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Research article

Extraction and characterization of novel alternative cellulosic fiber for sustainable textiles from *Aloe barbadensis* Miller stems (agricultural waste)

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A R T I C L E I N F O

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A B S T R A C T

Novel research has been conducted on *Aloe vera*, focusing on stems fiber (agricultural waste), for the extraction of cellulosic fiber, an area lacking prior scientific exploration. This fiber is being reported for the first time in the scientific community. *Aloe barbadensis* Miller variety was subjected to various cultivation methods, including the application of inorganic and organic fertilizers, along with the removal of lower leaves to promote stem growth. Stem fibers were extracted using the water retting method and subsequently analyzed. The moisture content was 55.35 % and 6.99 % ash content in the fibers. The bacteriostatic analysis of *Aloe vera* fibers was assessed against four bacterial strains, with both ethanol and water extracts showing varying degrees of inhibition zones. The UV–Visible spectrum exhibited a distinct λ_{max} at 247 nm in ethanol, while FT-IR analysis provided characteristic peaks at 3759, 1590, 1750, 1663, 1250, 564, SEM images displayed the smooth surface morphology of the fibers, and X-ray diffraction analysis indicated a high degree of crystallinity (78.67 %), suggesting a well-structured and crystalline nature. Energy dispersive X-ray (EDX) analysis was conducted to determine the elemental composition of the fibers, revealing the presence of carbon, oxygen, calcium, and copper, with carbon being the predominant element in cellulose. These results showed promising properties suggesting potential applications in textile industry as an alternative sustainable natural cellulosic fiber.

1. Introduction

The world is undergoing constant change, driven by evolving demands, priorities, climate shifts, costs, and quality considerations. Climate change, particularly, has a profound impact on all life forms, posing a significant threat due to the adverse effects of global warming. Failure to address this issue could threaten humanity's future [1–5].

In the era of industrial revolution, Industry 4.0 is currently underway. However, transitioning to Industry 5.0 and 6.0 necessitates a holistic approach to business supply chains, emphasizing a zero-waste model, net-zero emissions, circular economy principles, upcycling techniques, and a strong focus on ecosystem sustainability. The textile industry stands as the second-largest contributor to

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greenhouse gas emissions, following the aviation/ transport sector [6–10]. Recognized brands are intensively engaged in developing biodegradable, less toxic, eco-friendly, and sustainable textile products, often incorporating agricultural waste and upcycling plastic waste. Cotton, a natural fiber, remains a popular choice worldwide for producing sustainable textiles. However, there is a growing demand for alternative textile fibres to meet the requirements of sustainable fashion worldwide [11–16].

Belonging to the Asphodelaceae family, the *Aloe vera* plant has emerged as one of the most commercially important medicinal plants worldwide. In fact, the processing of *Aloe vera* leaves generated a revenue of 2.4 billion US dollars in 2019 alone, a figure expected to rise to 3.2 billion US dollars from 2020 to 2027 [17,18]. Compound annual growth rate is 9.4 % and its market size is 553.1 billion USD in 2021 and it will reach up to 1134.86 billion USD in 2029.

The global market for *Aloe vera* is predominantly led by the USA (65 %), with India (10 %) and China (10 %) following closely behind. The widespread exploitation of *Aloe vera* worldwide can be attributed to the diverse spectrum of beneficial properties associated with the various bioactive compounds like polysaccharides, such as glucomannans, aloin, an anthraquinone C-glycoside, acetylated mannose linked to glucose by β-1–4 glycosidic linkage, found in this plant [19]. It can thrive in conditions with limited water availability, making it well-suited for areas affected by water scarcity exacerbated by climate change. Embracing sustainable practices encourages the adoption of water-efficient methods across various aspects of life [20]. The *Aloe vera* plant has garnered attention for its diverse applications beyond traditional uses. Recent research has focussed into its chemical composition, revealing its potential in various fields. Studies have identified numerous bioactive compounds in *Aloe vera*, such as octacosanol, subenniatin B, dinoterb, arjungenin, nonadecanone, and quillaic acid, known for their insecticidal properties. These compounds, along with others, exhibit antibacterial, antifungal, and potential health benefits [21,22]. The plant's rinds contain these compounds, making them valuable for insecticidal applications. *Aloe vera* has been explored for various applications, including the development of natural insecticides using its discarded peels. These peels, previously considered agricultural waste, have shown promise in deterring insects from crops, offering a sustainable and environmentally friendly alternative to traditional pesticides. The significance of *Aloe vera* lies in its potential to address agricultural challenges, particularly in regions where insects pose a threat to crops, such as parts of Africa, the Americas, and India [23]. By repurposing *Aloe* peels as insecticides, researchers aim to not only mitigate insect-related issues but also contribute to greener and more sustainable agricultural practices. These findings highlight the multifaceted nature of *Aloe vera*, its value beyond its well-known medicinal properties. The plant's chemical composition and newfound applications highlight its versatility and potential impact on agriculture and environmental sustainability [24,25]. Utilizing locally available medicinal herbs from the forest has long been practiced for treating various ailments. Beyond their medicinal use, these plants hold significance in rituals, spiritual healing, and other cultural practices. This indigenous knowledge of medicinal plants not only aids in improving community healthcare but also serves to preserve cultural traditions and biodiversity [26,27].

Aloe vera stands out prominently in both traditional and modern contexts due to its remarkable therapeutic, cosmetic, and nutritional properties. The gel-like substance presents in its leaves, commonly referred to as "*Aloe* gel" or "*Aloe* latex," is the key to its beneficial attributes. Stored in the parenchyma cells of the inner leaf layer, this gel contains a diverse array of bioactive compounds, including vitamins, minerals, enzymes, and polysaccharides [28,29].

The primary aim of our research is to explore the most effective method for extracting *Aloe vera* fiber from the plant's stem and assess its potential antimicrobial properties for potential biomedical applications. Our current research represents a breakthrough in the textile and scientific community, as we utilized *Aloe vera* stems (agricultural waste) to extract natural medicated fibers for textile production.

This alternative natural fiber fills a gap, as previous reports focused solely on fiber extraction from *Aloe vera* leaves, which are not available on a large scale globally due to its limited fiber yield in the leaves. In the textile industry, *Aloe vera* gel is primarily used for textile dyeing and finishing including special value-added finishing and technical textile (UV protection, anti microbial, wound healing, Cosmo textiles, wearable electronics). *Aloe vera* leaves, particularly due to the presence of acemannan, have significant applications in the textile industry because of their immune modulation, antibacterial, antifungal, and antitumor properties. *Aloe vera* treated textiles exhibit excellent antimicrobial activity, which is essential in healthcare and hygiene-sensitive environments. Components like acemannan and anthraquinones in *Aloe vera* inhibit the growth of bacteria such as *Staphylococcus aureus* and *Escherichia coli*, with efficacy that persists through multiple washes. *Aloe vera*'s wound healing properties are utilized in medical textiles, promoting cell proliferation and tissue regeneration, making it ideal for wound dressings. *Aloe vera* also offers natural UV protection, beneficial for outdoor textiles, providing an additional layer of protection against harmful UV rays. Its succulent and gummy characteristics enable its use in eco-friendly dyeing processes, acting as a natural mordant to facilitate dyeing without harmful chemicals, aligning with sustainable textile processing methods. In cosmetotextiles, *Aloe vera*'s moisturizing properties enhance comfort and provide therapeutic effects. Also, advancements have integrated *Aloe vera* into wearable electronic textiles, where its biocompatibility and functional properties improve the performance and comfort of electronic devices worn on the body (Intelligent manufacturing). At the same time, its fibers are not commercially used for manufacturing garments due to their low fibrous content and inability to produce durable, high-strength textiles. The extraction and processing of *Aloe vera* fibers on an industrial scale are challenging and cost prohibitive. The fibers lack the necessary mechanical properties, such as tensile strength and flexibility, required for mainstream textile applications, limiting their use to finishing and enhancing textiles rather than serving as the primary material. Established fibers like cotton, hemp, sisal, linen, banana, bamboo, flax, abaca, jute, coir, ramie, kapok, pineapple,cashmere, mohair, angora, alpaca, vicuna, guanaco, llama, qiviut, asbestos (not used due to health concern), seaweed fiber, different rayons, wool, silk, all azlon, alginate, chitosan, polyester, polyamide, acrlyic, polyolefin, elastomeric, aramid based, polyvinyl, polyurethane, carbon, glass and basalt dominate the market, making it difficult for less common *Aloe vera* fibers to compete on price and performance. There is limited awareness and research on *Aloe vera* fibers' applications, especially regarding their mechanical properties and performance in textiles. Growing consumer demand for sustainable textiles is met with a lack of understanding about *Aloe vera* fibers among manufacturers and consumers, limiting their adoption. Compliance with industry standards and regulations is a hurdle for *Aloe vera* fibers, potentially requiring additional certifications [30–36]. The production of *Aloe vera* leaf fiber is indeed limited, and this scarcity extends to the lower stem part of the plant as well. *Aloe vera* is primarily cultivated for its gel, widely used in the cosmetic and pharmaceutical industries due to its soothing and healing properties. The gel is also used for the synthesis of *aloe vera* nano powder for varies industrial nano applications. This focus on gel production means that other parts of the plant, such as the leaf fibers and stems, are often underutilized or discarded as agricultural waste [37,38]. If the textile industry were to cultivate *Aloe vera* on their own land, they could use both the stems and leaves for fiber extraction and blend them with other natural fibers like banana, sisal, and cotton. The gel could be used as a fertilizer for the cultivation and in textile finishing for special treatments such as UV absorbent, antimicrobial, and anticancer finishes, as reported by many researchers [39,40]. Similarly, phenolic compounds in *Aloe vera* can be used to dye textile goods along with other anti microbial benefits [41]. The lower stem part of the *Aloe vera* plant, also known as the basal stem or rhizome, is not typically harvested for fiber production. This part of the plant is essential for its growth and stability, anchoring it in the soil and storing essential nutrients. Harvesting it for fiber would be impractical and could jeopardize the health and sustainability of *Aloe vera* crops. *Aloe vera* plants have a relatively slow growth rate, taking several years to mature enough to produce significant amounts of gel and other by-products. This slow growth further limits the availability of any part of the plant for large-scale fiber production. Although *Aloe vera* has many beneficial uses, its cultivation is primarily geared towards gel extraction rather than fiber production. The limited availability of leaf fibers and the critical role of the basal stem in plant health make it unlikely that these parts will become abundant sources for fiber production in the future to come [7,42–44].

