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Review

Exploring the synthesis and biomedical potential of banana stem fiber for antimicrobial and wound healing applications

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Received: 18 January 2025 / Accepted: 14 May 2025
Published online: 06 June 2025

Abstract
Need for non-toxic materials especially for biomedical application remains the most important driving force for the discovery of nature-derived biomaterials. In particular, fibers and extracts from plants with medicinal value are vastly investigated. One such source is the banana fiber. The lignocellulosic and protein-based structures of banana fibers contribute to their biodegradability and biocompatibility, which are essential attributes for medical use. Despite their promising biocompatibility, banana fibers face challenges such as variability in their mechanical properties and limited raw state performance. This necessitates precise fiber synthesis and advanced processing to obtain biocompatible fibers for biomedical use. This review discusses the chemical constituents, extraction methods, characterization of natural fiber derived from banana pseudo stem, along with the antimicrobial and tissue regeneration potential of banana fiber based biomedical materials recently developed. Further, steps involved in the conversion of banana fiber to useful biomedical material are presented along with fabrication techniques. In addition, challenges and limitations that hurdle research progress, and potential for future biomaterials through functionalization are discussed. Review findings support potential for research intervention at the integration of banana fibers, biopolymers and nanotechnology towards development of efficient wound healing materials. Inherent to the comprehensive coverage of topics, the authors assure that this review will potentially act as a valuable source of information that could boost research and development of banana fiber-based wound healing biomaterials.

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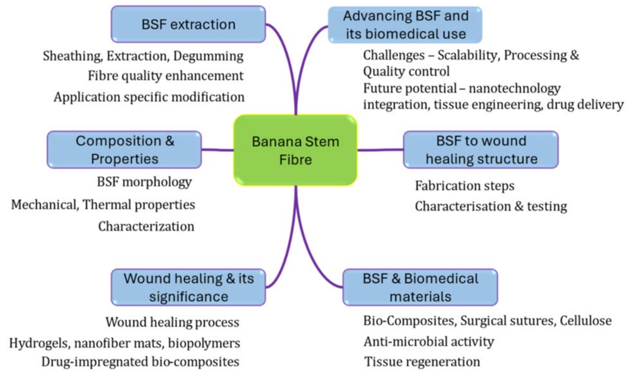
Graphical Abstract



Article Highlights

1. Details on banana stem fiber (BSF) extraction processes, fiber modifications/treatments for biomedical applications could facilitate integration of BSF in biomedical research and developments.
2. Details on fabrication of various wound healing structures utilizing nanotechnology facilitates development of efficient alternatives to traditional wound care.
3. Studying challenges/limitations aid in proper research planning.

Keywords Banana stem fiber · Biomedical materials · Bio-composite patches · Functional textile · Nanofibers · Natural fibers · NFRPC · Wound healing

1 Introduction

1.1 Overview of natural fibers in biomedical applications

Natural fibers have emerged as transformative materials in biomedical applications, combining sustainability with functional versatility. Derived from plants and animals, these fibers exhibit biodegradability, renewability, biocompatibility, which enables them offer an eco-friendly solution to synthetic counterparts. Some examples include cellulose, hyaluronic acid, collagen, silk, and banana fiber [1, 2]. Natural fibers derived from plants like jute, flax, hemp, sisal, banana pseudo stem have tensile strengths in the range of 393–773 MPa, 345–1100 MPa, 550–900 MPa, 500–800 MPa, 529–914 MPa respectively which is higher compared to cotton 264–800 MPa but lower than synthetic fibers. Similarly, fiber density of jute, flax, hemp, sisal, banana pseudo stem ranges between 1.3–1.46 g/cm^3, 1.5 g/cm^3, 1.47 g/cm^3, 0.76–1.58 g/cm^3, 1.3–1.35 g/cm^3 respectively which is on par with cotton 1.5–1.54 g/cm^3 as well as synthetic fiber [2]. Their low density and high tensile strength enable the development of lightweight yet durable biomaterials. However, a major challenge is their limited raw-state performance. Advanced chemical (e.g., alkalization) and physical (e.g., plasma) modifications are required for improving their compatibility and functionality. These fibers, when reinforced with composites, enhance mechanical properties such as stiffness and durability of the composite materials enabling their use in applications ranging from orthopedics and prosthetics [2, 3].

Natural fiber based composites: Natural fiber—biopolymer (mostly chitosan) reinforced composites also known as green composites pave way for sustainable development [4]. Chitosan based green composites prepared using cellulose-modified fiber, bamboo charcoal, modified bamboo charcoal exhibited tensile strength and modulus of 22–80 MPa, 25–75 MPa, 75–110 MPa and 236–3316 MPa, 4600–5400 MPa, 5400–7000 MPa respectively [5]. Such chitosan blends, nanocomposites and fiber reinforced composites are prepared by numerous methods like solvent/solution casting, spray/dipping coating, dry/freeze casting, layer-by-layer method, and extrusion techniques and find application in water treatment, biomedicine, paper industry, agriculture and construction industries [6]. In addition, natural fiber reinforcements were found to increase the mechanical strength of hydrogel wound dressings [7]. For instance, kapok and hemp fiber reinforcement with alginate gel improved its tensile strength to 174 cN and 185 cN (1.24% and 1.48% elongation than hydrogel without reinforcement) [8]. However, the use of natural fibers in biomedical applications demand adequate processing in order to make them suitable for it [9]. Bio-composites functionalized with nanomaterials, biopolymers showcase reduced toxic effects and improved biocompatibility that directly increase their applicability in biomedical field. Specifically, for drug delivery, orthopedics, and tissue engineering [10, 11].

Natural fiber-based medical textile: Sustainable economy calls for the use of natural fibers and nature-derived bio materials in every possible field of engineering and technology in order to reduce the ecological impacts created by synthetic materials. For instance, medical textile demands sterile and toxin-free materials and thus, constantly motivate and encourage the use of natural fibers, natural materials and dyes in their products and processes [12]. Research interventions towards use of salt-free dying of cotton using cationic-agents were demonstrated to result in an acceptable dissolved oxygen content of 6.39 mg/l—highlight the shift towards sustainable developments [13]. Similarly, color fastness and absorption in fabrics are achieved using natural extracts like tannins from tea-leaf and thyme [14]. Even, crease-resistance property is improved by cross-linking citric acid and dimethylol dihydroxy ethylene urea (DMDHEU) [15]. The introduction of natural dyes in textile products enable their use in healthcare applications as wound dressing materials, surgical garments etc. [16].

In addition to providing sustainable and toxin-free solutions, natural fibers and biomaterials aid in functionalizing textile products with properties like flame resistance, UV resistance, antimicrobial activity, and healthcare monitoring paving the way towards smart textiles [17]. Such functionalized textile finds enormous applications in biomedical field [18]. For instance, non-woven wound dressings were developed by functionalizing padded cotton fabric with plant extracts from Bikash leaf (Mikania micrantha), Durba grass (Cynodon dactylon) and coriander herb (Coriandrum sativum). These dressing materials exhibited anti-bacterial activity against both gram-negative and gram-positive bacteria [19, 20]. Whereas, the use of colloidal zinc oxide extracted from carrot, orange peel and Tulsi (Holy Basil) extracts on padding with cotton fabric exhibited UV protection function in addition to antibacterial functions [21, 22].

Chitosan coatings on textiles resulted in imparting antibacterial properties to the material, making them suitable for biomedical applications especially, wound care [23]. Other applications of chitosan in textile finishing includes antimicrobial functions, blood coagulation and odor control [24]. FTIR spectra of bio-polymer blends of chitosan depict their applicability to biological applications. For instance, chitosan/cellulose blend show a shift in the OH and NH peak to 3483 cm^{-1}, 3479 cm^{-1} from 3528 cm^{-1} as the cellulose content increases. This represents the interaction of the amine in chitosan with OH in cellulose [25]. In another experiment, chitosan/titania, chitosan/silica coating on cotton fabric resulted in decrease of absorbance at 1640, 1314, 1200 and 894 cm^{-1}. And shifting of band at 3331 cm^{-1} to 3320 cm^{-1} and 3329 cm^{-1} for titania and silica blend respectively are noted [26]. These results demonstrate biomedical significance achieved with functional coating over textile fabrics.

Limitations: Washing fastness of functionalized material becomes an important factor in functionalized textile when they are meant to be reused with washing. Cotton knit fabric functionalized with mixture of propolis and honey is demonstrated to retain its antioxidant activity (ABTS radical reduction above 90%) even after three washing cycles. However, its retention is not tested beyond three washing cycles and thus, remains an open question [27]. Nanocapsules containing Chamomile extract prepared by microemulsion on cotton fabric was demonstrated to exhibit good washing fastness [28]. Similarly, cotton fabric functionalized with melatonin containing nanosponges were demonstrated to retain the nanosponges only till two washing cycles [29]. Washing fastness is an important factor that determines the durability of functionalized textile material [30]. Thus, special care should be taken while washing functionalized textile and strict adaptation of recommendations that come with the product are suggested for improving material durability [31]. However, wound dressing materials are meant for one-time use and thus demands good drug release capability. For instance, drug-loaded patches developed using banana fiber with chitosan were demonstrated to exhibit good drug release profile and accelerated wound healing [32]. Pictorial representation of applications of natural fibers in biomedical field is given by Fig. 1.

Future advancements integrating nanotechnology and biofunctionalization aim to expand natural fiber applications, positioning them as sustainable, high-performance materials in healthcare. Especially, electrospun fibers (EFs) derived from natural polymers are revolutionizing biomedical fields with their large surface area, excellent biocompatibility, and biological activity. Their fabrication process involves fixing critical parameters, such as polymer solution properties (e.g., viscosity, molecular mass, conductivity) and electrospinning factors (e.g., voltage, flow rate, humidity). This enables the development of EFs with multistage structures, including porous and core–shell forms, which find applications in tissue engineering, wound healing, and drug delivery [1]. This synergy of natural fibers and biomedical innovation underscores their pivotal role in eco-conscious and efficient healthcare solutions.

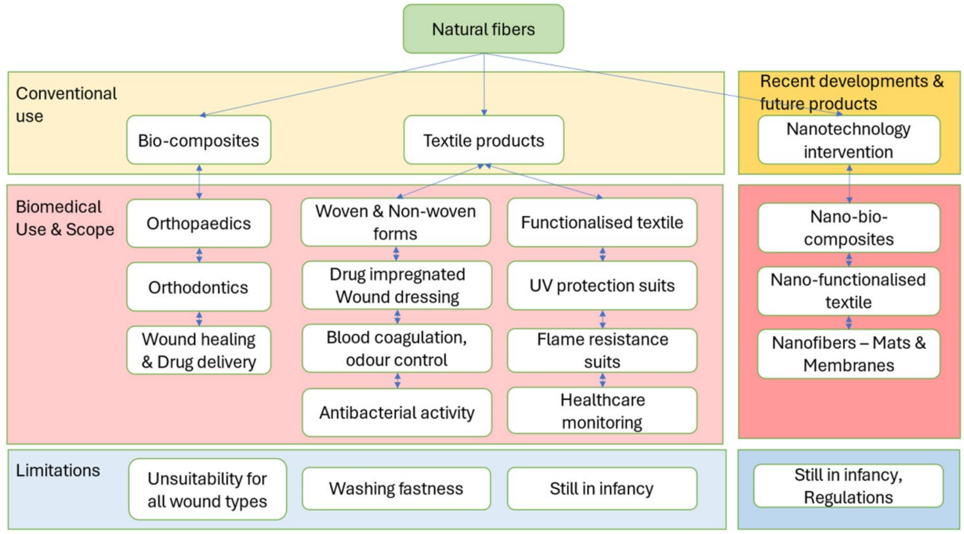


Fig. 1 Overview of natural fiber applications in biomedical field

These references cumulatively highlight the recent advancements in researches with respect to natural fibers and bio-material. Being introduced to the capabilities of natural fiber and its application in bio-medical materials, an introduction to banana plant and its biomedical significance followed by banana stem fiber and its significance is presented in the below sub section.

1.2 Introduction to banana plant

Banana plant is herbaceous and belongs to family Musaceae (genera Musa, Musella and Ensete) with majority of them falling under genus Musa. Majority of edible bananas are derived from a combination of *Musa acuminata* (genome A) and Musa balbisiana (genome B) as diploids (AA/AB) or triploids (AAA/AAB/ABB) or tetraploids (AAAA/AAAB/AABB) [33].

Banana plant grows in humid (relative humidity of 75–85% and temperature 15 °C–35 °C) and well-drained soil under good irrigation. Banana cultivation is predominant in Asia, Latin America and Africa. India and China top the productions chart, and their production is specifically for domestic consumption. Central and South America and Philippines are the largest exporters of banana fruit and European Union, United States of America, China, Russia, and Japan, top the importers chart [34]. About 120 countries around the world cultivate banana and nearly 1000 varieties of banana exist in the world [35]. Cavendish is the most traded variety.

