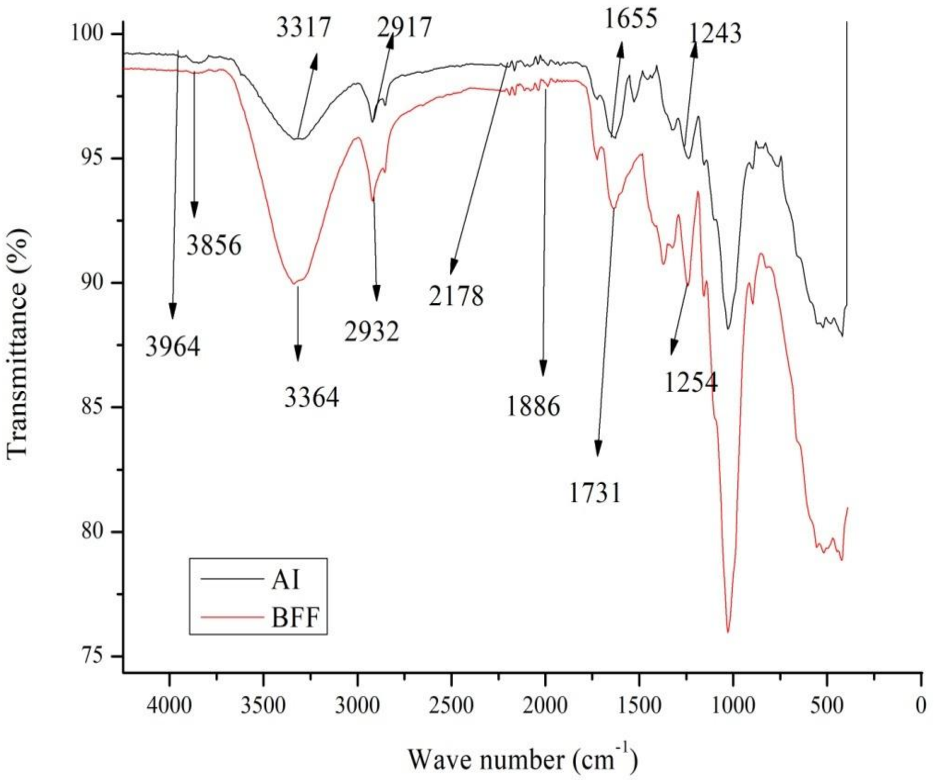


Fig .3 FTIR of AI AND BFF Fibers

The functional groups in AI and BFF fibers were analyzed using FTIR spectroscopy, as shown in Figure 3. The hydrogen-bonded OH stretching and the presence of alcohols or water are responsible for the peaks at around 3964 and 3856 cm (Velmurugan T et al 2025; Manimaran P et al 2018). Indicating the stretching vibration of the O-H bond in hydroxyl groups (—OH), the wave number between 3317 and 3364 cm^{-1} indicates the existence of β cellulose, which is common in alcohols or phenols (Rao J et al 2024; Hindi J et al 2025). The presence of cellulose and hemicelluloses is indicated by the wave number around 2917 and 2932 cm^{-1}, which corresponds to C-H stretching attributed to vibrations from CH and CH_2 groups (Selvaraj M et al 2023; Udhayakumar A et al 2023; Rao J et al 2024 a). The stretching vibration of an alkynes group (–C≡C–) or nitrile group (–C≡N), unsaturated hydrocarbons, or nitriles is often associated with the wave number 2178 cm^{-1} in (Khan Aet al 2022; Rao J et al 2024 b). The acetyl group in lignin and hemicelluloses is stretched by the C=O carbonyl bond, forming the peak at 1655 cm^{-1} (Tamanna et al 2021; Rao J et al 2024 c). The existence of hemicelluloses is notably suggested by the curve at 1731, 1886 cm—1, which represents C = O stretching (esters, ketenes, or aldehydes) (Loganathan T.M et al 2020; Dev et al 2025). The -COC groups, indicative of hemicelluloses, are shown by the points noted at 1243 and 1254 cm^{-1} (Reddy B.M et al 2021).