The holistic approach comprises of the cultivation of the *aloe vera* plants, utilization of green fertilizers derived from *Aloe vera* plants, fiber extraction from leaves and also from the stem with high yield, pure and blended yarn spinning, weaving or knitting, dyeing or printing with reactive, vat, sulphur, direct, indigo and other natural dyes, bacterial coloration technology, and finishing using various chemicals and *Aloe vera* gel. We have completed the cultivation and yarn extraction technology with characterization and its suitability for alternative natural fiber. The other steps are also completed, and our technology is ready to transfer to the industries and we also filed patent on our novel technology. Our technology is readily transferable, and we are open to collaborating with companies to facilitate mass-scale production using intelligent manufacturing systems with net-zero emissions [45–48]. The world requires alternative natural fibers for sustainability, to reduce global warming, and to mitigate the impact of climate change. That's why we decided to work on alternative fibers for the textile industry. Also, there is a need for specialized fibers for medical and other technical textile applications. This research addresses both major aspects of the existing research gap.

2. Materials and methods

2.1. Cultivation and preparation of Aloe vera plant for fiber extraction

Varieties of *Aloe vera* plants were surveyed across several nurseries, among which *Aloe barbadensis* stood out as the most prevalent species and was chosen as the specimen for cultivation. Six *Aloe barbadensis* plants were acquired and identified as *Aloe barbadensis* Miller, with voucher number LCW-1018. The planting of *Aloe barbadensis* occurred on March 30, 2023, within the Botanical Garden of Lahore, Pakistan. Sandy soil, providing adequate aeration and spacing for growth, was selected for cultivation. The planting site received bright, indirect sunlight. Watering practices were tailored to environmental conditions, and fertilizers, both organic and inorganic, were utilized to enhance growth. Inorganic fertilizer, specifically urea, was employed during the spring and summer months. Thirty grams of urea were dissolved in 1 L of water and applied to the soil every 4–6 weeks, with additional nitrogen applications in April, May, and June 2023. This regimen promoted the growth of *Aloe vera* stems and leaves.

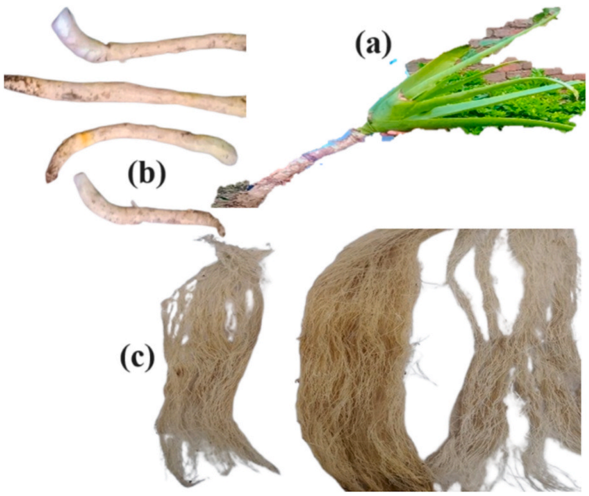


Fig. 1. *Aloe vera* (a) stem growth (b) separation of stem part (c) fiber extraction.

Organic fertilizer, concocted from a mixture of 40 % soil, 40 % cow dung, and 10 % kitchen waste of vegetable and fruit peels, coffee grounds, eggshells, and leaves, was also utilized. This organic blend underwent decomposition by microorganisms in a large clay pot over one month. Following decomposition, 1 kg of the organic fertilizer was applied to the soil every two weeks for the six *Aloe vera* plants. The application of organic fertilizer notably enhanced the growth of *Aloe vera*. While the addition of both organic and inorganic fertilizers increased leaf quantity, the stem length of *Aloe vera* did not show significant improvement. To encourage stem growth, lower leaves were pruned using a clean knife, facilitating more rapid stem elongation (Fig. 1 a). After six months of growth, spanning from March to August 2023, the *Aloe vera* plants reached a stage suitable for sample collection in both stem and leaves. To carefully extract the *Aloe vera* plant from the soil, healthy and mature specimens were singled out. Employing a garden trowel, the earth around the plant's base was gently loosened to facilitate easy removal. Grasping the plant near its base, it was delicately lifted from the soil, ensuring minimal disruption to the roots. Any excess soil clinging to the plant was then removed by shaking. Upon uprooting, the *Aloe vera* plant was cautiously placed in a bucket to safeguard its leaves and roots. Subsequently, the plant was gently shaken to dislodge any loose soil or debris adhering to the roots. Using a soft-bristled brush under running tap water, the leaves and stems were scrubbed to eliminate stubborn dirt or residual soil. Following this, the *Aloe vera* plant was air-dried for several hours.

Before cutting, a clean cutting surface was prepared. The *Aloe vera* plant was carefully inspected to pinpoint the stem for separation from the leaves. Employing a sharp knife, a precise incision was made, commencing at the base of the leaves to minimize damage to the stem. Gloves were utilized to shield the hands from the *Aloe vera* latex, which may cause irritation. A clean cloth was employed to wipe away any latex residue from the cut end of the stem. Protective gloves were utilized to shield the hands from the razor blade during the procedure. A robust, youthful stem was carefully selected for the removal of its epidermis. Employing a sharp razor blade, a precise incision was made on the stem to initiate the process. Subsequently, the blade was maneuverer steadily along the stem, peeling off the epidermis in a controlled manner. The discarded epidermal layer was then disposed of, and the weight of the stems from six *Aloe vera* plants was recorded. These prepared stems were now primed for fiber extraction (Fig. 1 b). Each *Aloe vera* leaf was laid flat upon a sanitized cutting board. Utilizing a sharp knife, the serrated edges of the leaves were trimmed away. A longitudinal incision was then carefully made along the length of each leaf, exposing its inner gel. This gel was gently scraped off the leaf's surface using a clean spoon and collected into a container. The harvested gel was promptly stored in a refrigerator, maintaining a temperature range of 4 °C–8 °C (Fig. 1).