Banana plant, being an herb, it has a pseudo stem or false trunk of 3 to 6 m high and it springs from an underground stem (main stem or rhizome) with adventitious roots. There are smaller stems (suckers) that sprout from the main stem. The pseudo stem is composed of layers of leaf sheaths (petioles) topped by actual leaves which are as wide as 65 cms. Each leaf has a midrib (petiole) and a lamina (blade). Each plant trunk can produce only one inflorescence and thus the trunk is cut after fruit harvest. However, the suckers replace the main trunk and start growing as a main plant making the plant a perennial one. About 70% of farming uses suckers while 30% use tissue cultured seeds. It takes 10 to 12 months for the first plant to yield its fruit [36]. Banana requires plenty of water to grow and can be cultivated throughout the year though wind is an enemy to banana farm and farmers chose their farming season accordingly.

Abaca: Abaca (*Musa textilis*) is a banana cultivar that can grow to heights of 4 to 6.7 m and are primarily cultivated for their fiber. They were grown as commercial crop in Philippines, Ecuador, Costa Rica. Philippines produces 85 to 95% of world abaca fiber. Abaca fiber is used for producing tea bags, bank notes, handcrafts such as handbags, cloth, mats, furniture etc. [37].

Benefits: Bananas, though primarily farmed for their fruit, almost every part of banana plant is useful. To mention a few, its flower bud and pseudo stem are cooked and eaten in south east Asian countries. Its leaves are used for serving food, wraps in stem cooking and for packing food as they are highly bio-compatible. Bananas are rich source of nutrients and hold numerous health benefits. Fibers extracted from banana trunk find numerous applications in manufacturing packages, textile, paper and as door mats [38]. Banana plant has numerous medicinal values and thus, holds a permanent place in the nature-inspired and nature-derived biomedical research [39, 40]. Experimental studies reveal that extract from various banana plant parts have antibacterial, antifungal, antidiabetic, antiulcer, and antitumor properties

[33, 41, 42]. Banana pseudo stem is rich in nutrients, dietary fibers and bioactive compounds; however, it is often left in plantations as biowaste. This underutilization of a potential natural source motivated this search for its use in biomedical applications. With this introduction to banana plant, banana stem fiber and its properties are presented in below section.

1.3 Banana stem fiber

Banana stem fiber (BSF) is emerging as a remarkable natural material. Derived from the pseudo-stem of banana plants, it showcases innovation at the intersection of agricultural waste utilization and advanced material science. As an abundant by-product of banana cultivation—where global production reached 115.7 million tones across 130 countries in 2018—this fiber holds immense industrial promise [43]. Structurally, BSF comprises 60–65% cellulose, along with moderate amounts of hemicellulose (6–8%) and lignin (5–10%), contributing to its tensile strength ranging between 529–914 MPa, elongation capacity spans 3–10%, and it features a Young's modulus of 17–32 GPa [3]. The material's porous microcrystalline cellulose structure enhances its versatility in specialized applications, including drug delivery and regenerative medicine. The pseudo-stem—forming the bulk of banana plant biomass—yields high-quality fibers suitable for diverse applications.

Banana fiber-reinforced composites: Being a natural fiber, BSF is used conventionally for the production of textiles, ornamental products, ropes and mats. However, recently, banana fibers are vastly investigated for the development of fiber-reinforced composite materials that find applications as green construction materials, automotive body parts and bumpers and packaging materials [44]. Enset fiber or false banana fiber are adequately used for paper production and composite manufacturing [45]. In addition, BSF are adequately used for the development of water filter membranes [46]. Recently, research interventions to use BSF composites for biomedical use are emerging. These include sustainable alternatives like wound dressing materials, reinforced composites for scaffolds, biodegradable sanitary pads and face masks. For example, the Philippine Department of Science and Technology innovated face masks using BSF, reducing reliance on single-use plastics [43]. By transforming agricultural waste into a sustainable, high-performance material, BSF addresses both environmental and technological challenges, unlocking new possibilities in biomedicine, composite materials, and sustainable design.

Banana fiber-based medical textile: Recently, functionalizing textile products were vastly investigated for environmental sustainability and biomedical applications. For instance, banana fibers treated with chitosan were demonstrated to absorb toxic substances like chromium better than untreated fibers. These results highlight the possibility of using functionalized banana fiber for water treatment [47]. Banana leaf dressings were used with partial thickness burn wounds and is a patient accepted dressing material inherent to its lesser pain [48]. Research efforts were made towards the development of spinnable banana fibers as a potential alternate to cotton [49]. In addition, incorporation of nanomaterials in composites and textile products results in numerous benefits.

Based on the previous discussions, it could be clearly identified that biomedical application of banana fibers can be broadly classified into three classes based on the nature of the product being used and they are (i) woven and non-woven fabric, (iii) fiber reinforced polymer composites, (iii) nanomaterial functionalized composites and fabrics, (iv) nanofibers. These materials are primarily used as drug delivery materials, wound healing structures, antibiotic agents from nanocellulose, scaffolds in tissue engineering, prosthetic materials in orthopedics, suture materials, and smart textiles. However, the use of BSF fabrics, composites and nano functionalization for biomedical applications are still in infancy and thus, there are lot of opportunities for research and development.

Plant fibers are primary used for manufacturing (i) textile products and (ii) composites. Researches pertaining to natural fiber reinforced polymer composites (NFRPC) materials and their use in biomedical field, and review of literatures on NFRPC in biomedical applications are available. Similarly, researches on drug-loaded woven and non-woven dressing materials and review of literature on functionalized textile products are available. However, specific review collections concentrating on a particular plant fiber, for a specific application are very few. Especially, the researches and reviews utilizing the potentials of banana fiber for biomedical applications are very meagre. This research gap along with the recent researches on potentials of BSF based composite materials served as motivation for this review. This review presents a novel content that explores the potentials of banana stem fiber for wound healing material fabrication. Literature collection for the review followed a qualitative approach which started with a detailed search of the research literature with keywords banana pseudo stem fiber, banana fiber composite, natural fiber, biopolymer, wound healing, wound dressing, biopolymer fiber composites, nanocellulose. This search has resulted in numerous papers which were initially filtered based on title followed by secondary filtering by abstract reading. Finally, the most relevant research articles are considered for the review and their contents were presented in the paper. The objectives of this review are to.

- Brief the primary uses of natural fiber, banana fiber in biomedical field highlighting their use in the form of composites, textiles and benefits harvested from nanotechnology interventions.
- Unravel the potentials of banana stem fiber supported by their characterization results, bioactivity results from biomedical materials based on banana fiber and elaborating the processing steps involved in converting raw banana fiber into useful product.
- Brief the wound healing mechanism highlighting different activities that aid in microbial inhibition and tissue regeneration. Unveil recently developed wound healing structures and importance of drug impregnated wound healing materials.
- Elaborate the steps involved in the conversion of raw banana fiber to different wound healing structures along with the tests for material characterization, antimicrobial activity. And, highlight the potential future scope for banana fiber based biomedical research and the limitations that hurdle the developments.

With this introduction, the paper starts with the steps involved in converting banana stem into a useful product in Sect. 2 followed by BSF properties, characterization studies, and its comparison with other natural fibers in Sect. 3. Section 4 presents a brief overview of wound healing process, recently developed wound healing structures, and importance of drug impregnation while, BSF-based materials currently investigated for biomedical applications are presented in Sect. 5. Section 6 discusses the steps, characterization and tests involved in the development of BSF wound healing structures. Section 7 reveals the challenges that hurdle research and development of BSF based biomedical solutions and future perspectives of BSF-based biomedical research are presented in Sect. 8. Section 9 concludes the study.

2 Conversion of banana stem to useful product

2.1 Extraction of banana stem fiber (BSF)

Banana stem fiber, derived from the pseudo-stem of banana plant, is valued for its structural and mechanical properties. Extraction of BSF from pseudo stem involves a series of steps starting from sheathing-off or removing outer layers which are often uneven due to weathering effects. The second step (extraction) involves separation of fibers from non-fibrous materials like lignin and pectin present in pulp in order to obtain fine fiber. This fiber separation can be achieved by two processes in the case of banana fiber and they are (i) Mechanical extraction using a decorticating machine and (ii) Retting based extraction. Third step involves degumming the extracted fiber which results in fine fibers that is ready for use. These fiber extraction methods are elaborated in details in following paragraph.

Extraction: Retting is a microbial process employed for extracting fibers from plant stem. This involves breaking down non-cellulosic materials like lignin and pectin by subjecting the plant stem to microbiological treatment for several days. There are different types of retting based on the source which is responsible for microbiological action and this includes, dew or cold retting, water retting, chemical retting, enzymatic retting. However, there are certain fibers (banana, sisal, flax, jute) that can be extracted by decortication (mechanical extraction by decorticator or Raspador) followed by washing and drying [50]. Banana fibers can be extracted by both retting methods and decortication however, the quality of the extracted fiber greatly depends on the method of extraction. A brief description of the four commonly adapted BSF extraction methods are given below:

- *Water retting* relies on microorganisms present in water to induce bacterial activity to decompose the non-cellulosic components in pseudo stem. This process involves submerging the pseudo stem in water, allowing microbial action to soften the tissues and separate the fibers.
- *Chemical retting* uses sodium hydroxide (NaOH) to accelerate the breakdown of lignin and pectin [51].
- Enzymatic retting or Bioprocessing is an eco-friendly extraction method that uses enzymes or microbial cultures to accelerate the degradation of non-cellulosic materials in plant stem [52]. The process involves soaking the pseudo-stem in enzyme-rich solutions, which accelerates microbial action. Recent researches revealed that using a consortium of bacterial cultures for retting induce synergistic effects, that resulted in reducing the retting time [53]. Bioprocessed fibers retain their structural integrity, making them suitable for both biomedical and environmental applications.
- *Mechanical extraction* is a cost-effective and scalable method that utilizes decorticators or stripping machines [54]. The process begins with shredding the banana stem, followed by passing the material through decorticators to separate the fibers, which are then cleaned and dried [51].

Degumming: The fibers as extracted from the plant stem contains gummy substances and impurities which affects their properties and usability. Degumming refers to the process of removing these impurities and binding agents from as extracted fibers. Degumming results in cleaner, softer, and more uniform fibers. Degumming is carried out by various methods like alkali treatment, enzymatic treatment, activated water treatment and ultrasound treatments [55, 56].

Most frequently adapted banana fiber extraction method combines mechanical extraction (tuxing, decorticating) followed by chemical treatment for degumming, as this method achieves faster results than retting process [57]. However, quality of the fiber greatly depends on the extraction method, process conditions, chemical/enzyme variants and concentrations used. For instance, higher tensile strength fiber could be extracted with water retting process while lower tensile strengths are achieved with chemical retting (tensile strength of Ethiopian Kusha fibers is 820.10 MPa when extracted by water retting whereas it reduced to 803.7 MPa when extracted by chemical retting). However, higher linear density (3.02Tex) is achieved with chemical retting as compared to water retting (2.71Tex) [58]. Even hydrophobicity of non-woven banana fiber was varied by varying the water repellent concentration [59]. Similarly, the BSF's color and texture were found to depend on the extraction process. Table 1 presents the variation in texture and color of BSF obtained with different retting methods and their corresponding application and limitation. It can be found that enzymatic retting results in good quality fibers however it consumes time.

Once raw fiber is extracted, it is subjected to moisture removal followed by chemical treatment such as bleaching in order to improve its quality specific to application needs. For example, textile applications demand bleaching, spinning and weaving while composite manufacturing requires different molding processes whereas biomedical applications demand functionalization with bioactive compounds. The series of steps adapted in extracting fiber from banana pseudo stem (an agricultural waste) and converting it to a useful product is represented by Fig. 2. In Fig. 2, the green boxes depict the transformation of banana pseudo stem to raw fiber and fiber modifications for imparting desired properties is represented by yellow box. Engineering the fiber to specific application is given by blue box. In detail, (i) when BSF is to be used for medical textile, it is woven as a fabric, (ii) when BSF is used in composite manufacturing (for scaffolds) various molding techniques are adapted, (iii) for wound healing application, it is converted to a non-woven patch and functionalized with drugs, (iv) whereas, for the fabrication of nanofiber mats and membranes, it is electrospun to mats.

2.2 Enhancing BSF quality and properties

Quality of the fiber refers to the color, texture and strength of the fiber. Chemical treatments significantly enhance the purity and functionality of banana stem fibers by removing impurities like lignin and pectin, making them more suitable for varied applications [60, 61]. This step brings in various qualities like (i) whiter and brighter fibers (which are aesthetically pleasing), (ii) smooth textured fiber that brings in comfort (in case of biomedical textile use) (ii) fibers with good mechanical strength (for reinforcement application). Such a modification requires specific chemical treatments/processes like bleaching, alkali treatment and thermal treatments and they result in fibers with enhanced biocompatibility, purity and functional properties.