Thermo Gravimetric Analysis of AIF and BFF fibers

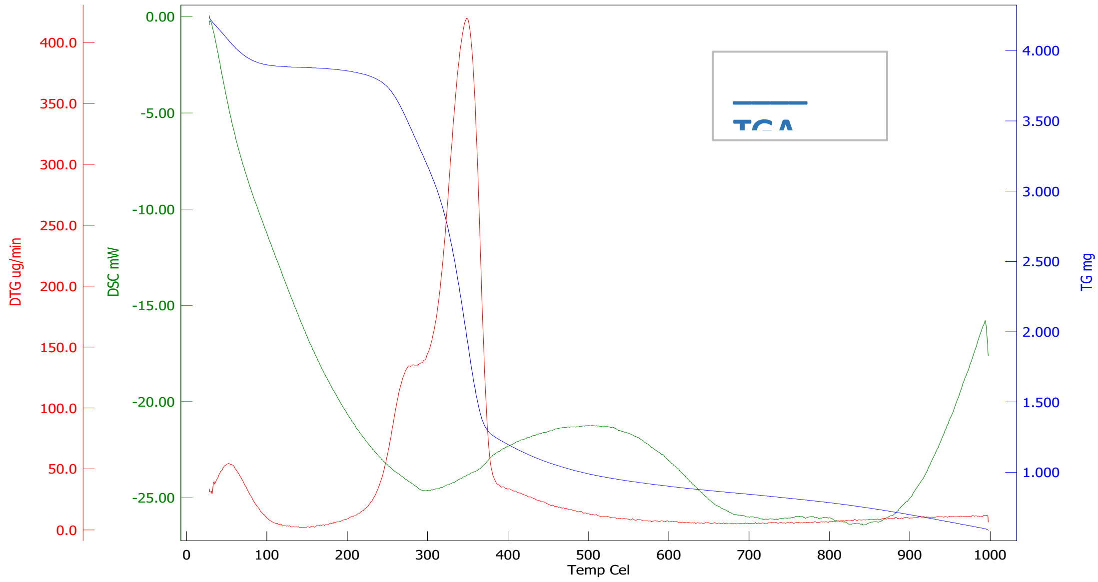


Fig .4 TGA of AI Fiber

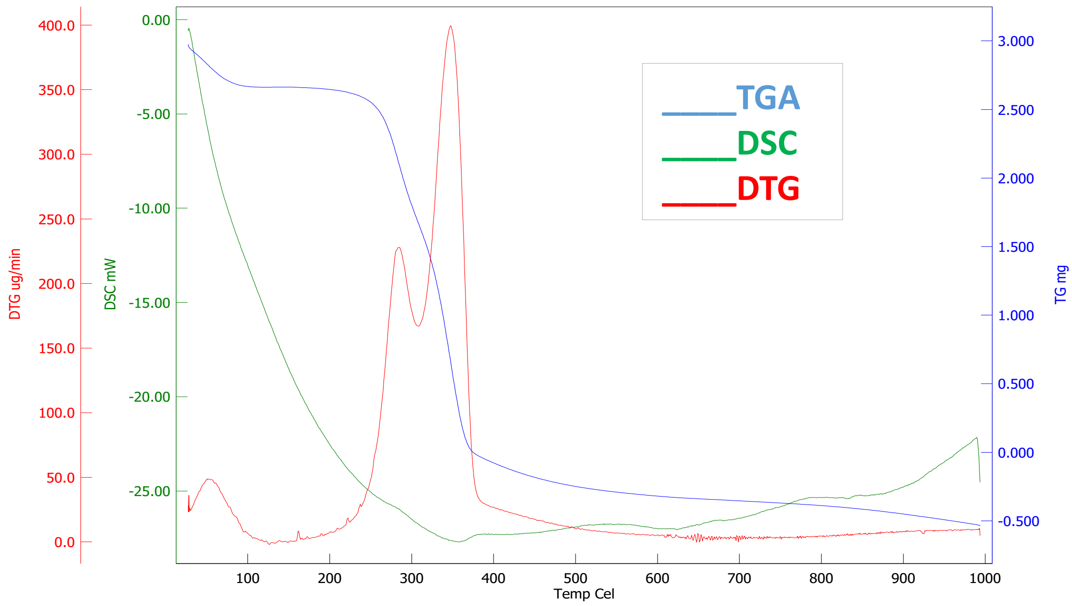


Fig .5 TGA of BFF Fibers

Fibers of AI and BFF – Thermal Behavior

The thermal behaviors in AI fibers were analyzed using Thermo gravimetric, as shown in Fig.4. The evaporation of physically adsorbed and bonded water molecules was the main cause of the little weight loss (~5%) that occurred during Stage I (30–120 °C). The DSC curves endothermic peak, which shows an energy-intensive desorption process, about 95 °C further supports findings. The majority of the mass loss occurs in Stage II (280–390°C), which is the primary thermal degradation zone. Indicating the highest rate of heat deterioration, the DTG curve shows a strong peak at approximately 370°C. The degradation of cellulose (320–380°C) and hemicellulose (280–320°C), the primary components of lignocellulosic fibers, occurs in this zone. During cellulose depolymerization, there appears to be substantial structural rearrangement and energy release, as shown by the large exothermic transition that occurs in the DSC trace. The decomposition of lignin, a more thermally stable and aromatic polymer, is indicated by Stage III (above 450°C), when weight loss significantly slows. Fixed carbon and inorganic ash concentration are responsible for the remaining weight after 900°C, suggesting that AI fibers have a limited capacity to char. The thermal behavior in BFF fibers were analyzed using Thermo gravimetric, as shown in Fig.5. The first moisture loss in Stage I (30–100°C) peaks endothermic at 90 °C. DTG peaks at ~310°C and 370°C indicate successive hemicelluloses and cellulose breakdown, whereas Stage II (260–390°C) shows significant weight loss (~60%). This section of the DSC curve exhibits high levels of exothermic activity. Reduced weight loss and a progressive breakdown of lignin are features of stage III (400–600 °C). A slight endothermic shift is seen at Stage IV (over 850°C), which might be imposed on by changes in the mineral phase or the transformation of the carbon residue. The lignocellulosic and heterogeneous character of the fiber has been demonstrated in this thermal profile. The degradation of polysaccharides occurs once the thermal stability of AI and BFF fibers is reached, which is approximately 250°C.

CONCLUSION

The analysis of AI and BFF fibers reveals the ways that they complement each other for the development of sustainable materials. AI fiber higher thermal degradation temperature provides enhanced stability under heat, while its rough and porous shape enhances fiber-matrix adhesion. BFF fiber, on the other combination, provides a smoother, more compact surface that lowers moisture absorption and improves dimensional stability. TGA/DTG results showed multi-phase thermal degradation characteristic of lignocellulosic fibers and thermally stable (up to 390° C), whereas FTIR analysis confirmed the