2.2. Fiber extraction from the prepared stem

Numerous methods have been employed in the past to extract natural fiber materials from plant sources [49–52]. After experimenting with various techniques, we developed our own customized method tailored specifically for *Aloe vera*. The extension of *Aloe vera* stem length during cultivation and the innovation of changing the retting water every 1–2 days, based on water turbidity, are designed to prevent cellulose decomposition. This method capitalizes on the combined effects of moisture and bacterial activity, which act upon the plant material, decomposing cellular tissue and dissolving the adhesive substances surrounding the fiber clusters. Once these surrounding materials dissolve, the fibers become readily separable from the stems. A 30-L capacity tank was selected for fiber extraction purposes. The tank was filled halfway with approximately 15 L of water. This volume of water was deemed sufficient to fully submerge all the *Aloe vera* stems. The *Aloe vera* stems were carefully placed into the water-filled tank, ensuring complete immersion. The tank was positioned in a shaded area to maintain an ambient temperature, typically around 25 °C, conducive to the retting process. Regular monitoring of the water in the tank was conducted throughout the retting process. As the retting commenced, the water gradually turned cloudy, indicating the breakdown and dissolution of the gummy substance present in the stem. Depending on the clarity and odor of the water, it was refreshed every 1–2 days to ensure optimal conditions for retting. During water changes, a significant amount of waste and toxins were removed. This waste material was repurposed as liquid fertilizer due to its rich chemical composition. Primary reason for adopting this approach (to change water after every 1–2 days) is to prevent the decomposition of cellulose in the fiber during the retting process as microbial degradation of cellulose can also occur in this suspended water [53–55]. The degree of polymerization (dp) decreases due to this decomposition process, and many studies support our claim. We have also observed this during textile processing. Wet fabric in ambient conditions always weakens, necessitating the use of different chemicals to improve tear and tensile strength. This is why we modified the traditional method found in the literature. After a duration of 3 weeks of retting, the outer skin of the *Aloe vera* stem was carefully scraped away. Gentle pressure was applied by fingers to expel the dissolved gummy substance from the stem. Subsequently, the stem was halved along its length and submerged in water once again. Following an additional 5 weeks of retting, the fibers became sufficiently loosened and were primed for extraction. The stems were then extracted from the water tank, and the outer skin was scraped off using a knife. Subsequently, the fibers were manually separated from each other by hand. The extracted fibers were spread out on a dry surface and exposed to sunlight in a well-ventilated area. After 3 days, the fibers were completely dried. These dried fibers were then stored in a cool, dry location (Fig. 1 c). To determine the yield of fibers from each stem, the fibers were weighed using a digital weighing balance, and the percentage of fibers relative to the total stem weight was calculated.

2.3. Characterization of the Aloe vera fiber

The different characterization tests were performed based on the previous literature cited methodology of different researchers [56, 57].

2.3.1. Antimicrobial activity of Aloe vera fibers

To assess the antibacterial efficacy of the fibers, bacterial strains were obtained from the Fungal Biology and Systematics Research Lab within the Department of Botany at GCU Lahore, Pakistan. The selected bacterial species included *Bacillus subtilis, Staphylococcus aureus, Escherichia coli,* and *Klebsiella pneumoniae.* Maintaining strict aseptic conditions, sterile inoculation loops were utilized to transfer bacterial colonies from each strain into separate 25 mL falcon tubes containing double distilled water. These tubes were then vortexed for 10 min to ensure a homogenized mixture.

The antibacterial properties of *Aloe vera* plant fiber extracts, both alcohol-based and water-based, were evaluated using the well diffusion technique against *Bacillus subtilis*, *Staphylococcus aureus*, *Escherichia coli*, and *Klebsiella pneumoniae*. These experiments were conducted under sterile conditions to mitigate the risk of contamination [23,58,59].

A sterile cotton swab was saturated with the liquid inoculum of each bacterial strain and evenly spread across the surface of LB agar plates, resulting in the creation of four distinct bacterial lawns on four separate plates. Each plate was punctured with four wells, each 7 mm in diameter, using a sterile cork borer. Varying concentrations of alcohol and water extracts were then added to the respective wells.

After 24 h of incubation at 37 °C, the diameter of the inhibition zones around each well was measured using a ruler to gauge the antibacterial activity of the extracts.

2.3.2. Moisture content

Oven drying simple technique was utilized to ascertain the moisture content [60] in *Aloe vera* plant fibers.

$$\text{Moisture Content (\%)} = [(Ws - (W_2 - W_1)] / W_s \times 100$$

Where:

W_1 = Weight of petri plate after drying in the oven.

W_s = Initial weight of the sample fibers before drying in the oven.

W_2 = Weight of petri plate + sample fibers after drying in the oven.

2.3.3. Ash content

The ash percentage [61] in *Aloe vera* fibers was determined by incinerating the fibers in a muffle furnace.

$$\text{Ash Content (\%)} = (W_2 - W_1) / W_s \times 100$$

Where: W_1 = Weight of crucible after drying in the oven; W_2 = Weight of crucible + ash after drying in the oven; W_s = Weight of fibers placed in the crucible.

2.3.4. UV visible spectroscopy

UV–visible analysis serves as a crucial investigative tool in the study of *Aloe vera* fibers. To conduct this analysis, the fibers were finely ground into a powder using a pestle and mortar. Subsequently, a solution containing 200 parts per million (ppm) of the fiber powder was prepared using various solvents, with 1 mg of sample dissolved in 5 mL of solvent. These solutions were allowed to stand for 24 h before being subjected to sonication for 1 h. Following this preparation, their UV–visible spectra were recorded using a Shimadzu UV–visible spectrophotometer. This analytical approach hinges on the fundamental principle that each compound exhibits a distinct λ_{max} value and transition, allowing for the identification and characterization of compounds present in the *Aloe vera* fibers [62].

2.3.5. FTIR spectroscopy

FT-IR analysis offers insights into the functional groups within a compound. In this study, fiber powder underwent FTIR spectroscopy, generating a spectral data set. The transmission mode was employed for recording the FTIR spectrum. By analyzing the transmittance, the functional groups present in *Aloe vera* plant fibers were identified [63].

2.3.6. SEM and EDX

A scanning electron microscope (SEM) was employed to examine the morphology of *Aloe vera* fibers. Prior to analysis, the fibers underwent cutting and grinding into a fine powder using a pestle and mortar. Subsequently, the fiber sample was coated with a layer of gold to enhance conductivity. Following this, it was mounted onto the SEM stub for examination. Morphological details were captured using the Everhart-Thornley detector. EDX detected the inorganic metals in the samples [64].

2.3.7. XRD analysis

The primary aim of this study was to examine the crystalline structure of fibers extracted from *Aloe vera* plants through X-ray diffraction (XRD) analysis. After a drying period of 48 h at room temperature, the fibers were desiccated and ground into a fine powder to ensure uniformity for the XRD procedure. For the XRD analysis, X-ray diffractometer equipped with a Cu-Kα radiation source was utilized, set at a wavelength of $\lambda = 1.5418$ Å. Operational parameters were standardized at 40 kV for voltage and 30 mA for current. To prepare the sample for analysis, a precise quantity of *Aloe vera* fiber powder was carefully deposited onto a glass substrate, ensuring an even and homogeneous distribution to guarantee accurate results. This prepared sample was then securely positioned onto the sample holder of the diffractometer for analysis [65]. To calculate the areas of crystalline and amorphous regions in XRD patterns, first we identify the characteristic peaks in the XRD pattern that correspond to the crystalline regions. Then use the height of the crystalline peak (I_200) and the minimum intensity between the crystalline peaks (I_am) to calculate the CrI using the formula:

$$\mathrm{Cr\ I} = \frac{\mathrm{I\ 200} - \mathrm{I\ am}}{\mathrm{I\ 200}} \times 100$$

The area under the peaks representing crystalline regions is integrated to quantify the crystalline content. Similarly, the area under the amorphous hump is integrated to determine the amorphous content. Typically, baseline correction is performed to accurately separate the crystalline and amorphous contributions. However, for plant fibers, calculations can be performed without baseline correction, directly integrating the areas under the respective peaks.

2.3.8. Thermal analysis (TGA DSC combined)

Combined TGA and DSC was performed on the SDT Q600 V8.3 Build 101. It combines simultaneous differential thermal analysis (DTA) or differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA) in a single measurement. This allows for comprehensive characterization of materials by analysing both heat flow and weight changes as a function of temperature or/and time.

Thermogravimetric Analysis (TGA) is a technique used to measure the amount and rate of change in the weight of a material as a function of temperature or time in a controlled atmosphere. TGA provides valuable information about the thermal stability, composition, and decomposition characteristics of materials. First, we prepared a small amount of the sample. Then the sample was heated in a controlled atmosphere, under inert gas conditions. The sample was subjected to a heating with a gradient of 10 °C per minute up to 800 °C. The instrument continuously measures the weight of the sample as it is heated.

Differential Scanning Calorimetry (DSC) is a thermal analysis technique used to measure the heat flow into or out of a sample as a function of temperature or time. It provides information about thermal transitions such as melting, crystallization, glass transitions, and other thermal events. A small sample was placed in a DSC pan. An empty reference pan was also prepared. The DSC experiment can be conducted in an inert atmosphere to prevent oxidation. The sample and reference pans were subjected to controlled heating and cooling with a gradient of 10 °C per minute. The DSC instrument measures the difference in heat flow between the sample and the reference as the temperature changes [66].