2.2.1 Alkali-treatment

The fiber as obtained from the decorticating machine contains gummy non-fibrous substances attached to it. These substances should be removed for neutralizing the fiber and improving their surface properties. This is carried out by boiling the fiber in aqueous alkaline solution (2–5% NaOH at 80–100 °C) followed by washing the fiber with water**.** Sodium hydroxide (NaOH) breaks down hemicellulose and residual lignin, creating active hydroxyl groups on the fiber surface. This treatment enhances surface reactivity and mechanical properties of the fiber which are essential for biomedical composite materials [52]. Such alkali-treated fibers exhibit good bio-compatibility with increased surface roughness and better cellular adhesion which are required for tissue engineering scaffolds and wound dressing applications [61, 62]. Treating BSF with 2% sodium hydroxide (NaOH) at 95 °C for 120 min is resulted in removal of lignin and hemicellulose, exposing the cellulose fibrils for further modifications. Post-treatment, the fibers are washed thoroughly and dried under controlled conditions to retain their structural integrity. This process results in a smoother fiber surface, reducing irregularities and enhancing its capacity to adhere to antimicrobial agents [63]. Alkali treatment resulted in increase in cellulose content to 63.49% which improved fiber's flexibility [64] and chemical bonding capacity with antimicrobial compounds, making the fiber more receptive to such agents [63, 65].

Table 1 Extraction method vs quality of BSF

Method	Ref. No	Chemicals/instruments used	Quality of fiber obtained	Applications	Limitation
Retting method	[51]	Biological or chemical action	Results in smooth, long and clean fibers	Textiles and composites	–
Water retting	[51]	Water	Results in smooth and whitish fibers		Demands availability of water resources and time consuming
Chemical retting	[51]	Sodium Hydroxide	Accelerated processing than water retting		Produces effluents
Mechanical extraction	[54]	Decorticators or stripping machines	Faster processing	For ropes, mats and composites	Requires chemical treatment for enhancing fiber quality
Enzymatic Retting	[52]	Enzymes or microbial cultures	Structural integrity is maintained	Biomedical applications	Processing time is more

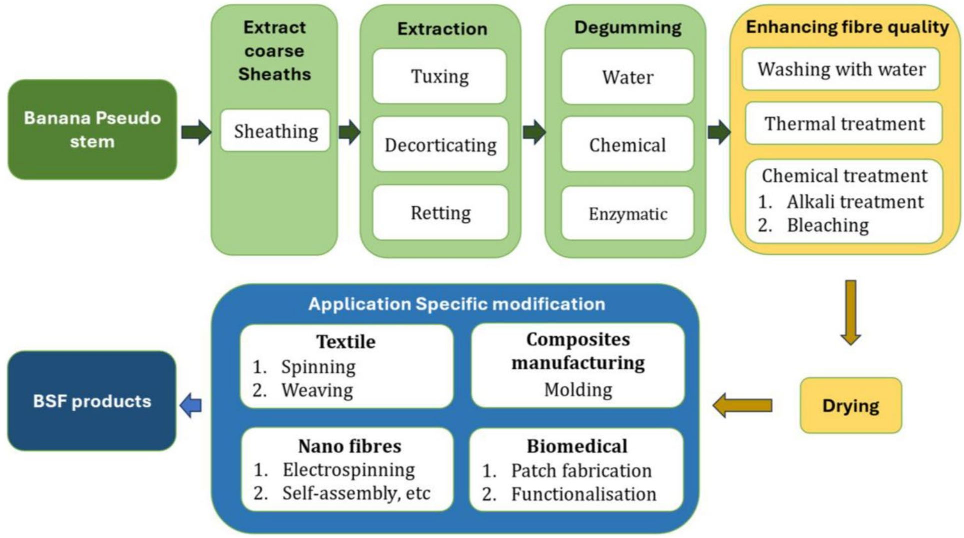


Fig. 2 Evolution of banana pseudo-stem into useful product

2.2.2 Bleaching

Presence of lignin and other natural pigments often makes banana fiber (untreated) slightly brownish or yellowish in color. Bleaching helps in removing these impurities from the fiber and making the fiber whiter and aesthetically pleasing [66]. Bleaching, uses sodium chlorite ($NaClO_2$), to remove traces of lignin and other non-cellulosic impurities from the fiber, exposing cellulose, imparting whiteness and purity to the fiber. During such treatments, lignin content was reduced from 18.57 to 1.10%**,** significantly enhancing fiber compatibility with antimicrobial coatings [64, 67]. This process is vital for making the fiber suitable for biomedical applications as it improves fiber's purity, and enables effective functionalization of the surface with antimicrobial agents.

2.2.3 Thermal processing

Thermal treatments, such as drying and carbonization, are employed to enhance the durability and stability of the fibers. Mild-thermal drying is preferred for biomedical applications in order to preserve the fiber's natural structure. Drying removes moisture and enables easy storing. Carbonization, though less commonly employed in fiber for bio-medical applications can be used to produce carbon-rich fibers for specialized medical devices [51, 52]. Table 2 shows the impact of thermal treatment, chemical treatment on yield and fiber characteristics for different extraction processes.

2.2.4 Sulfation or acid-hydrolysis

Sulfation, using sodium sulfite (Na_2SO_3), and acid hydrolysis with sulfuric acid (H_2SO_4) are employed to purify and modify banana fiber. Acid hydrolysis produces nanocellulose which find applications in wound healing and scaffold engineering. Sulfation results in increasing the crystallinity of cellulose up to 84.05% which enables better integration with antimicrobial agents and stability of chemical bonds [65]. Care must be taken to prevent excessive damage to the fibers during chemical treatments [68, 69].

Table 2 Effect of thermal treatment on fiber quality [103]

Extraction method	Duration	Temperature	Yield (%)	Color of fibers
Water retting	1 month	37 °C	45–55	Whitish
water retting + thermal treatment	2 h	100 °C	50–62	Whitish
Soaking in cold caustic soda	120 h	Room temperature	35–50	Dark brown

2.2.5 Blending with other fibers

Banana fibers have been successfully blended with ramie fiber in a long-staple jute processing system. The blend, with approximately 50% banana fiber, produced fine yarn (213 tex) with a tenacity of 15.71 cN/tex at a spinning speed of 3500 rpm. This finding highlights the potential of banana fibers, which were previously discarded after fruit harvesting, for creating value-added textile products [70, 71]. The diverse extraction methods for banana stem fiber play a crucial role in determining its quality, yield, and applicability in various industries. By optimizing these processes, banana stem fibers can be transformed into valuable materials for textiles, composites, biomedical applications, and sustainable packaging.

2.3 Application specific modifications

2.3.1 Composite manufacturing

Two or more materials with distinct properties combine to create composite materials with enhanced properties. Composites exist in nature and well-known examples of natural composites are wood, stone and bone. The primary constituents of a composite are (i) fibrous reinforcement and (ii) a mineral matrix. Natural composites are light-weight at the same time possess good mechanical strength and stiffness. And thus, find numerous applications. Though they are used in their natural form initially, technological developments led to the arena where man-made composites that mimic the properties and characteristics of natural composites are (almost) possible to manufacture [72]. Similar to the natural composites man-made composite materials are made from two constituents namely (i) fiber reinforcement and (ii) base matrix material. Recently, researches in the field of natural fiber-reinforced polymer composites (NFRPCs) are skyrocketing inherent to their ability to provide sustainable solutions [73]. Banana fibers exhibit high tensile strength, high tensile modulus, low elongation at break, and low density which enable their fruitful use in composite manufacturing for various sectors like construction, automobile, biomedical, etc., [74]. NFRPCs manufacturing is broadly classified into two methods namely (i) open-molding process which includes various methods like Hand lay-up process, Vacuum/pressure bag technique, filament winding and spray-up methods, and (ii) closed molding process which includes compression molding, pultrusion method and injection molding [75]. Among these techniques, most frequently used methods are discussed below,

Hand lay-up process: Hand lay-up is the oldest technique which involves manually spreading the fiber in the mold and applying the matrix material over it. Subsequently, rollers are used to achieve uniformly packed mold that is devoid of air cracks. This method is adequate and economical when woven fabrics are used as reinforcement [76]. Inherent to its simple processes, this method is the most economical one and used for producing laminated composites [77, 78].

Vacuum bag molding: Vacuum bag molding involves placing fibers laminates in a vacuum bag and curing them under pressure. This enhances the bonding between the matrix and the fibers. When alkali-treated BSF is used in vacuum-molded composites, the tensile strength increases dramatically: The tensile strength reaches 2337 MPa, and the composites exhibit greater fracture toughness compared to untreated fibers, making them ideal for high-performance applications [38].

Compression molding: Compression molding involves placing the composite material in a pre-heated mold and applying compressive force to obtain a uniform material of desired shape. In this process, the mold is initially opened to place the required composite materials and then closed while applying compression. Compression molded materials exhibit good mechanical properties than materials obtained by injection molding [79].

Injection molding: Injection molding involves injecting the composite material into the mold by applying pressure and subsequent cooling of the mold to get composites of desired shape [79]. Both injection and compression molding are used to produce lightweight, high-strength parts by mixing chopped fibers with thermoplastics or thermosets [71, 77].

Pultrusion: Pultrusion involves pulling the fiber through the matric material bath followed by shaping the material as desired. This method enables manufacturing composite in the form of strips and ropes [80].

2.3.2 Textile products

Conversion of natural fiber into textile product involve two steps, namely spinning and weaving. Spinning involves conversion of extracted fiber to yarn form by various methods. Open-end spinning is the most commonly used for spinning banana fibers whereas, ring spinning and bast-fiber spinning are other variants that are also used. Once the fiber is spun to yarn it is bleached, dyed as per requirement and then weaved to get the desired fabric [37].

2.3.3 Biomedical applications

Natural fiber products both in the form of bio-composites and textile products find applications in biomedical field. Thus, conversion of fiber to product follows the same basic process steps explained in the previous two sub-sections however, tests for biocompatibility and material strengths on-par with prosthetic materials are ensured for biomedical use.

2.3.3.1 Bio-composites Composites are vastly investigated for use in orthopedics, orthodontic implants. However, the use of composites for biomedical applications demands biocompatibility and thus, highly biocompatible filler materials, matrices like polylactic acid (PLA) are chosen and their mechanical properties like flexural strength, tensile strength and fracture toughness are used [81, 82]. Even, use of natural fibers in biocompatible synthetic polymers were investigated in earlier researches [83]. For instance, composites from Ramie, Hemp fiber and Ramie, Coir fiber in bioresorbable polypropylene matrix were demonstrated to exhibit properties that suits their use as joint and bone fixtures [77]. However, the use of natural fiber reinforced plant-based polymer composites has become a boon that offer biocompatible solutions for biomedical use. Specifically, composite limb sockets made from Banana and Ramie fibers in plant oil resins have demonstrated higher tensile strength when compared to other plant fibers making them suitable for limb prosthetics [84]. Recent researches demonstrated the use of natural fiber/PLA bio-composites for 3D printing by melt extrusion process [85].

2.3.3.2 Medical textile Textile products both in woven and non-woven forms are used for biomedical applications especially as wound dressings. The need for toxin-free, sterile materials often encourages the use of natural fibers in biomedical applications. In addition, Textile products functionalized with pharmaceutical carriers are emerging as potential materials for continuous and controlled drug delivery [30]. For instance, bio-composite fabricated using woven cotton fabric in PLA matric loaded with amoxicillin drug was demonstrated to be a potential wound dressing with antibacterial inhibition against *Staphylococcus aureus* [86]. Further, textile products can be functionalized to exhibit UV resistance, flame resistance, antimicrobial functions and healthcare monitoring [17]. In summary, for biomedical applications, banana fibers are to be modified as either biocompatible composites or functionalized textiles.

2.3.4 Nanofiber processing

Banana stem fibers can also be processed into nanoscale fibers for advanced applications, particularly in the biomedical field. Synthesis of Nanofibers can be broadly classified into two approaches namely, (i) top-down approach—CNC, and CNF are extracted from natural sources and (ii) bottom-up approach—Nanofibers are synthesized from precursor spinnable solutions (isolated cellulose derivatives) [87]. A short note of top-down approach of nano fiber synthesis techniques is presented in order differentiate it from bottom-up approaches.