accurate removal of non-cellulosic components. A combination of AI and BFF may improve performance qualities in nonwoven fabric applications, particularly for thermal insulation, according to the different morphological and thermal behaviors. In the ecologically concerned textile and composite sectors, our findings support the feasibility of both fibers as affordable, biodegradable substitutes for synthetic fibers, packaging and cushioning materials, sound absorbing panels, eco-friendly pet animal livestock mat.

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Data Availability

Data are available on reasonable request.

Credit Authorship contribution statement

Meena Kandhasamy: Conceptualization, Data curation, Formal analysis, Investigations, Methodology, Writing –original Draft, Writing – review and Editing. **S. Grace Annaporani:** Writing – review and Editing, Supervision.

Declarations

Conflict of interest the authors declare that they have no conflict of interest.

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Review of literature

Abutilon indicum Fiber

Tropical and subtropical areas are native to the majority of the bast fiber-producing plant Abutilon indicum. Retting or mechanical decortication are methods used to remove the fibers from the stem. According to earlier research, AI fibers are appropriate for environmentally friendly composite and textile applications because of their low density, high biodegradability, and moderate tensile strength. According to Arun Ramnath et al. (2023), their lightweight yet moderately stiff properties are a result of their 58–65% cellulose concentration and around 12–16% lignin level. By bleaching, combining with other natural fibers, and applying alkali treatment, some researchers have tried to improve the mechanical and thermal qualities of AI fibers (Ramnath et al., 2024). However, their utilization in advanced textile structures such as thermal-insulating nonwovens remains limited.

Borassus flabellifer (Palmyra palm) fiber

The mesocarp of the mature fruit of the Borassus flabellifer, a species that is commonly found in South and Southeast Asia, is where palmyra fruit fiber is found. Cellulose, hemicellulose, lignin, and trace levels of fat or wax are found in the chemical composition study (Saravanan et al., 2024). According to Godi Sindhu et al. (2024), the cellulose content ranges from 70.27 to 72.31%, the hemicellulose from 25.48 to 30.12%, the fat/wax from 1.12 to 1.49%, and the lignin from around 12 to 16%. Due to their high lignin concentration and inherent coarseness, these fibers provide exceptional durability and moisture resistance. The fibers from palmyra fruit have been investigated for use in cushion fillings, matting, and composites because of their biodegradability and durability. According to Srinivasababu et al. (2014), they are also less thermally conductive than synthetic fibers, which make them attractive options for insulation applications.