3. Results

Aloe vera, a succulent plant with a rich history of medicinal use, boasts numerous health benefits. Its gel, extracted from the inner leaf, is renowned for its soothing and therapeutic properties, particularly in treating skin conditions such as burns, sunburns, and wounds. Its anti-inflammatory and antimicrobial characteristics have made it a key ingredient in topical ointments and skincare products. *Aloe vera* has shown promise in easing digestive problems like constipation, and emerging research suggests its potential in managing diabetes and reducing cholesterol levels. The versatile *Aloe vera* plant continues to be highly regarded as a natural remedy, prized for its diverse medicinal applications. Studies indicate its potential in managing diabetes and lowering cholesterol levels. Leveraging its natural healing properties, *Aloe vera* remains a valuable and easily accessible resource in both traditional and modern medicine.

3.1. Extraction of cellulosic fibers from Aloe vera stem

The stems of six plants were used for the extraction of fibers. The weight of six stems was 64.008 g, 86.733 g, 95.099 g, 65.7 g, 126.801 g and 67.518 g. After applying the water retting method for 5 weeks, the fibers of each stem were separated easily, and their weight was 10.256 g, 12.201 g, 12.801 g, 10.387 g, 16.552 g and 10.182 g respectively of each stem as shown in Table 1 below.

3.2. Moisture content analysis

Moisture analysis was conducted to assess the moisture content in the fibers. The moisture content in the fibers was found 38.471 %, 38.250 %, 37.446 % in experiment # 01, 02 and 03 respectively, indicating a significant presence of moisture. This abundance of moisture in the fibers has been shown to accelerate wound healing rates by up to 50 %. *Aloe vera* stem fibers have significant potential in wound healing, primarily due to their moisture-retaining properties and bioactive components. Moisture is important for effective wound healing as it promotes cell migration and tissue regeneration. *Aloe vera* fibers can retain moisture, creating a humid micro-environment that facilitates the healing process. This moisture retention helps prevent scab formation, allowing for faster re-epithelialization of the wound surface [67]. *Aloe vera* contains various bioactive compounds, including polysaccharides, vitamins, enzymes, and minerals, which contribute to its therapeutic effects. Polysaccharide compounds, particularly mucopolysaccharides,

Table 1
Comparison between weight of stem and extracted fibers.

Contents	Stem 01	Stem 02	Stem 03	Stem 04	Stem 05	Stem 06
Weight (g)	64.008	86.733	95.099	65.70	126.801	67.518
Extracted fibers (g)	10.26	12.2	12.8	10.39	16.55	10.18
Fiber (%)	16.03	14.07	13.47	15.81	13.05	15.08

have humectant properties, meaning they help retain moisture in the wound area, which is essential for healing. *Aloe vera* has been shown to reduce inflammation, which can be beneficial in managing the healing process by minimizing pain and swelling [68]. The natural antimicrobial properties of *Aloe vera* help prevent infections in wounds, which is critical for promoting healing and avoiding complications. *Aloe vera* fibers can be incorporated into wound dressings, either directly or through electrospinning techniques, which create nanofibers that enhance the dressings' properties. These dressings not only provide a barrier against pathogens but also allow for the exchange of gases and moisture, further supporting the healing process. The extracted *Aloe vera* stem fibers play a multifaceted role in wound healing by maintaining moisture, providing bioactive compounds that promote healing, and preventing infections. Their incorporation into wound dressings represents a promising approach to enhance wound care and improve healing outcomes [33]. In short, the high moisture content in the fibers serves multiple beneficial purposes. It reduces the likelihood of infections, thereby reducing the need for antibiotics. It plays a crucial role in promoting angiogenesis, the formation of new blood vessels. The heightened moisture levels also stimulate collagen production and enhance the pace of cell migration. Consequently, there is an improvement in healing outcomes, leading to a decreased risk of complications such as limb amputation, wound infections, and fatalities.

3.3. Ash content analysis

Ash content analysis is a laboratory technique utilized to measure the quantity of inorganic residue (ash) present in organic material samples. The percentage of ash content in fibers was approximately 7 % (6.988 %, 6.872 %, 6.902 % in experiment # 01, 02 and 03 respectively), indicating a sufficient presence of inorganic residue.

The ash comprises a significant number of essential elements possess beneficial properties that are crucial for enhancing treatments for chronic wounds. They contribute to improving the physical attributes of wound dressings, including mechanical strength and moisture vapor transfer capabilities. These inorganic constituents enhance the chemical properties of wound dressings, facilitating the release of drugs and the absorption of exudate and moisture. They play a vital role in improving the biological properties of wound dressings [69].

Ash content refers to the inorganic residue remaining after the organic matter has been burned away, providing insight into the mineral composition of the plant material. High ash content may indicate contamination with soil or other extraneous materials. The ash derived from *Aloe vera* stem fibers primarily consists of various essential minerals for biological functions. In contexts such as dietary supplements or medicinal uses, the mineral content represented by the ash can be important. Ash content can affect the

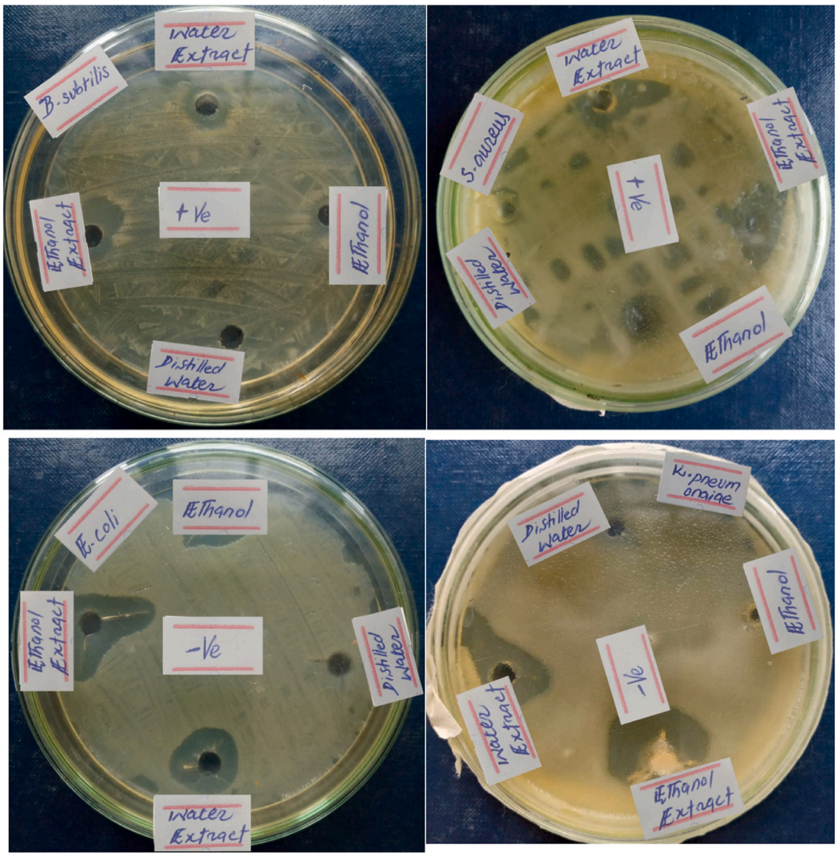


Fig. 2. Antimicrobial testing zone of inhibition (mm) of water and ethanol extract of fibers against four types of bacteria.

processing behavior and properties of the fibers in textile applications. Major components typically found in the ash include silica absorbed from the soil; potassium (K), which is important for cellular function and regulation of fluid balance; sodium (Na), which plays a key role in maintaining osmotic balance and nerve function; calcium (Ca), which is vital for bone health, muscle function, and cellular signaling; magnesium (Mg), which is involved in numerous biochemical reactions, including energy production and protein synthesis; and phosphorus (P), which is crucial for energy transfer and storage in the form of ATP, as well as for bone formation. Trace elements such as iron (Fe), zinc (Zn), manganese (Mn), and copper (Cu) are also present and necessary for various enzymatic functions and metabolic processes. The minerals found in the ash originate from the soil in which the *Aloe vera* plants grow. As the plant absorbs water and nutrients from the soil, these minerals accumulate in its tissues. When *Aloe vera* fibers are burned to determine ash content, the remaining inorganic materials reflect the mineral profile of the growing environment, including both macro and trace elements essential for plant health and development [43,58,70,71].

3.4. Antimicrobial activity of Aloe vera fibers extract

The antibacterial activity (Fig. 2) of both ethanol and water extracts of fibers was assessed against *Bacillus subtilis, Staphylococcus aureus, Escherichia coli*, and *Klebsiella pneumoniae*. Zones of inhibition were observed around the wells containing the extracts. As a control, ethanol and distilled water were also tested, but no zones of inhibition were observed.

In Fig. 2, the water extract of fibers exhibited a 3.5 mm zone of inhibition against *B. subtilis*, a 4 mm zone of inhibition against *S. aureus*, a 3 mm zone of inhibition against *E. coli*, and a 7 mm zone of inhibition against *K. pneumoniae* (Table 2).