2.3.4.1 Top-down approach Top-down approach involves extraction of CNFs from natural sources by either chemical or mechanical methods. Chemical methods include (i) TEMPO mediated oxidation, (ii) acid digestion, (iii) catalytic decomposition and (iv) chemical vapor deposition while mechanical methods include (i) ball milling, (ii) grinding, (iii) homogenization, and (iv) ultrasonication treatments. CNFs extracted in the form of hydrogels and aerogels are used for drug delivery, wound healing and tissue engineering in biomedical applications [88]. For instance, mechanical shearing is used to reduce fiber size into nanoscale fibers. These fibers possess a high surface area and enhanced mechanical properties, making them suitable for applications like wound dressings and scaffolds. Similarly, (i) steam explosion is used to produce banana nanowhiskers from banana fiber [89] and (ii) banana fibers when subjected to alkali treatment followed by oxidizing in HNO3–NaNO2 resulted in production of cellulose nanofibers [90], (iii) ground banana pseudo stem powder is subjected to alkali treatment followed by acid hydrolysis and homogenization to obtain cellulose nano fibers [91], (iv) TEMPO mediated—oxidation was followed to synthesize cellulose nano fibers [92]. A comparison of the acid hydrolysis, TEMPO mediated oxidation and enzymatic extraction revealed that, cellulose extracted using enzymatic methods resulted in higher crystallinity of 68.98% and thermal stability till 250 °C while TEMPO mediated extraction resulted in higher yield (25.25%) [93]. Such cellulose nanofibers find application in pharmaceuticals, tissue engineering, nano-bio-composites and catalysis.

2.3.4.2 Bottom-up approach Nanofibers can be fabricated by different methods and most frequently adapted methods are (i) electrospinning, (ii) self-assembly, (iii) template synthesis, and (iv) phase separation [94]. Electrospinning uses an electric field to draw fibers from a polymer solution. For example, naturally occurring cellulose produced from banana pseudo stem were used to electrospun a fibrous mat devoid of defects utilizing Taguchi's orthogonal array. And hydroxyapatite (HA) nanoparticles were incorporated with cellulose to fabricate a scaffold with increased proliferation of bone cells as compared to neat cellulose scaffold [95]. In self-assembly method, smaller materials arrange themselves into patterns by hydrogen bonding and ionic bonds. A major limitation with this method is its less productivity [96]. In phase separation technique, gelation of polymer is used to form porous nanofiber and the remaining solvent is separated out. The gel formed is freeze dried while the solvent is removed. Whereas, template synthesis method uses a predefined template and polymer solution is used to fabricate nanofibers. Nanotubes, nanorods and nanowires can be obtained by this method [94]. With this brief review of steps involved in conversion of banana fiber to useful product, the properties and characterization of banana fiber are presented in the below section.

3 Properties of banana stem fiber

3.1 Chemical composition

Banana stem fiber (BSF), is highly valued for its abundant availability, sustainability, and multifunctional properties and is suitable for diverse applications in industries like bioplastics, composites, and biomedical devices inherent to its natural lignocellulosic composition. Its chemical composition, primarily consisting of cellulose, hemicellulose, lignin, and minor components like pectin, waxes, and extractives (3–5%) which enable structural integrity, biodegradability, and adaptability for specific uses [97, 98]. The high cellulose content provides tensile strength and stiffness, making BSF ideal for hybrid composites and bioplastics. *Musa acuminata* stem fiber (MASF), a type of BSF, which boasts 73.12% cellulose content—higher than many other natural fibers such as jute, hemp, and rice straw. Treated with 5% NaOH solution to remove impurities. MASF fibers extracted from outer and middle layers of pseudo stem demonstrated 20% higher tensile strength and exhibited a rough surface morphology that facilitate adhesion of fiber to the matrix while fabricating composites. However, it exhibits limited heat resistance, with significant mass loss beyond 245 °C [99].

Hemicellulose, an amorphous polysaccharide constituting 12–20% of BSF, imparts flexibility, water retention, and swelling properties, making it particularly useful for absorbent materials like wound dressings. It begins to decompose at 200–250 °C, marking the initial degradation phase of BSF [97]. Morphologically, BSF consists of elementary fibers (10–15 µm) and narrow fibers (3–4 µm), with the latter playing a significant role in water transport within the pith. These unique structural features further distinguish BSF for specialized applications [100]. Additionally, the holocellulose in BSF is predominantly glucose (71.76%), complemented by xylose (11.20%) and arabinose (7.34%), which enhances its suitability for pulping and papermaking [100].

Lignin, present in concentrations of 5–10%, contributes to the fiber's rigidity, UV resistance, and microbial protection due to its aromatic structure. Thermal decomposition occurs at 300–350 °C, ensuring untreated BSF's stability under moderate temperatures [97]. Notably, the Agbagba plantain cultivar exhibited highest fiber recovery of 3% compared to Omini, Paranta and Panbola cultivars. Final decomposition temperature is 392 °C for Agbagba, which showcases its thermal stability [101]. Minor components like pectin, waxes, and extractives influence surface roughness and adhesion properties but are typically removed during alkali treatment for improved compatibility with polymer matrices. However, lignin removal is critical for biomedical applications to reduce toxicity and enhance biocompatibility.

Banana pseudo-stem fibers' unique chemical composition and structural features make them a promising material for a variety of applications. In biomedical fields, their high cellulose content ensures biocompatibility and absorbency, while hemicellulose contributes to moisture retention. In composite manufacturing, the strength provided by cellulose and the flexibility of hemicellulose make BSF a sustainable alternative to synthetic materials. Furthermore, lignin's thermal stability allows its use in insulation and moderate-temperature applications. These features underscore BSF's potential in advancing sustainable material innovation, offering a renewable and eco-friendly solution for industrial and biomedical challenges.

3.2 BSF cellular structure and properties

The cellular structure of banana pseudo stem fiber reveal their diameter ranges from 80–250 µm [102] which makes the fiber highly flexible. BSF exhibits a density ranging from 0.8 to 1.3 g/cm^3 [98, 103], depending on growth conditions and processing methods. This value is significantly lower than synthetic fibers like glass (2.5 g/cm^3) [104], making BSF ideal for lightweight composite applications. The fiber has a high aspect ratio of 100 that enhances stress transfer efficiency in composite materials, making BSF particularly effective for reinforcement applications. Additionally, BSF's natural porosity facilitates water retention and improves bonding in polymer matrices, making it ideal for bio composite applications [105, 106]. Scanning Electron Microscope (SEM) images of BSF fiber is given by Fig. 3. Figure 3a and b depicts the scaly, bundled structure of banana fiber. The multicellular structure is further confirmed by the transverse images in Fig. 3c and d. The lumens are clearly seen from resolution improved transverse images in Fig. 3e and f.

3.3 Scanning electron microscopy (SEM) observations

SEM analysis of untreated BSF features a rough and porous surface with waxy coatings and lignin layers. Such a surface morphology facilitates mechanical interlocking in composites but, limits fiber bonding with the matrix [107–109]. Alkaline treated fibers present a smooth surface with increased porosity and exposed microfibrils, resulting from the removal of wax, lignin (5–10%), and hemicellulose (12–20%). Enhanced surface area and porosity improve interfacial bonding with polymer matrix [60, 61]. SEM analysis of BSFs extracted from different banana cultivar exhibited variations in their structural properties. For instance, fibers from *Musa sapientum* L. form distinct fiber groups with larger lumens whereas, those from *Musa acuminata* were broken and separated. Similarly, fibers properties varied across the layers of the pseudo stem [110]. Alkali treated fibers were smooth and regular when compared to untreated fibers [111].

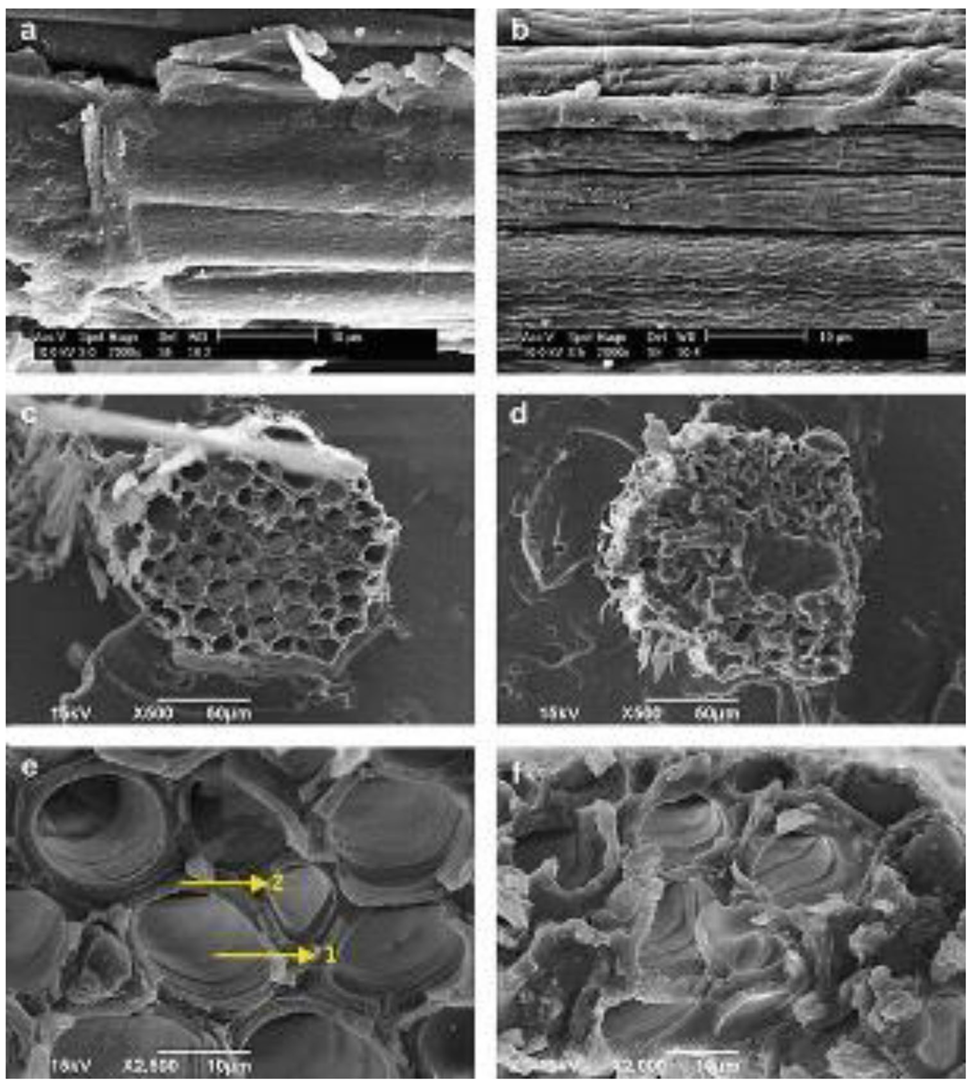


Fig. 3 SEM images of BSF. **a** and **b** Scaly & cellular BSF—with horizontal marks depicting fiber bundle structure. **c** and **d** Transverse section of BSF—multicellular structure, fibrils in bundles. **e** and **f** Structure of raw fiber—arrow no.1 indicates fiber-cell walls, arrow no.2 indicates lumen in cross section (Reproduced from [38] Under the Creative Commons Attribution 3.0 License)

3.4 Characterization of tensile properties

Banana fiber exhibits a tensile strength of 529–914 MPa [103, 104], depending on processing techniques. In addition, BSF's stiffness defined by Young's modulus ranges between 27 and 32 GPa, suitable for applications requiring high rigidity [104]. Treated fibers show up to 40% increase [107], achieving tensile strengths as high as 1200 MPa. Notably, alkali treatment enhances tensile strength of BSF by improving fiber-matrix adhesion, resulting in up to a 71% increase in tensile strength. Treated BSF composites exhibit superior stress–strain behavior compared to untreated fibers [102]. Sodium hydroxide (NaOH) treatments result in stronger hydrogen bonding at the fiber-resin interface which directly impacts its strength. In addition, it is found that the maximum tensile strength of banana fiber reinforced thermosets was found to depend on the fiber length, loading and NaOH used for treatment [112]. The optimal NaOH concentration for such treatments is 5%, which minimizes amorphous components and maximizes mechanical properties [106]. It is found that tensile properties of BSF improved with alkali treatment [111]. Alkali, acid and bacterial treatments directly affect the physicochemical characteristics of banana fiber [113]. Banana fibers exhibited a tensile strength of 590 MPa which is higher than sisal and jute which showed 350 MPa and 249 MPa respectively [109].

3.5 X-ray diffraction (XRD)

BSF consists of crystalline as well as amorphous regions. Crystalline cellulose imparts stiffness and strength while amorphous components like hemicellulose and lignin lower mechanical performance [54]. X-ray diffraction (XRD) patterns indicate that BSF has a crystallinity index (CI) of 60–65% [54, 101], attributed to high cellulose content. Increased cellulose content leads to increase in crystallinity, which improves tensile properties. In addition, microfibrillar angle of BSF is between 10° and 11° [103] contributing to its stiffness and tensile strength. A lower microfibrillar angle typically correlates with improved mechanical properties. Alkali treatment results in improving CI to 75%, [114] correlating with enhanced tensile strength and thermal stability. Removal of amorphous components sharpens diffraction peaks, particularly at $2\theta \approx 22.5°$ (cellulose Iβ), confirming increased crystallinity [114, 115]. These changes highlight the alkali treatment's role in improving BSF's suitability for high-performance applications. XRD pattern of 1% NaOH treated banana fiber revealed three peaks at 15.2, 16.5 and 22.4 corresponding to the cellulose crystalline phase and an amorphous phase corresponding to lignin. In addition, alkali treatment increased BSF's crystallinity to 73.9% whereas, raw fiber is 63.5% crystalline [116].