These results are evidence of the antimicrobial activity of the fibrous material, indicating its potential for use in medical textiles (technical textiles). Being a healing plant with medicinal properties, it holds extensive applications in wound healing, allergies, and skin-related diseases [72].

3.5. UV–Visible analysis of fibers

UV–visible spectroscopy is a technique that measures the absorbance or transmittance of a sample in the ultraviolet and visible regions of the electromagnetic spectrum (200–800 nm). This technique is used to identify and quantify various compounds based on their absorbance characteristics. Different functional groups absorb light at specific wavelengths. By identifying the absorbance peaks in the UV–visible spectrum of *Aloe vera* stem fiber, we can infer the presence of certain chemical groups. The recorded λ_{max} is 247 nm, with an absorbance value of 5.80 a.u (Fig. 3). The positioning of the spectrum peak in the ultraviolet region indicates that the observed transitions are likely n-π^* transitions. These transitions typically involve relatively lower energy requirements compared to other types of transitions. Consequently, transitions with lower energy demands manifest as peaks at longer wavelengths. Hence, the increase in wavelength corresponds to a reduction in the energy gap necessary for exciting electron transitions. As we can see in UV Visible graph, the peaks are not sharp, but broader peaks so this is a continuous phenomenon of excitation and deexcitations. The absorbance values at specific wavelengths can be used to quantify the concentration of particular compounds in the *Aloe vera* fiber. To explain the UV–visible spectroscopy results for *Aloe vera* stem fiber, we will consider common absorbance peaks and their possible correlations with the compounds present in *Aloe vera*: Peaks around 280–290 nm are mostly due to the phenolic Compounds. Phenolic compounds, which are known to be present in *Aloe vera*, typically absorb in this region. These compounds contribute to the antioxidant properties of *Aloe vera*. The presence of a peak in this region indicates the presence of phenolic compounds, which are important for their protective effects and potential health benefits. Similarly the peak area around 320–330 nm referred the presence of flavonoid, another class of polyphenolic compounds, absorb in the near-UV region. *Aloe vera* is known to contain flavonoids, which have various biological activities, including anti-inflammatory and antioxidant effects. A peak in this region suggests the presence of flavonoids, contributing to the overall bioactivity of the fiber. The peak area around 400–450 nm confirmed the presence of Carotenoids and Other Pigments. Carotenoids and other plant pigments absorb in the visible region. These pigments are responsible for the coloration of plant materials and have antioxidant properties. The presence of a peak in this region may indicate the presence of carotenoids and other pigments, which play roles in protecting the plant from oxidative damage and contribute to its health benefits. Now in the *Aloe vera* stem fiber UV–visible spectrum, absorbance in the 280–290 nm range suggests the presence of phenolic compounds, which are known for their antioxidant properties. These compounds help protect the plant from oxidative stress and contribute to its medicinal properties. Understanding the specific absorbance peaks and their corresponding functional groups helps in elucidating the chemical composition and potential applications of *Aloe vera* stem fiber in various fields, including medical and technical textiles.

Table 2
Zone of inhibition (mm) of water and ethanol extract of fibers against 4 types of bacteria.

Dilution	*B. subtilis*	*S. aureus*	*E. coli*	*K. pneumonaiae*
Ethanol extract	4.0 ± 0.03	4.5 ± 0.06	3 ± 0.05	8 ± 0.03
Ethanol	0 ± 0.01	0 ± 0.02	0 ± 0.08	0 ± 0.02
Aqueous extract	3.5 ± 0.07	4 ± 0.06	3 ± 0.04	7 ± 0.05
DW	0 ± 0.02	0 ± 0.0.4	0 ± 0.02	0 ± 0.02

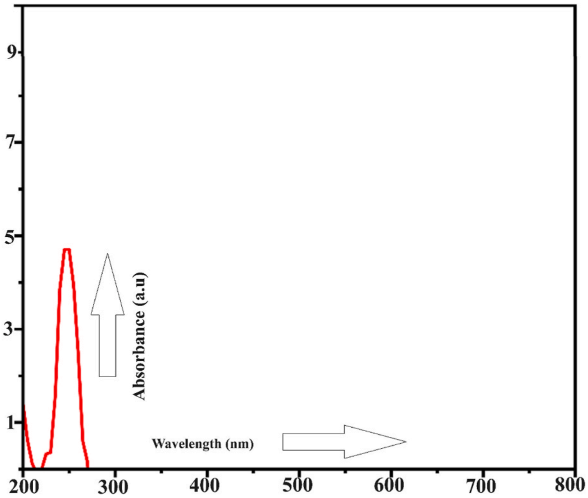


Fig. 3. UV–Visible spectrum of fibers in ethanol.

3.6. FTIR spectroscopy

FTIR analysis was performed to evaluate the functional groups present in the *Aloe vera* fibers (Fig. 4). O-H Stretching peak observed at 3759 cm^{-1} is associated with the stretching vibrations of the hydroxyl (O-H) groups. In *Aloe vera* fibers, these groups are in cellulose, hemicellulose, and residual water. The broad nature of this peak is often due to hydrogen bonding. 1590 cm^{-1} peak was due to C=O Stretching and this peak is indicative of the carbonyl (C=O) stretching vibration. It is commonly found in hemicellulose, pectin, and lignin. In *Aloe vera* fibers, it could be due to the presence of uronic acids in hemicellulose or the esters and aldehydes in lignin. Similarly, a 1750 cm^{-1} peak was observed due to C=O Stretching, which is another carbonyl stretching vibration, this peak typically corresponds to the ester carbonyl groups. In *Aloe vera*, it could be attributed to the acetyl groups present in hemicellulose or esterified pectins. 1663 cm^{-1} peak was Amide I Band, and this peak corresponds to the amide I band, which is primarily due to the C=O stretching vibrations in proteins or peptides. In *Aloe vera* fibers, it might be due to residual proteins or peptide linkages. Another peak at 1250 cm^{-1} was observed due to C-O-C Stretching and this peak is associated with the asymmetric stretching vibration of the C-O-C bonds in cellulose and hemicellulose. It indicates the presence of glycosidic linkages between sugar units in the polysaccharides of the *Aloe vera* fibers. Finally, the 564 cm^{-1} peak was due to C-H Bending and this peak is often related to the bending vibrations of C-H bonds. In *Aloe vera* fibers, it could be indicative of the presence of cellulose and hemicellulose, as these components contain numerous C-H bonds. These peaks confirm the complex composition of *Aloe vera* fibers, primarily consisting of various polysaccharides, proteins, and other organic compounds.

3.7. X-Ray diffraction spectroscopy

The X-ray diffractogram provides insight into the crystalline structure of *Aloe vera* fibers. In this diffractogram, intensity is plotted

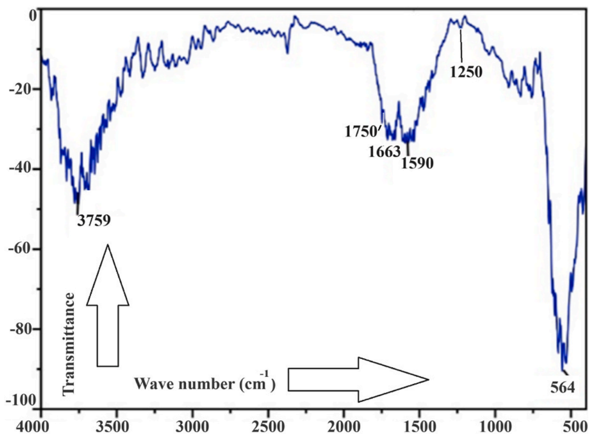


Fig. 4. FTIR analysis.

on the y-axis, while 2θ degrees are plotted on the x-axis. The Joint Committee on Powder Diffraction Standards (JCPDS) files are essential for identifying and characterizing crystalline materials. For cellulose fibers, the relevant JCPDS file number often referenced is 00-056-1719, which corresponds to the crystalline form of cellulose Iβ. The 2θ degrees values of *Aloe vera* stem fiber was found at 11.9°, 16.4°, 22.7° and 30.8°. Similarly, miller indices (hkl) were 110, 110, 200 and 004. The crystalline region was 78.67 % while the amorphous region was 21.33 % (Fig. 5).

3.8. SEM and EDX analysis

Scanning electron microscope is utilized to examine the morphology and structure of the materials. *Aloe vera* fibers are examined under different magnification power that determines the morphology of material. SEM showed (Fig. 6) the smooth surface of the *Aloe vera* fibers may be due to the presence of wax content [73,74]. fig 6a is low magnification image (1000×, 50 μm marker) shows a relatively large-scale view of the *Aloe vera* fiber surface. The surface appears rough and irregular with several pores and voids. The rough surface and presence of pores can be attributed to the natural morphology of the plant fiber, which includes microfibrils and cellulose bundles. These pores are likely pathways for water and nutrient transport within the plant. The irregularities can be due to the extraction process, which may have removed some non-cellulosic components, revealing the underlying cellulose structure. Fig. 6b showed medium magnification image (10,000×, 5 μm marker) and at this magnification, individual fibers and microfibrils become more distinguishable. The image shows entangled fibers with a more defined structure. The entangled nature of the fibers indicates the complex network of cellulose microfibrils. This network contributes to the mechanical strength and flexibility of the fibers. The visible microfibrils are composed of cellulose chains, which provide the fiber with its structural integrity. High Magnification View (25,000×, 2 μm marker) was shown in Fig. 6c. This image provides a closer look at the fiber's internal structure, revealing more detailed features such as the alignment of microfibrils and smaller particulates. The alignment of the microfibrils suggests a high degree of crystallinity within the fiber, which is characteristic of cellulose. The presence of small particulates might indicate residual non-cellulosic materials such as hemicellulose or lignin, which were not completely removed during the extraction process. Fig. 6d, ultra-High Magnification View (50,000×, 1 μm). At this magnification, the image shows a very detailed view of the microfibrils and nanofibers. The surface appears even more textured with minute details. The detailed texture at this scale can be attributed to the crystalline and amorphous regions of the cellulose. The crystalline regions are highly ordered and contribute to the mechanical strength, while the amorphous regions are less ordered and provide flexibility. The balance between these regions determines the overall properties of the fiber. Overall, we can say that the presence of pores and voids in Fig. 6a can be related to the natural vascular system of the *Aloe vera* plant, which helps in the transport of nutrients and water. The entanglement observed in Fig. 6b indicates the fibrous nature and the potential for the fibers to form strong, interlocked networks. The alignment and detailed structure of microfibrils in Fig. 6c and d highlight the cellulose's role in providing strength and rigidity to the fibers. The rough and textured surfaces seen at higher magnifications suggest that the fibers may have high surface area, which can be beneficial for certain applications such as adsorption or as reinforcement in composites. These SEM images of *Aloe vera* fibers reveal a complex and hierarchical structure, with features ranging from macroscopic pores to microscopic and nanoscopic fibrils. The combination of crystalline and amorphous regions within the fibers contributes to their unique mechanical properties, making them suitable for various applications, including sustainable textiles. The detailed observations provide insights into the natural architecture of *Aloe vera* fibers and their potential for use in eco-friendly and high-performance materials.

EDX analysis was conducted to identify the presence of carbon, copper, oxygen, and calcium in *Aloe vera* fibers. The table in Fig. 7 presents the percentage of each element detected in the fibers. Carbon exhibits the highest percentage among the detected elements, accounting for 52.39 % by weight. Oxygen follows closely, comprising 44.58 % by weight. Calcium constitutes 1.86 % by weight, while copper represents 1.16 % by weight. It's noteworthy that copper and calcium may exist in oxide forms and various other compound forms within the fibers. EDX analysis determines the presence of carbon, copper, oxygen, and calcium in *Aloe vera* fibers. These findings indicate that *Aloe vera* fibers hold promise as a natural and sustainable resource for advanced wound dressings and other healthcare-

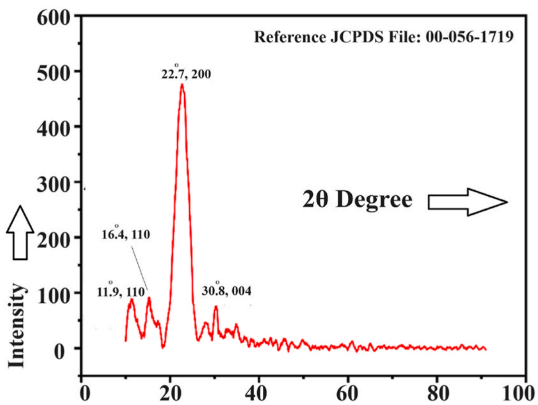


Fig. 5. XRD analysis.

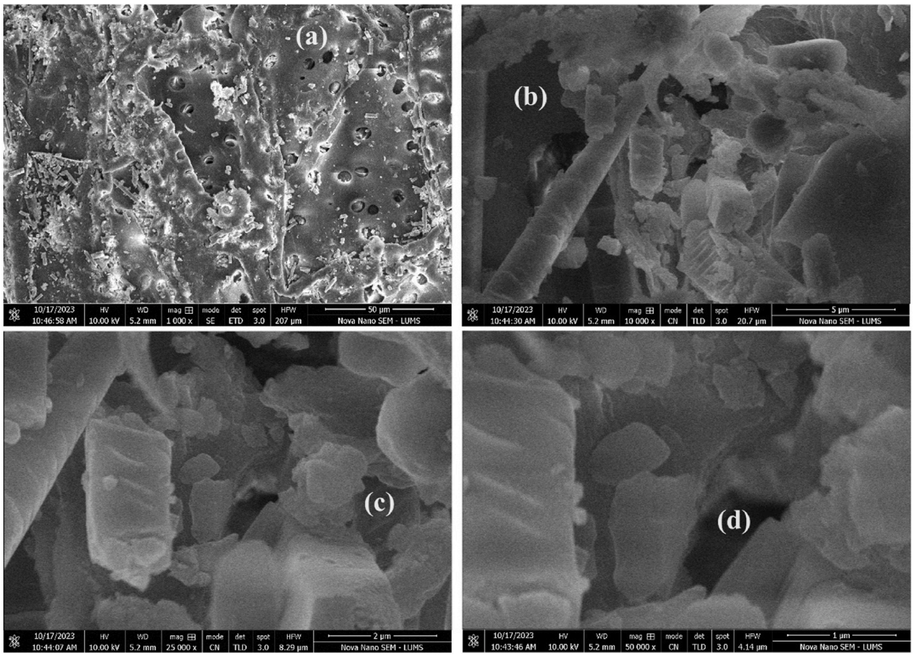
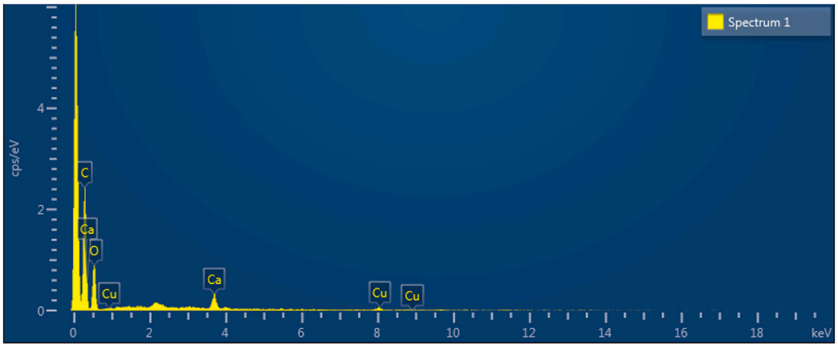


Fig. 6. SEM images (a) 50 μm (b) 5 μm (c) 2 μm (d) 1 μm.



Percentage weight and apparent concentration of elements in *Aloe vera* fibers

Elements	Apparent Concentration	Weight%
C	63.03	52.39
O	46.33	44.58
Ca	4.47	1.86
Cu	2.13	1.16

Fig. 7. EDX and elemental analysis.

related materials.

3.9. Thermal analysis (TGA DSC combined)

TGA data (green line) analysis (Fig. 8) showed an initial weight loss from 0 to 100 °C which indicates the evaporation of moisture. Major weight loss from 300 to 400 °C Showed the decomposition of the main organic components like cellulose and hemicellulose. Further weight loss from 400 to 600 °C corresponded to the decomposition of more stable organic fractions and possible carbonization.

DSC data (blue line) explained the endothermic peak (Fig. 8) from 50 to 100 °C which represents the absorption of heat due to

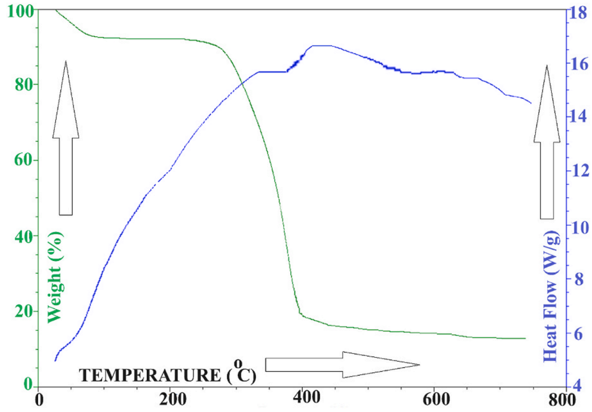


Fig. 8. TGA (green) and DSC (blue) of *Aloe vera* stem fiber.

moisture evaporation. Exothermic peaks from 300 to 400 °C indicates the release of heat during the oxidative decomposition of the main polymeric components. Additional Exothermic Peaks from 400 to ~600 °C reflect further decomposition and possible carbonization of the material.