3.6 Fourier transform infrared spectroscopy (FTIR)

FTIR results obtained with BSF reveals O–H stretching at (3300–3400 cm^{-1}) which indicates hydroxyl groups, are common in cellulose and hemicellulose[54, 61, 109] and C–H stretching at (2900–2920 cm^{-1}) reflects aliphatic carbons in cellulose chains. However, lignin reduction during treatment is evidenced by aromatic C=C Peaks at (1500–1600 cm^{-1}). The reduced intensity peaks signify delignification. And C–H in methoxy groups at (1260 cm^{-1}) diminishes post-chemical treatments, indicating lignin removal [61, 109].

BSFs after chemical modifications presents additional peaks in the FTIR spectra. Peaks such as 688 cm^{-1} (C=C, C–H alkynes/alkanes), 1054 cm^{-1} (C–N stretching) [19], and others reflect the structural and chemical modifications after the composite preparation. The enhanced O–H peak intensity suggests improved hydroxyl group accessibility, essential for further functionalization. While new or modified peaks (e.g., C–N stretching) indicate structural changes, such as incorporation of amines or removal of impurities [61]. FTIR analysis of raw fiber exhibited O–H, C–H, C–O–C stretching at 3430 cm^{-1}, 2920 cm^{-1} and 1058 cm^{-1} respectively and C=C benzene stretching ring around 1635 cm-1. However, chemical treatments did not modify the vibrational spectra of BSF [116]. FTIR studies indicate that acid treatment of banana fibers resulted in higher amount of sp3 carbon revealing its crystalline nature while raw fiber has sp2 carbon [117].

FTIR spectra obtained with BSF fibers extracted by different degumming processes is given by Fig. 4. It is once again proven that the quality of fiber extracted by enzymatic retting (green) is good compared to other methods. And fiber extracted by mechanical processing resulted in reduced values of transmittance making the curve to appear below others (blue).

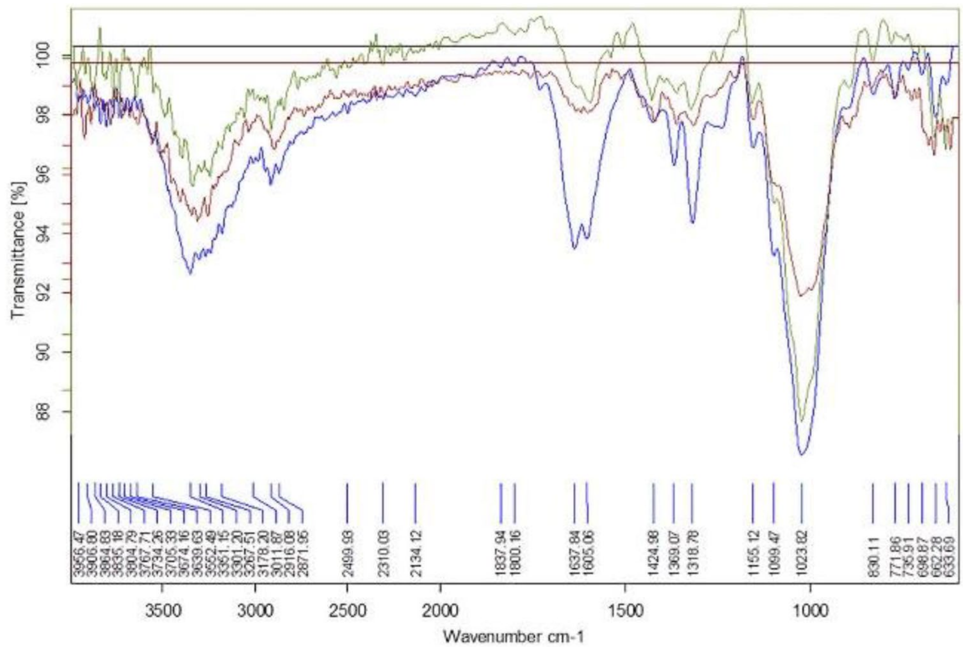


Fig. 4 FTIR spectroscopy of BSF extracted by various methods Blue (mechanical), red (chemical), green (biological) (Reproduced from [107] under the terms of the Creative Commons Attribution 4.0 License, http://www.creativecommons.org/licenses/by/4.0/)

3.7 Thermal and degradation properties

As a lignocellulosic material, banana stem fiber (BSF) displays distinct thermal and degradation properties that underpin its versatility for applications such as bio composites, biomedical devices, and eco-friendly packaging. TGA of BSF depicts its various thermal decomposition stages.

- Moisture evaporation: Initial weight loss occurred in the temperature range of 29–120 °C, attributed to the evaporation of free and bound water in the fibers. The weight loss percentage ranged between 5–8% [54].
- Cellulose and hemicellulose decomposition: Significant weight loss was observed between 250–370 °C for fibers and 228–384 °C for cellulose nanocrystals. Decomposition in this range is primarily due to the breakdown of hemicellulose, α-cellulose, and volatile product formation [54, 67, 118].
- Lignin and carbonaceous matter degradation: The third degradation phase above 400 °C involved the decomposition of lignin and carbonaceous residues, forming char [67].
- Chemically extracted fibers exhibited higher thermal stability than untreated fibers, with degradation temperatures increasing by approximately 10 °C.

The fiber remains stable up to 260 °C, allowing for high-temperature processing without significant degradation [105] which demonstrates its good thermal stability. However, BSF's are hydrophilic in nature having a moisture content of 8–12% [102] which influences their dimensional stability and adhesion between composites [104]. Inherent to its cellulose and hemicellulose content, BSF absorbs 60–75% of its weight in water showcasing its hydrophilic nature. This high absorption necessitates surface modifications for applications requiring stability. Surface treatments are often employed to mitigate excessive moisture absorption for specific uses. Surface Treatments such as, alkaline treatment reduces hydroxyl groups, lowering water absorption by up to 40% and silane treatment could enhance hydrophobicity, improving performance in polymer matrices [60, 61].

Effect of NaOH treatment: Fibers treated with 5% NaOH showed the enhanced thermal stability, retaining integrity up to 60–80 °C, showing the least weight loss at 68%. However, increasing NaOH concentrations (> 5%) did not significantly improve stability, suggesting 5% as the optimal treatment level [118]. Banana stem fibers, particularly when treated with 5% NaOH, demonstrate promising thermal stability and degradation properties, making them suitable for bio-composite processing. Its thermal stability up to 200 °C ensures suitability for biomedical and composite applications, while its biodegradability and safe degradation by-products support eco-friendly initiatives.

3.8 Biodegradability

BSF films decomposes within 30 days under optimal composting conditions of 21% soil moisture [119], whereas synthetic fibers like polyester persist for decades. Cellulose facilitates microbial degradation, breaking down into simpler compounds like glucose and hemicellulose degrades faster due to its amorphous structure. However, Lignin's degrade slower but add strength [51, 98]. Being a natural fiber, BSF decomposition is devoid of microplastics or toxic by-products, making it an ideal candidate for compostable products. BSF is inherently non-toxic, making it safe for integration into biomedical applications. Alkali treatment aids in improving BSF's biocompatibility by removing impurities. A comparative summary of the properties of normal BSF and BSF fiber obtained after treatment are presented in Table 3.

3.9 Comparison with other natural fibers

A comparison of the properties of BSF with other natural fibers like jute, banana, coir, flax, sisal, and cotton is presented in Table 4. It is clear that BSF demonstrates tensile strength comparable to jute and flax, making it suitable for reinforcement in composite materials [51, 60, 97]. However, BSF has a lower elongation at break than coir and cotton, which indicates its greater stiffness. In addition, BSF thermally degrades within the range of 200–350 °C, which is comparable to other natural fibers [3, 67]. This ensures its compatibility with thermoplastic composites, making it suitable for various industrial processing needs. The water absorption capacity and density of BSF are similar to those of jute, coir, and flax. These properties make it effective for lightweight applications where moisture sensitivity is a critical factor. BSF uniquely possesses moderate inherent antimicrobial properties, unlike many other natural fibers [61, 120]. These properties can be significantly enhanced through surface modifications, offering additional benefits for applications in healthcare and packaging industries.

Banana stem fiber stands out among natural fibers due to its balanced mechanical strength, thermal stability, moisture resistance, and unique antimicrobial properties. These features make it a versatile and eco-friendly alternative for applications in composites, textiles, and biodegradable materials.

Table 3 Summary of Banana stem fiber characterization

Characterization studies	Ref. No	Normal BSF	Treated fiber
Physical characterizations			
SEM	[60, 61]	Rough and porous surface with waxy coatings and lignin layers	Alkali treatment • Smooths the surface with increased porosity and exposed microfibrils • Improves interfacial bonding with polymer matrices
UTM	[103, 104]	Tensile strength—529–914 MPa	• As high as 1200 MPa • Alkali treatment increases tensile strength up to 71%
	[102]	Elongation at Break—3–9%	–
	[104]	Young's Modulus—29 to 32 GPa	Treated BSF exhibits superior stress–strain behavior
XRD	[54, 101]	Crystallinity Index (CI) 60–65%	Alkali treatment increases CI by 75%
Chemical characterization			
FTIR	[61, 109]	• O–H Stretching at (3300–3400 cm^{-1}) • C–H Stretching at (2900–2920 cm^{-1})	• Lignin reduction aromatic C = C Peaks at (1500–1600 cm^{-1}) • Disappearance of C–H in Methoxy Groups at (1260 cm^{-1}) • Peaks at 688 cm^{-1} (C=C, C–H alkynes/alkanes), • 1054 cm^{-1} (C–N stretching)
Thermogravimetric Analysis			
TGA	[54, 67]	• Moisture Evaporation—5–8% • Thermal stability up to 200 °C • Cellulose and hemicellulose decomposition—250–370 °C • Lignin and Carbonaceous Matter Degradation—above 400 °C	• Post chemical treatment degradation temperatures increased by ~ 10 °C • 5% NaOH—retain thermal integrity up to 60–80 °C

Table 4 Constituents and properties of various plant-derived fibers [2, 51, 97, 104]

Fibers	Source	Constituents			Properties					
		Cellulose	Hemi cellulose	Lignin	Density	Tensile Strength	Elongation at break	Thermal degradation	Water absorption	Anti-microbial property
Banana stem	Banana Pseudo stem	60–65	6–19	5–10	~ 1.35	450–750	1–3	200–350	10–12	Moderate
Jute	Jute plant	61–71	12–20	11–14	1.3–1.5	393–773	1.5–2	200–350	~ 12	Low
Coir	Coconut husk	36–43	0.15–4	41–45	1.15–1.4	131–220	30	200–230	8–12	Low
Flax	Falx plant	71–75	18–20	2–3	1.5	500–900	1.2–1.6	200–370	10–12	Low
Cotton	Cotton seed	~ 90	~ 6	~ 1	1.5	~ 400	8–10	~ 230	~ 8	Low
Sisal	Leaves	65–70	10–14	9–12	1.45–1.5	610–720	2–4	250–360	~ 10	Low

3.10 Properties of BSF-based products

A comparison of the properties of BSF based products are studied to understand its potentials. Banana fabrics exhibited 22% more tear strength and good air permeability than cotton making them an alternative to cotton fabric [105]. Similarly, banana fiber (20%) reinforced poly lactic acid composite exhibited a tensile strength of 52.57 MPa, Flexural strength of 70.35 MPa, Impact strength of 155.45 J/m [106]. Banana fibers-based biofilms are biodegradable compared to synthetic packaging materials which enable them to emerge as eco-friendly packaging materials [68]. Nanofiber membranes developed from BSF showcased 90% cell viability which reveal their potential wound healing and drug release capabilities [69]. Silanized-chitosan treated BSF bio-composites were demonstrated improved thermal properties [121].

3.11 Challenges and potential enhancements

A major challenge in advancing BSF applications is the dependence of its mechanical and thermal properties on environmental conditions such as soil quality, altitude, and climatic conditions of the plantation. The unique combination of biodegradability and biocompatibility in BSF establishes it as a transformative material for sustainable and biomedical applications. By optimizing functionalization and treatment processes, BSF's potential in environmental and healthcare sectors will continue to grow. However, advancements in mechanical and chemical extraction methods, such as enzymatic treatments, are essential to further improve fiber purity and mechanical performance. The structural and mechanical attributes of BSF highlight its potential as a sustainable and versatile material [105]. With optimized treatment methods, BSF can further cement its position as a high-strength, eco-friendly alternative to synthetic fibers, expanding its applications in high-performance bio-composites, textiles, and biomedical device. With the elaborate introduction to natural fibers, banana fibers followed by properties of BSF explained in previous sections, the following section introduces the wound healing process followed by recently developed wound healing structures and drug-impregnated bio composites in Sect. 4.

4 Wound healing process & its significance

A brief description of the wound healing process is presented below which enables understanding the requirements better while designing wound healing material and selection of drug for wounds. Wound healing is a complex biological process that helps restore tissue integrity while preventing infections, and antimicrobial activity plays a pivotal role in accelerating the process. Basically, there are two types of wounds and they are (i) unintentional wounds (accidental) and (ii) intentional wounds (resulting from surgery). Surgical site infections (SSI) affect approximately 1–2% of hospital patients, underscoring the need for advanced wound healing and antimicrobial strategies [122]. Wound healing occurs in four distinct stages namely, (i) Haemostasis: blood clot formation acts as a primary barrier against microbial invasion, (ii) Inflammation: immune cells release antimicrobial peptides and ROS to eliminate pathogens, (iii) Proliferation: fibroblasts and endothelial cells drive tissue growth, (iv) Remodeling: collagen synthesis ensures scar formation in a pathogen-free environment [122]. A schematic representation of wound healing process is presented in Fig. 5. Series of steps that occur in each stage of wound healing is represented by boxes below their heading.

Key immune cells, such as neutrophils and macrophages, drive this mechanism. Neutrophils release potent antimicrobial substances during respiratory bursts, while macrophages transition between M1 (pro-inflammatory) and M2 (anti-inflammatory) states to clear debris and facilitate tissue regeneration [123]. However, persistent microbial flora

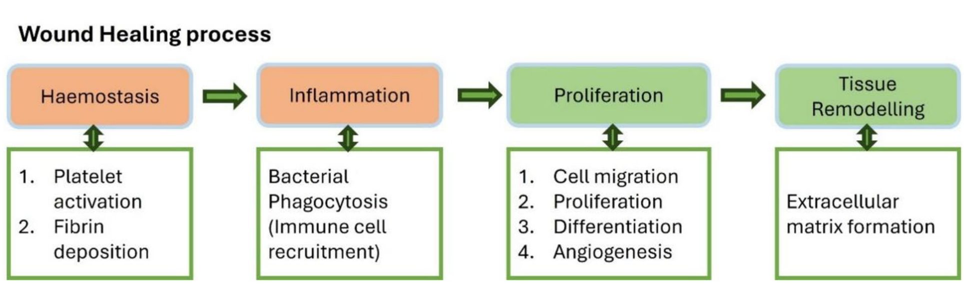


Fig. 5 Wound healing and its stages

and delayed neutrophil apoptosis can hinder wound healing process. The absence of neutrophil lysis or M1-to-M2 macrophage conversion prolongs inflammation, preventing the transition to the proliferation stage [123]. In addition, reactive oxygen species (ROS), including hydrogen peroxide (H_2O_2) and superoxide (O_2^-), serve dual functions: as antimicrobial agents and as signaling molecules critical to wound repair. Moderate ROS levels enhance healing efficiency, promoting about 40% improvement in tissue repair processes. But excessive ROS accumulation further delays neutrophil apoptosis by triggering strong inflammatory responses that delay healing. Thus, biocompatible solutions that enable efficient wound care are the need of the hour.

Two significant functions that enable efficient wound healing are (i) antimicrobial functions and (ii) tissue regeneration functions. Antimicrobial action takes place by different mechanisms like (i) disrupting bacterial cell walls, (ii) inhibition of nucleic acid synthesis, (iii) disruption of cytoplasmic membrane function, (iv) inhibition of energy metabolism, (v) impact on bacterial motility, and (vi) biofilm inhibition. The mechanism of action depends on the type of phytochemical present in the wound healing material [124, 125]. Tissue regeneration takes place by (i) collagen deposition and ECM formation, (ii) stimulation of VEGF and FGF and (iii) infection control and inflammation reduction. Various biological activities (antimicrobial and tissue regeneration) responsible for promoting wound healing and the various wound healing structures recently developed are represented in Fig. 6.

4.1 Ideal wound dressing and recent advancements

The primary function of a wound dressing is to protect the wound from external microorganisms. An ideal wound dressing material should (i) generate a clean, moist and warm environment that promotes wound healing, (ii) absorb excess wound exudate, (iii) devoid of release of foreign materials that harm the wound, (iv) facilitate breathability, (v) allow hydration and (vi) be pain-free while removing [126]. In addition, it should have a neutral pH and be devoid of starch and other chemicals [127]. Recent advancements in wound dressing materials not only protect wounds but also promote wound healing. Such an advancement is made feasible by the use of materials with inherent bioactivity and tissue regeneration capabilities or by bioactive drug impregnating wound dressing. Recent day wound dressings include the use of hydrogels, films, foams, polysaccharides, granules, gels as well as composites made from natural polymers and fibers which are detailed below [128, 129].

Hydrogels: Hydrogels are particularly effective for chronic wounds and burns, as they provide hydration and help prevent infection, promoting faster healing and reduced risk of complications. Nano cellulose derived from plant sources are crosslinked with hydrogel-forming agents such as alginate or chitosan for the synthesis of hydrogels [130–133]. Hydrogels exhibit high moisture retention, essential for optimal wound healing conditions [134]. The incorporation of antimicrobial agents, including silver nanoparticles or essential oils, further enhances the bioactivity of the hydrogel during the gel formation process [135]. The addition of antimicrobial agents, impart antibacterial properties, to help prevent infections during the healing process.

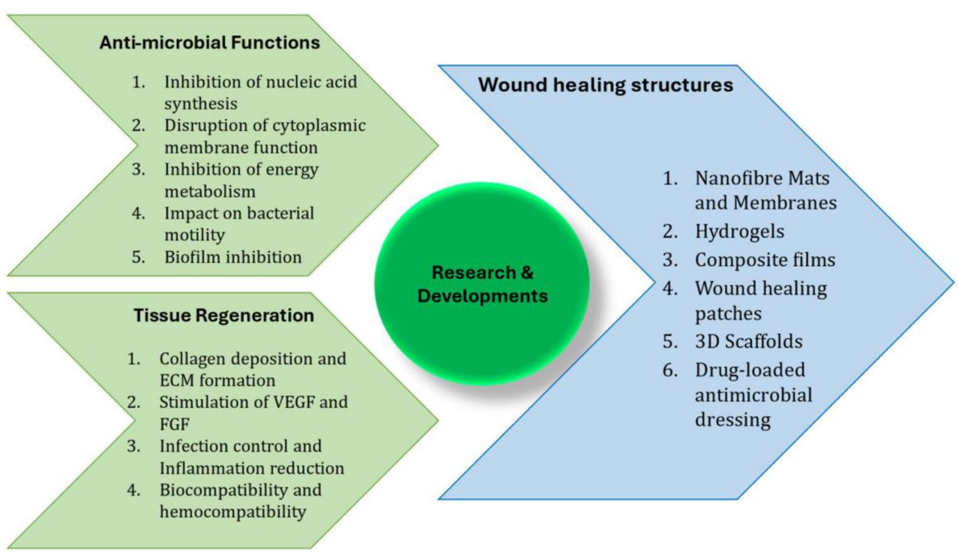


Fig. 6 Biological activity responsible for wound healing and various wound healing structures

Innovative solutions such as dopamine-substituted multi-domain peptide (DAP)-based hydrogels provide a promising approach for healing wounds. These hydrogels, incorporating antimicrobial lysine residues and ROS scavenging properties, significantly reduce the inflammatory stage and accelerate wound closure. When tested on full-thickness dermal wounds in mice, DAP hydrogels demonstrated enhanced skin adhesion, collagen alignment, vascularization, and shortened healing times [136]. The integration of advanced materials like antimicrobial hydrogels with functionalized components has reduced infection rates by 65% and increased recovery speed by 30% [122, 136]. Pure hydrogel dressings are mechanically weak and brittle and thus, reinforcing them with natural fibers is frequently investigated [8]. However, the use of natural fibers in biomedical applications demand adequate processing in order to make them suitable for biomedical use [9].

Chitosan based wound dressing: Tough-chitosan dressings developed using non-woven technique were demonstrated to promote wound healing than alginate based wound dressing materials [137]. Similarly, Graphene oxide, zinc oxide incorporated chitosan nanocomposite films were demonstrated to accelerate wound healing [138].

Composite films: Composite films are synthesized by blending BSF with biodegradable polymers such as polyvinyl Alcohol (PVA) or polycaprolactone (PCL) [130, 131]. The resulting films are cast through solvent evaporation or hot-pressing methods. Composite films exhibit properties such as flexibility, biocompatibility, and biodegradability, making them suitable for wound healing applications. They form an effective barrier against microbial contamination, protecting the wound from external pathogens. These composite films are used as protective wound covers or skin substitutes, providing a durable and supportive layer over wounds during the healing process.

3D scaffolds: Fibers are processed into nanocellulose and combined with biodegradable polymers for 3D printing or freeze-casting. Pores are introduced into the scaffolds to mimic the extracellular matrix (ECM) [65, 132, 133], creating a structure that supports cellular infiltration and tissue regeneration. These scaffolds facilitate cellular infiltration and vascularization, which are crucial for the formation of new tissue and blood vessels at the wound site. The gradual degradation of the scaffold aligns with tissue regeneration [130, 139], ensuring that the support provided by the scaffold diminishes as new tissue forms. Deep wound healing and tissue engineering applications benefit from these 3D scaffolds, as they provide a structure for tissue growth and repair in more severe injuries [139].

Nanofiber Mats and Membranes: The fabrication of nanofiber mats and membranes involves advanced processes like electrospinning and wet-spinning. In electrospinning [130], cellulose derived from plants are dissolved in a polymer matrix, such as polyvinyl alcohol (PVA) or chitosan, and processed under an electric field to form nano-fibers. Wet-spinning is another technique that creates fibers with controlled dimensions, ideal for making wound dressings. Such ES fibers could be tailored to exhibit properties like, (i) high surface area for enhanced cell attachment, crucial for tissue regeneration, (ii) controlled porosity for effective oxygen exchange and management of wound exudates, contributing to optimal healing conditions. These nanofiber-based materials are used as advanced wound dressings [130, 131], accelerating the healing process and reducing scarring, particularly for superficial and acute wounds. For instance, cellulose acetate derived from.

4.2 Drug impregnated patches as antimicrobial dressings

Drug-loaded dressings (of different materials) offer long-lasting antimicrobial activity, preventing infections and maintaining a clean environment around the wound. For instance, Tetracycline is incorporated into nanocomposite films made of chitosan and cellulose nanocrystals (CNC) derived from fiber. These tetracycline-loaded nanocomposites exhibited a zone of inhibition of 36.3 mm for *E. coli* and 39.3 mm for *S. aureus*, indicating effective antibacterial activity against both gram-negative and gram-positive bacteria [67]. Even, neem/chitosan coating of surgical sutures made from silk fiber were demonstrated to speed-up wound healing at the surgical site. In addition, concentration of neem/chitosan addition is found to result in increased zone of inhibition with *E. coli* and *S. aureus* [140]. These materials also prevent biofilm formation and secondary infections, which are common in chronic wounds. However, drug selection primarily depends on its significance. For example: *Rosmarinus officinalis* L. is well-known for its antispasmodic, mild analgesic and has significant antimicrobial, anti-inflammatory, anti-oxidant, anti-apoptotic, anti-tumorigenic, antinociceptive, and neuroprotective properties [141]. Whereas, juice of Vitex negundu leaves were found to show antibacterial, antifungal and anti-inflammatory activity and is traditionally used to treat wounds and skin infections [142].

Natural drugs: Wound healing materials are combined with bioactive substances such as collagen, honey, or aloe vera to enhance the healing properties of the material. These materials are then processed using compression molding or freeze-drying to create porous patches [131]. Such patches support tissue regeneration, helping to repair damaged skin or tissue. They also help reduce inflammation and accelerate epithelialization [143, 144], the process through which new tissue forms to close the wound. Post-surgical wounds and diabetic ulcers benefit significantly from these patches, as they promote faster recovery and help reduce complications like infection.

Chitosan as drug: Chitosan, a natural polymer with inherent antimicrobial properties, is used as drug with bio-composites. The addition of chitosan to CNC derived from banana pseudo stem, improved the mechanical properties of the composites while imparting antimicrobial functionality. The antibacterial efficacy of chitosan-CNC composites as tested by disc diffusion method revealed a zone of inhibition of 36.3 ± 0.6 mm and 39.3 ± 0.6 mm against *E. coli* and *S. aureus* respectively [67] which is more than raw cellulose composite [145]. This reveal the superior antibacterial activity of Chitosan + CNC composites and its ability to disrupt bacterial cell membranes through electrostatic interactions [67, 131].