4. Conclusions

The *Aloe vera* stem fiber was reported for the first time in the scientific world in this publication. The fiber was extracted by using water retting methods and in our next study we will explore more methods to get better fiber in terms of color and application in textile goods with good yield. These fibers displayed a high moisture content, presence of essential inorganic elements such as copper, calcium, and iron and antibacterial activity against common pathogenic bacteria made this fiber favorable for medical textile applications. UV–Visible and FTIR spectroscopic analyses offered insights into their chemical composition. X-ray diffraction revealed the fibers' both crystalline and amorphous nature suggesting potential stability and durability along with potential for blending and dyeing and printing. SEM images depicted the morphology of the fibers and potential presence of wax contents. This alternative, sustainable natural fiber not only provides a medicated fabric for wound healing, allergies, and other skin diseases but also offers a regular cellulosic fiber that can be used alone or blended with natural and synthetic fibers for the manufacturing of eco-friendly textile goods. It can be dyed with natural, microbial, and synthetic dyestuffs. Its cultivation and other climatic conditions are favorable in all types of weather. *Aloe vera* stem is often considered agricultural waste if it is cultivated solely for the extraction of gel for cosmetic and other industrial applications. However, for the circular economy, achieving net zero emissions, and reducing carbon footprint, this fiber is ideal for the textile industry and is suitable for Industry 4.0, Industry 5.0, and Industry 6.0. It is also conducive to producing 3D and 4D printing products with this healing plant stem fiber. Industrial revolution 6 is currently in the planning stages. While the world is transitioning from Industry 4.0 to Industry 5.0, the future lies in Industry 6.0. A comprehensive first book on Industry 6.0 will be available soon. I hope this book will be a valuable guide to both academia and industry. We acknowledge that there is currently limited information and data on Industry 6.0, but we are gathering real industrial data from organizations and consulting with actual industrial experts.

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Not applicable.

Availability of the data and materials

The data related to this work has been mentioned in this manuscript.

CRediT authorship contribution statement

Hammad Majeed: Writing – review & editing, Writing – original draft, Software, Project administration, Methodology, Investigation, Conceptualization. **Tehreema Iftikhar:** Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Data curation. **Rehman Manzoor:** Visualization, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] A. Don, et al., Carbon sequestration in soils and climate change mitigation—definitions and pitfalls, Global Change Biol. 30 (1) (2024) e16983.
[2] H. Majeed, T. Iftikhar, Q. Abbas, Climate resilience plastic degradation potential of Pseudomonas putida isolated from the soil of plastic waste dumping sites to reduce GHG emissions, Z. Phys. Chem. 238 (5) (2024) 797–807.
[3] I. Akhtar, et al., The role of natural products in COVID-19, in: The COVID-19 Pandemic, Apple Academic Press, 2022, pp. 393–445.
[4] T. Iftikhar, et al., Thyme, in: M. Zia-Ul-Haq, et al. (Eds.), Essentials of Medicinal and Aromatic Crops, Springer International Publishing, Cham, 2023, pp. 399–429.
[5] H. Majeed, T. Iftikhar, S. Mustafa, Statistical approach for newly isolated and identified microbial lipases production, Polym. Bull. (2024). https://doi.org/10.1007/s00289-024-05445-0.
[6] L.J. Suarez-Visbal, et al., Transformative circular futures in the textile and apparel value chain: guiding policy and business recommendations in The Netherlands, Spain, and India, J. Clean. Prod. (2024) 141512.
[7] M. Irfan, et al., A review on molecular scissoring with CRISPR/Cas9 genome editing technology, Toxicology Research 13 (4) (2024).
[8] H. Majeed, T. Iftikhar, Ecofriendly reactive printing of cellulosic fabric with sustainable novel techniques, Cellulose 31 (11) (2024) 7067–7081.
[9] T. Bashir, H. Majeed, T. Iftikhar, Isolation and screening of thermophillic bacteria and its subsequent evaluation for lipases production, Pakistan J. Bot. 56 (2) (2024) 759–764.
[10] A. Shahbaz, et al., Porous materials: covalent Organic Frameworks (COFs) as game-changers in practical applications, a review, Rev. Inorg. Chem. 44 (1) (2024) 117–133.
[11] J.K. Bediako, et al., Adsorbents for water decontamination: a recycling alternative for fiber precursors and textile fiber wastes, Sci. Total Environ. (2024) 171000.
[12] H. Majeed, T. Iftikhar, K. Maqsood, Temporal and thermal dynamics exploration of different detergents' formulations components on fungal alkaliphilic lipases stability, Z. Phys. Chem. 238 (3) (2023) 563–570.
[13] A. Karuppuchamy, K. Ramya, R. Siva, Novel banana core stem fiber from agricultural biomass for lightweight textile applications, Ind. Crop. Prod. 209 (2024) 117985.
[14] H. Majeed, et al., Green synthesis of Eucalyptus globulus zinc nanoparticles and its use in antimicrobial insect repellent paint formulation in bulk industrial production, Heliyon 10 (2) (2024) e24467.
[15] H. Majeed, et al., Tamarindus indica seed polysaccharide-copper nanocomposite: an innovative solution for green environment and antimicrobial studies, Heliyon 10 (10) (2024) e30927.
[16] T. Aziz, et al., Rational synthesis, biological screening of azo derivatives of chloro-phenylcarbonyl diazenyl hydroxy dipyrimidines/thioxotetrahydropyrimidines and their metal complexes, Heliyon 9 (1) (2023) e12492.
[17] W.J. Martínez-Burgos, et al., Aloe vera: from ancient knowledge to the patent and innovation landscape–A review, South Afr. J. Bot. 147 (2022) 993–1006.
[18] [cited 2024 24 May]; Aloe Vera Market Report]. Available from, 2022.
[19] M. González-Delgado, et al., Joint water and salinity stresses increase the bioactive compounds of Aloe vera (Aloe barbadensis Miller) gel enhancing its related functional properties, Agric. Water Manag. 285 (2023) 108374.
[20] H. Majeed, T. Iftikhar, U. Mukhtar, Novel approach to water-efficient bulk industrial textile printing production of cotton fabric, Int. J. Biol. Macromol. 262 (2024) 130064.
[21] K. Khaldoune, N. Fdil, M. AitAli, Exploring Aloe vera: a comprehensive review on extraction, chemical composition, biological effects, and its utilization in the synthesis of metallic nanoparticles, Biocatal. Agric. Biotechnol. (2024) 103052.
[22] K. Wise, et al., Fertiliser supplementation with a biostimulant complex of fish hydrolysate, Aloe vera extract, and kelp alters cannabis root architecture to enhance nutrient uptake, Sci. Hortic. 323 (2024) 112483.
[23] O. Ramírez, et al., Aloe vera peel-derived nanovesicles display anti-inflammatory properties and prevent myofibroblast differentiation, Phytomedicine 122 (2024) 155108.
[24] M.M. Fares, S.K. Radaydeh, Novel mustard oil/aloe vera gel microemuslions as potential biomaterials, J. Mol. Liq. 397 (2024) 124077.
[25] M.H.G. Jahromi, et al., Differential phytochemical responses of Feverfew to green synthesized calcium nanostructures formed on pectin and Aloe vera extract, Food Chemistry Advances (2024) 100676.
[26] M.C. Ceballos-Santa, et al., Aloe vera-based biomaterial ink for 3D bioprinting of wound dressing constructs, J. Biomed. Mater. Res. B Appl. Biomater. 112 (2) (2024) e35379.
[27] C. Altinkaynak, et al., Anti-microbial, anti-oxidant and wound healing capabilities of Aloe vera-incorporated hybrid nanoflowers, J. Biosci. Bioeng. 135 (4) (2023) 321–330.
[28] D.S. Melenshia, et al., Effect of reconstituted, lyophilized cold aqueous extract of Aloe vera on human whole blood clotting time-A pilot study, J. Ayurveda Integr. Med. 15 (2) (2024) 100887.
[29] W.X.L. Felicia, et al., Chitosan/aloe vera gel coatings infused with orange peel essential oils for fruits preservation, Curr. Res. Food Sci. 8 (2024) 100680.
[30] M.I.H. Mondal, J. Saha, M.A. Rahman, Functional applications of aloe vera on textiles: a review, J. Polym. Environ. 29 (2021) 993–1009.
[31] A. Nsangou, et al., Aloe vera gel as a biomordant in the finishing of vegetable textiles: a review, Bul. Inst. Polit. Iaşi. 68 (72) (2024) 4.
[32] Q. Zhou, et al., A green in situ synthesis of silver nanoparticles on cotton fabrics using Aloe vera leaf extraction for durable ultraviolet protection and antibacterial activity, Textil. Res. J. 87 (19) (2017) 2407–2419.
[33] L. Maduna, A. Patnaik, A review of wound dressings treated with Aloe vera and its application on natural fabrics, J. Nat. Fibers 20 (1) (2023) 2190190.
[34] N.D. Efeze, et al., Bio-textiles against arthropod pests: a review, Environmental Engineering & Management Journal (EEMJ) 23 (4) (2024).
[35] M.M. Hossain, et al., Advancements of eco-friendly natural antimicrobial agents and their transformative role in sustainable textiles, SPE Polymers 5 (3) (2024) 241–276.
[36] H. Veena, K. Shanmugam, A review of textile fabrication using bioactive compounds derived from natural products, Proceedings of Anticancer Research 7 (6) (2023) 7–12.
[37] P. Singh, et al., Sustainable utilization of Aloe vera waste in the diet of lactating cows for improvement of milk production performance and reduction of carbon footprint, J. Clean. Prod. 288 (2021) 125118.
[38] L.Z. Putri, Analysis of aloe vera nano powder (Aloe vera L.) using X-ray diffraction (XRD), in: Journal of Physics: Conference Series., IOP Publishing, 2023.
[39] O.I. Ogidi, U.E. Enenebeaku, Medicinal potentials of Aloe vera (Aloe barbadensis Miller): technologies for the production of therapeutics, in: Sustainable Utilization and Conservation of Africa's Biological Resources and Environment, Springer, 2023, pp. 295–321.
[40] Y.H. Hammo, Effect of NPK fertilizer and growing media on the growth and gel production of two species of aloe plant (Aloe vera and Aloe butteneri), Mesopotamia J. Agric. 51 (3) (2023) 109–121.
[41] G. Canche-Escamilla, et al., Extraction of phenolic components from an Aloe vera (Aloe barbadensis Miller) crop and their potential as antimicrobials and textile dyes, Sustainable Chemistry and Pharmacy 14 (2019) 100168.