Plant extracts as drug: Materials are treated with antimicrobial agents such as silver nanoparticles, zinc oxide, or natural extracts like neem and turmeric [131]. Coating or impregnation techniques ensure the uniform distribution of these agents throughout the material. CNC derived from banana pseudo stem is mixed with gel-forming agents and freeze-dried to create lightweight, porous sponges [132]. These sponges can be infused with drugs or growth factors, enabling sustained release of bioactive compounds at the wound site and are particularly useful for chronic wound management and drug delivery systems [65, 132, 133], as they provide both mechanical support and therapeutic benefits.

Phytochemicals in plant extracts: Polyphenols or Phenolic compounds, by their inherent antioxidant capacity and radical scavenging activity, generate reactive oxygen species (ROS), which disrupt microbial biofilms and exhibit antimicrobial effects which directly helps in faster tissue regeneration and wound healing [125]. Phenolic compounds like catechins and gallocatechins are strong antioxidants, prone to scavenge free radicals which aid in protecting cells from oxidative stress and damage, thereby promoting tissue regeneration [146–148]. However, flavonoids accelerate collagen synthesis, angiogenesis thereby inhibiting microbial growth and inflammation [124, 149–151]. Saponins enhance wound sterilization and reduce inflammation whereas, steroids/terpenoids increase fibroblast proliferation, collagen synthesis and aid in wound healing. Tannins/polyphenols are strong astringents that promote wound contraction and tissue repair [152]. Flavonoids form the class of natural products researched primarily for their anti-infective behavior. They are excellent antibacterial agents and proven to retard biofilm formation [153]. Different flavonoids elucidate antibacterial activity through unique processes for example, flavonoids, such as quercetin and kaempferol, contribute to antimicrobial activity by intercalating into microbial DNA, inhibiting transcription and replication, and inducing oxidative stress, which leads to microbial apoptosis. Quercetin inhibits nucleic acid synthesis whereas cytoplasmic membrane function is inhibited by sophoraflavanone G, and (−)-epigallocatechin gallate. While energy metabolism is inhibited by licochalcone A and C [124]. The synergistic effect of phenols and flavonoids aid in accelerated wound healing.

Combined chemical and functional modifications: Blending polyvinyl alcohol (PVA) with CNC, combined with antimicrobial agents like tetracycline, enhances both antibacterial efficacy and film stability. These films maintain their mechanical integrity while providing extended protection against microbial contamination [65]. In another experiment, silver nanoparticles were synthesized over a pre-deposited chitosan multilayer hydrogel using an in situ electrochemical synthesis. This method uses pre-programmed electrical signals to enable formation of chitosan layer along with in situ growth of silver nanoparticles [154]. The synthesized nanoparticles were spherically shaped and ~ 15 nm in size. The layered architecture of the hydrogel resulted in porous segments and compact boundaries that aided in pH dependent drug (AgNP) release [135, 154, 155]. In addition to silver nanoparticles, even ZnO nanoparticles were used for functionalizing composites for imparting antimicrobial properties [156, 157]. Even nanoconjugates that encapsulate drugs can be loaded to biomaterials as functionalization. The moieties attached to nanoconjugates enable drug targeting, increasing solubility, stability and controlling release conditions. For example, coating wound healing materials with silver nanoparticles or biopolymers enhances its biomedical utility [69]. Drug incorporated wound dressings and suture materials are ideal for infected or at-risk wounds, including those with a high risk of developing bacterial infections, such as surgical sites or wounds in immunocompromised patients. With this brief discussion on recently advancements in wound care materials, researches highlighting especially BSF based wound care materials are elaborated in the below section.

5 BSF based materials & their biomedical applications

Being an agricultural waste product, the use of BSF for medical applications minimizes reliance on synthetic materials and thus, supporting sustainability and eco-friendly initiatives [61, 62, 102, 158]. Banana pseudo stem fibers (BSF) were effectively incorporated in numerous biomedical applications however there is still a lot of room for research interventions. BSF in the form of composite patches, suture materials and cellulose nano fibers enable sustained drug delivery, promote wound healing and could act as good prosthetic materials. BSF based biomedical materials serving various functions are discussed below:

BSF composite:

Composites developed from natural fiber reinforcements have shown good mechanical properties than those fabricated from synthetic fibers, enabling their use in prosthetic sockets [83]. Specifically, Composites made from treated BSF's have demonstrated enhanced mechanical properties like tensile strength which enable their use as biomedical prosthetics [63]. In addition, the introduction of chitosan y-glycidoxypropyltrimethoxy-silane (GPTMS) in to banana fiber reinforced bio-composites made from maleic anhydride and montmorillonite filler materials resulted in reduced water absorption due to the hydrophobic behavior of chitosan. These composites exhibited better thermal and mechanical properties too [121]. However, BSF composites fabricated with BSF, chitosan, gaur gum loaded with natural drug were demonstrated to promote wound healing [32]. These experiments highlight the potential property modifications feasible with banana fiber reinforced composites which enable their use across wide biomedical applications ranging from exudate absorbable wound care products to hydrophobic and strong prosthetic materials.

BSF cellulose and hydrogels:

Nano cellulose is synthesized from cellulose rich plants acid hydrolysis, mechanical treatment or enzymatic treatment [159, 160]. For example, cellulose nano fibers were synthesized from BSF by alkali treatment, followed by acid hydrolysis and homogenization [145]. For instance, microcrystalline cellulose synthesized from banana fibers with an antioxidant activity of 92% at 100 µl/ml were demonstrated to act as excellent drug delivery vehicle [161]. While crosslinking BSF nano cellulose with konjac glucomannan followed by free-drying resulted in composite aerogels which were capable of inhibiting *E. coli* and *S. aureus* [132]. These aerogels can be used as potential wound healing materials. In addition, CNF extracted from banana pseudostem when cross-linked with gelatin and glutaraldehyde resulted in biomedical hydrogel used as facemasks [120]. Such nano cellulose derived from banana plant find numerous biomedical applications which includes, (i) fabrication of bone plates and scaffolds, (ii) capacitors for insulin pumps and pacemakers, (iii) biosensing, (iv) drug delivery, (v) tissue engineering, (vi) wound healing, (vii) enzyme immobilization, (viii) tablets for oral administration [51].

BSF functionalized fabric:

Natural fibers are significant investigated for their application in textile ad textile products. Especially, banana fibers are vastly investigated for development of woven and non-materials for biomedical use. For instance, banana fabric coated with green tea (*Camellia sinensis*) and Tulsi (*Ocimum sanctum*) extracts exhibited antimicrobial activity against *S. aureus* and *E. coli*. Extract coated fabric resulted in a ZOI of 2.8 cm, 2.4 cm against *E. coli* and *S. aureus* while untreated fabric exhibited 1.7 cm and 1.5 cm ZOI against *E. coli* and *S. aureus* respectively [162]. In addition, experiments on studying property modifications of banana fiber were carried out. For example, the hydrophilicity of non-woven banana fabric was reduced by introduction of water repellents [59]. While banana fibers coated with glutaraldehyde crosslinked chitosan were found to absorb chromium (VI) from water [47]. These examples highlight that BSF's can be tailored for particular applications by appropriate modifications.

Drug-coated BSF surgical suture:

Surgical suture materials were developed from BSF. The wound healing efficacy of BSF suture material without coating and with coating were studied in comparison with commercially available Bombyx mori silk fibroin (BMSF) suture. Antimicrobial agents such as chloramphenicol and clotrimazole are incorporated into the hydrogel, alongside growth factors like epithelial growth factors to promote tissue regeneration. The fibers are immersed in this hydrogel solution and dried at 37 °C for 24 h [61], enabling drug impregnation. Efficiency of drug-impregnation is determined by measuring weight changes before and after the coating process. These experiments highlight the medical use of BSF and the effect of drug impregnation on healing efficacy.

BSF nanofiber membrane:

BSF has been used to develop electrospun nanofiber membranes with antimicrobial and wound-healing capabilities. Cellulose acetate synthesized from esterification of banana fiber and chlorhexidine (CHX) are dissolved in 2:1 acetone: *N*, *N* dimethyl acetamide solvent. This mixture is electrospun to a nano fiber membrane which exhibited good antimicrobial activity against *E. coli* and *S. aureus* with a ZOI of 18.38 mm and 22.51 mm respectively. These results support their use for wound healing applications [69]. These references act as evidences for innovative applicability of BSF in biomedical field. Figure 7 presents the images of BSF and materials synthesized from BSF. Figure 7a is the digital image of untreated banana stem fiber while alkali-treated fiber is presented in Fig. 7b. Figure 7c is the Nanocellulose synthesized from BSF and Fig. 7d is the Hydrogel produced by crosslinking BSF cellulose with gelatin and glutaraldehyde.

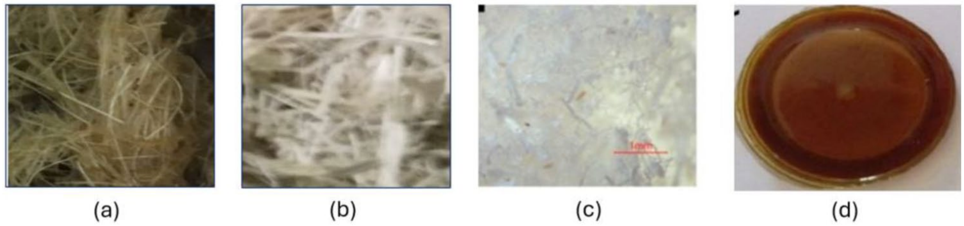


Fig. 7 BSF and BSF based biomedical materials **a** Untreated BSF, **b** Alkali-treated BSF, **c** Nano cellulose from BSF [91] (Reproduced from [91] under the Creative Commons Attribution (CC BY) license (https://www.creativecommons.org/licenses/by/4.0/), **d** Hydrogel from BSF [120] (Reproduced from [120] under a CC BY 4.0 license)

5.1 Antimicrobial action

BSF suture materials impregnated with Chloramphenicol and clotrimazole were developed and tested for biomedical use. Chloramphenicol inhibits bacterial protein synthesis, while clotrimazole compromises fungal cell wall integrity. Experimental results demonstrate the modified BSF based sutures with functional coatings resulted in an inhibition zone of 32 ± 2 mm, 29 ± 3 mm and 6 ± 0.5 mm diameters against *Escherichia coli* (*E. coli*), *Staphylococcus aureus* (*S. aureus*) and *Candida albicans* (*C. albicans*) respectively [61]. While, BSF bio-composite patch with herbal drug (vitex nirgundi) showed zone of inhibition of 30 mm, 26 mm, 27 mm against *E. coli*, *S. aureus* and *M. lutens* respectively [32]. However, BSF patches without cross-linking and drug inclusion showed reduced inhibition of micro-organisms say 18 mm, 19 mm, 17 mm, 19 mm against *E. coli*, *K. pneumonia*, *S. aureus*, *S. mutans* respectively [145]. These results support the fact that biopolymer cross-linking and drug loading could improve the antimicrobial efficacy of composite patches. In addition, banana cellulose fibers derived from banana pseudo stem were demonstrated to exhibit strong antibacterial activities [145]. Hydrogels fabricated by crosslinking gelatin and glutaraldehyde with cellulose exhibited good antimicrobial activity against *Escherichia coli*, *Staphylococcus aureus*, *Candida albicans*, with a ZOI of 20.6 mm, 17.5 mm, 14.7 mm which serves as an addition proof for BSF's infection control application [120]. A list of antibacterial inhibitions exhibited by banana pseudo stem variants is presented in Table 5.

Table 5 Antibacterial activity exhibited by BSF based biomaterials

Ref. No	Bacteria	Zone of Inhibition (mm)	Sample under study
[32]	*E. coli*	30	BSF composite patch
	S. aureus	26	
	M. luteus	27	
[145]	*E. coli*	18	200 µg of BSF cellulose
	K. pneumonia	19	
	S. aureus	17	
	S. mutans	19	
[120]	*E. coli*	20.6	BSF hydrogel
	S. aureus	17.5	
	C. albicans	14.7	
[69]	*E. coli*	18.38	BSF nanofiber membrane
	S. aureus	22.51	
[162]	*E. coli*	1.7 cm	Untreated Banana fabric
	S. aureus	1.5 cm	
[162]	*E. coli*	2.8 cm	*C. sinensis* and *O. sanctum* extract coated Banana fabric
	S. aureus	2.4 cm	
[61]	*S. aureus*	29	BSF suture string
	E. coli	32	

5.2 Testing drug-release activity

The drug release profile of Hydrogels integrated with BSF for antimicrobial drug (chloramphenicol) was assessed in Phosphate Buffer Solution with pH 6.3, 6.8, and 7.7. the drug release pattern exhibited an initial burst release of 35% and a sustained release of 87% over 144 h. [61]. Microcrystalline cellulose (MCC) extracted from banana pseudo stem were studied for their drug release activity in simulated intestinal fluid at pH 7.4 and found that inclusion of MCC in alginate beads increased binding of drugs and aided in sustained release of drugs. The MCC exhibited a highest drug release of 425 mg (Isoniazid) after 6 h. in simulated intestinal fluid [161]. BSF composites loaded with Nirgundi drug exhibited highest percentage of drug release of 91.15% after 120 min [32]. Drug release kinetics are determined by measuring absorption spectra at 497 nm using a UV-Visual spectrophotometer. BSF composites demonstrates a sustained release of embedded agents which prevents microbial biofilm formation and disrupts bacterial and fungal growth mechanisms [61, 62, 158].