[42] M.B. AL-Ethawi, H.H. AL-Taae, Effects of fertilizers on the traits of Aloe vera Plants infected with fungus Rhizoctonia solani, Texas Journal of Agriculture and Biological Sciences 7 (2022) 37–49.
[43] J. Semerel, et al., Valorization of Aloe barbadensis Miller.(aloe vera) processing waste, Journal of Renewable Materials 11 (3) (2023).
[44] H. Majeed, T. Iftikhar, M. Zohaib, Extension of guava shelf life through the application of edible coating formulated with mango and lemon leaves extracts, Ind. Crop. Prod. 216 (2024) 118671.
[45] T. Bashir, T. Iftikhar, H. Majeed, Bulk industrial textile production of bio scouring for cellulosic fabric utilizing indigenous hot springs triacylglycerol acylhydrolases from Bacillus toyonensis and Bacillus thuringiensis, Cellulose 31 (2) (2024) 1353–1381.
[46] H. Majeed, H.N. Bhatti, I.A. Bhatti, Replacement of sodium alginate polymer, urea and sodium bicarbonate in the conventional reactive printing of cellulosic cotton, J. Polym. Eng. 39 (7) (2019) 661–670.
[47] W. Xu, et al., Sustainable Transition in Textile and Apparel Industry, Elsevier, 2024 141081.
[48] P.S. Singha, et al., Effects of Biofertilizers in Improving the Growth and Development of the Traditional Medicinal Plant Aloe vera L.(Aloe barbadensis Miller). Current Traditional Medicine 10 (2) (2024) 97–108.
[49] E. Kassegn, et al., Experimental study on single fiber tensile properties of sisal fibers using a digital image correlation method as a strain measurement, J. Nat. Fibers 21 (1) (2024) 2325557.
[50] Y. Zhang, et al., Separation of lignin derivatives from hemp fiber using supercritical CO2, ethanol, and water at different temperatures, Int. J. Biol. Macromol. (2024) 130390.
[51] Z.G. Sakoshev, et al., Morphological and physicomechanical characterization of synthetic and natural fibers, J. Polym. Res. 31 (3) (2024) 86.
[52] A.N, B. and N. K.J, Characterization of alkali treated and untreated new cellulosic fiber from Saharan aloe vera cactus leaves, Carbohydr. Polym. 174 (2017) 200–208.
[53] B.C. Behera, et al., Microbial cellulases – diversity & biotechnology with reference to mangrove environment: a review, J. Genet. Eng. Biotechnol. 15 (1) (2017) 197–210.
[54] E.A. Bayer, Y. Shoham, R. Lamed, Cellulose-decomposing bacteria and their enzyme systems, in: M. Dworkin, et al. (Eds.), The Prokaryotes: Volume 2: Ecophysiology and Biochemistry, Springer New York, New York, NY, 2006, pp. 578–617.
[55] T. Bhatia, et al., A review on cellulose degrading microbes and its applications, Ind. Biotechnol. 20 (1) (2024) 26–39.
[56] R. Siva, K. Nikhil Kumar, S. Mupparaju, Study on physicochemical properties and morphology of surface-modified and raw Coccinia grandis natural fiber, Mater. Today: Proc. 47 (2021) 4454–4458.
[57] R. Siva, et al., Characterization of mechanical, chemical properties and microstructure of untreated and treated Cissus Quadrangularis fiber, Mater. Today: Proc. 47 (2021) 4479–4483.
[58] S. Kumar, et al., Recent advances in therapeutic and biological activities of Aloe vera, Biocatal. Agric. Biotechnol. (2024) 103084.
[59] A. Malek Hosseini, et al., Comparison of aloe vera gel dressing with conventional dressing on pressure ulcer pain reduction: a clinical trial, BMC Res. Notes 17 (1) (2024) 25.
[60] Z.O. Basyigit, C.N. Kuyucak, H. Coskun, Advancements in cotton textile design: addressing temperature and moisture challenges, Fibers Polym. (2024) 1–19.
[61] A. Kumar, et al., Extraction, physicochemical and structural characterisation of palm grass leaf fibres for sustainable and cleaner production of textile and allied cellulosic applications, J. Clean. Prod. (2024) 141733.
[62] A.A. Almetwally, H.M. Elfowaty, Optical-related properties and characterization of some textile fibers using near-infrared spectroscopy, Autex Res. J. 24 (1) (2024) 20230014.
[63] S. Ovalı, O. Eryılmaz, S. Uyanık, Exploring the potential of sustainable natural cellulosic fiber from Sorghum bicolor (Sorghum vulgare var. technicus) stem for textile and composite applications, Cellulose (2024) 1–14.
[64] S. Gao, et al., Identification of fibers and dyes in archaeological textiles from Bazhou, Xinjiang (220-420 CE), and their Silk Road origins, J. Archaeol. Sci. 164 (2024) 105941.
[65] Z. Huang, et al., A triple-crosslinking strategy for high-performance regenerated cellulose fibers derived from waste cotton textiles, Int. J. Biol. Macromol. (2024) 130779.
[66] A. Hadou, et al., Extraction and characterization of novel cellulose fibers from Dracaena draco plant, Mater. Chem. Phys. 313 (2024) 128790.
[67] R. Barbosa, et al., Aloe Vera extract-based composite nanofibers for wound dressing applications, Mater. Sci. Eng. C 124 (2021) 112061.
[68] D. Massoud, et al., Aloe vera and wound healing: a brief review, Brazilian Journal of Pharmaceutical Sciences 58 (2023) e20837.
[69] L.W. Sanchez, R.R. Watson, Chapter 21 - fruits, vegetables, and herbs: bioactive foods promoting wound healing, in: R.R. Watson, V.R. Preedy (Eds.), Fruits, Vegetables, and Herbs, Academic Press, 2016, pp. 451–464.
[70] K. Khaldoune, N. Fdil, M.A. Ali, Exploring Aloe vera: a comprehensive review on extraction, chemical composition, biological effects, and its utilization in the synthesis of metallic nanoparticles, Biocatal. Agric. Biotechnol. 57 (2024) 103052.
[71] A. Milind, et al., A review on aloe vera, International Journal of Pharmacy & Life Sciences 15 (1) (2024).
[72] O.U. Nsofor, et al., Evaluation of antibacterial activity of Aloe vera extract on some bacterial pathogens, International Journal of Phytology Research 3 (1) (2023) 26–29.
[73] R. Siva, T.N. Valarmathi, K. Palanikumar, Effects of magnesium carbonate concentration and lignin presence on properties of natural cellulosic Cissus quadrangularis fiber composites, Int. J. Biol. Macromol. 164 (2020) 3611–3620.
[74] S. Ramasamy, et al., Study of various properties of chemically treated lignocellulosic Cissus quadrangularis stem fiber for composite reinforcement, J. Nat. Fibers 20 (1) (2023) 2161689.