5.3 MTT assay

MTT results revealed the Chitosan films with 10% banana peel powder exhibited more than 100% cell viability against NIH3T3 fibroblast cell which reveals its non-toxic nature [144]. Silver nanoparticles synthesized from *Capparis zeylanica* L. exhibited a cell viability of 40% on A549 cell line which conformed its cytotoxicity [163]. MTT assay results from BSF composites with vitex nirgundi drug revealed a cell viability of 140.72 ± 1.72% which indicates its non-toxic nature [32]. In addition, BSF suture materials with drug impregnation exhibited a cell viability of 84% against L929 mouse fibroblast after 72 h of incubation [61].

5.4 DPPH assay

DPPH assay results from raw banana fiber and alkali treated banana fiber samples revealed a free radical scavenging of 18% and 15% respectively. However, chitosan and gaur gum exhibit about 19% of antioxidant activity. These results confirm antioxidant behavior of banana fiber [32].

5.5 Tissue regeneration

BSF biomaterials exhibit excellent biocompatibility, with L929 fibroblast viability exceeding 84%, meeting ISO standards for medical use. Additionally, BSF enhances keratinocyte migration, critical for re-epithelialization and dermal tissue recovery. BSF demonstrated a hemolysis rate of just 0.78%, well below the permissible limit of 5%, confirming its safety for direct blood contact. BSF accelerates epithelial cell migration and proliferation, resulting in a 30% faster epithelialization rate compared to untreated wounds [61]. Furthermore, its ability to align collagen fibers and minimize fibrovascular tissue width contributes to reduced scarring. Wound healing potential of BSF based bio-composite patch is assessed by scratch assay and the results revealed that cell migration started after 6 h. and wound closure is achieved after a period of 48 h. A relative wound width of 41% is obtained for BSF patch which is less compared to control [32]. Furthermore, the bacterial load in wounds treated with BSF sutures is significantly reduced, as indicated by lower colony-forming units (CFUs). Further, Tissue regeneration and effective wound healing involves faster wound contraction which expedites wound healing [152]. In addition, BSF added wound dressing retained required moisture which promoted faster wound closure and healing [152, 164]. In summary, BSF promotes tissue regeneration by inhibiting bacterial action, disrupting microbial biofilm formation by antioxidant activity and stimulation of VEGF and FGF. These investigations establish BSF as a versatile material for wound care and infection prevention.

5.6 Need for phytochemical analysis

Phytochemicals constitute the primary and secondary metabolites obtained from plant sources. Phytochemical analysis is carried out to understand the bioactive constituents of a nature-derived sample responsible for its medicinal value while its antimicrobial, antioxidant, biocompatibility functions are confirmed by various assays. Phytochemicals present in pseudo stem extracts differ from that found in fiber. Being a natural fiber, BSF has cellulose bound phenolic compounds and lignin-associated antioxidants which are responsible for its bio-activity. Cellulose bound phenolic compounds are mainly phenolic acids and flavonoids. Literature results depict that insoluble bound-phenolic compounds (IBPs) are more than free phenolic compounds [165]. As these compounds are bound to the cell walls, they are rich in plant stem and leaves (about 70%) as compared to the food matrix [166]. In addition, researches depict that phenolic compound-rich foods are also rich sources of dietary fibers [167]. Alkali, acid and enzymatic hydrolysis are used for quantifying the IBPs. In an experiment, to study IBPs in litchi pulp, acid hydrolysis resulted in 2.6 and 1.9 times more oxygen radical absorbance capacity (ORAC) and cellular antioxidant activity (CAA) compared to free phenolic extracts [168].

Phytochemical analysis of pseudo stem extract quantifies the amount of free soluble phenolic compounds in the pseudo stem. Whereas, to understand the phytochemicals in fiber, IBPs profiling of the pseudo stem should be carried out. IBPs profiling of pseudo stem which quantifies the biological activity of banana stem fiber, remains an open research question to the best of our knowledge and thus requires research intervention.

5.7 Potential wound healing structures possible from BSF

BSF-based composites show good antioxidant and antimicrobial properties which support their usability for biomedical applications. The experimental findings, such as its ability to inhibit bacterial growth, accelerate epithelialization, and sustained drug release, are complemented by clinical results that highlight faster healing rates and infection reduction. The use of BSF for composites as construction materials, filter membranes, food packaging films, laminates are more however, research and analysis of banana fiber in biomedical applications is very meagre. Previous researches on use of natural fibers in biomedical applications highlight that there is plenty of room for investigating the properties and characteristics of banana stem fiber for biomedical use, both as woven and non-woven products. Research and development towards conversion of BSF into various wound healing structures like nano fiber mats, membranes, hydrogels, films, patches or scaffolds could result in efficient biomedical products.

6 Fabrication of BSF composites for biomedical applications

Banana stem fiber (BSF) has garnered attention as a promising material for wound healing applications due to its biodegradability, mechanical strength, and biocompatibility. BSF, when used in composite form, demonstrates enhanced properties, making it suitable for medical applications such as wound dressings. Series of steps adapted in the development of BSF based wound healing composites starts with the selection of materials and follows a series of steps as detailed in the below section.

6.1 Selection of materials for composite fabrication

Banana fiber being the primary, fixed materials of choice, it is either obtained in fiber form or extracted following appropriate method and is made available for further processing.

Selection of matrix material—A biopolymer matrix is to be chosen for the proposed bio-composite. Chitosan, being a polysaccharide with excellent film-forming capability, antimicrobial properties, and biodegradability, improved flexibility, tensile strength, and cellular proliferation is a preferred matrix for hybrid patches [131, 169]. Starch, pectin, alginate, and cellulose derivatives are often blended to customize properties for specific biomedical needs. The use of other biopolymer matrices could even enable efficient properties and thus seeks research interventions.

Investigating the need and selection of cross-linking: Natural gums introduced with biopolymers enhances the composites overall elasticity, swelling, adhesion and stability. Recent researches have used chitosan + gaur gum that enabled a strong hydrogen-bonded matrix for BSF reinforcement [32]. Gaur gum, xanthan gum, glycerin are known materials that could act as good cross-linkers.

Drug selection: Experimental results support the use of drugs with wound healing materials for effective wound healing. And thus, selection and use of an appropriate drug enable efficient outcomes. Drugs can be either nature-derived material or formulated chemicals, their adhesion to the base material should be ensured [32, 170].

6.2 Fabrication of BSF-based wound dressing

Preparation of base & matrix, materials: The first step in processing BSF involves preparing the fibers for further use. Chemical treatments, surface modification techniques improve the biological activities of banana stem fiber (BSF), making it more suitable for biomedical applications such as antimicrobial sutures and wound-healing aids. The chosen biopolymer and cross-linkers are converted to a usable matrix form to hold the fiber reinforcement.

Fabrication of composite: Composites are fabricated following any one of the composite manufacturing techniques in order to obtain a uniform composite. Methods such as solvent casting, compression molding, and freeze-drying are used, often employing crosslinking agents like NaOH for stability [61, 67]. BSF composite patches were fabricated following compression molding at 10 tons of pressure and dried at 45 °C [32]. Films can be created through solvent casting, followed by cross-linking with NaOH to further strengthen the composite material. Even nano-fiber mats can be fabricated by adapting appropriate technique.

Drug loading: Herbal extracts or growth factors are incorporated into composites for sustained therapeutic release. Some examples include Rosemary, Aloe vera, lemon myrtle oil and *Vitex negundo* L. Drug loading is the third step in the composite fabrication process [169, 171]. Drug loading can be carried out by repeated absorption and drying cycles [32] or by adapting drug coating techniques. This process ensures controlled drug release over time, which is critical for effective wound care.

6.3 Characterization of banana fiber-based composite materials

Once a drug-loaded BSF-composite is fabricated, its physicochemical properties are characterized to ensure its mechanical strength, stability, reliability and biocompatibility. This can be carried out by various characterization techniques and based on the results, process conditions and material concentrations that result in fabrication of composite with desired properties. Most frequently used material characterization techniques are detailed below:

Scanning electron microscopy (SEM): SEM uses an electron beam and scans the sample surface which enables interaction of the electron beam with the atoms over the sample surface. This interaction produces various signals that are used to retrieve information about surface morphology and composition of the sample. SEM equipped with Energy dispersion X-ray spectroscopy (EDS) enables elemental analysis and chemical characterization of samples. With EDS, the purity of synthesized materials can be found [172]. SEM evaluates surface morphology, and thus changes in surface morphology resulting from processing and treatment can be found using SEM [173].

Universal testing machine (UTM): Tensile properties reveal a materials strength, ductility and elasticity. These properties are found by applying steady pressure and recording the breaking point of the material under study. Various tensile properties include tensile strength, Young's modulus and elongation at break. Tensile properties are assessed using a Universal Testing Machine (UTM) [54]. Fibers are cut into standardized lengths and clamped at both ends before being subjected to uniaxial tension.

X-ray diffraction (XRD): XRD passes X-rays over the samples and measures the diffraction angle and intensities of the diffracted light. XRD analyses the crystalline structure, orientation, phase composition, analyses strain and detect defects in the sample under study, which are crucial factors influencing mechanical and thermal properties. It is used in industries as well as research for identifying unknown materials, characterize and quantify phases in materials [174].

Fourier Transform Infrared Spectroscopy (FTIR): Fourier transform infra-red spectroscopy passes infrared (IR) radiations through the test samples. Some of this radiation is absorbed while some gets transmitted depending on the constituents of the sample under study. The absorbed energy is converted to vibrational or rotation energy by the molecules in the sample. The signal after partial absorption is received at the detector as a spectrum, (either transmittance or absorbance) in the range 4000 to 400 cm^{-1}. By analyzing the intensity and position (wavenumber) of the peaks in the spectra in comparison with known reference spectra, functional groups present in the sample as well as specific compounds in the sample can be identified. FTIR analysis can be used to (i) identify unknown materials, (ii) identify contaminants if any in sample, (iii) monitor or analyze changes resulting from chemical treatments or chemical reactions over a period of time. FTIR analysis is used to characterize materials for research and development, pharmaceuticals, to identify unknown materials/pollutants in forensics/environmental monitoring etc., [175]. In this research, FTIR analysis will be helpful in understanding the functional groups added, removed from the sample after each stage of fabrication. In addition, the reactions happening after each stage could be monitored and the presence of functional groups that induce positive/negative biological activity if any, could be identified.

Thermal and degradation properties: Thermogravimetric Analysis (TGA) is employed to investigate the thermal stability, degradation behavior, and suitability of banana stem fibers for composite applications [54, 67, 118].

6.4 Testing for biological activity

Physico-chemically characterized composites are tested for their biological activity. Various tests were conducted to quantify the biological activity of the developed wound healing material. Microbes for antimicrobial testing are selected primarily based on their clinical relevance. In addition, representative strains from different groups are chosen. Bacterial species are broadly categorized into two groups (i) gram-negative with outer membrane and (ii) gram-positive without outer membrane. Gram-negative bacteria are more resistant to antibiotics than gram positive strain. In order to test a material sample for antibacterial activity, it is normally tested against a species of gram-negative bacteria and gram-positive bacteria. For instance, bacterial species primarily responsible for wound infections are *Staphylococcus aureus*, *Pseudomonas aeruginosa*, and *Streptococcus* species. And thus, for studying wound healing activity, all or any of them is chosen based on availability [176]. Microorganisms for laboratory testing can be obtained from commercial suppliers like Merck, or from National microbial culture collection and gene bank centers. In India, microbes for laboratory use can be obtained from suppliers like Greencraft Labs, Microbial Type Culture Collection and Gene Bank (MTCC, Chandigarh), or Microbial Culture Collection (MCC, Pune). Some of the most frequently used assays are detailed below:

Test for antimicrobial activity—disc diffusion assay: Disc diffusion assay is the most frequently used test to measure antimicrobial action of a sample against microbes. This method involves inoculation of microorganisms on agar plates, followed by placing antimicrobial agent in microbial cultures and measuring the zone of inhibition around the antimicrobial agent [177].

Testing drug release activity: UV–visible spectroscopy is used to identify and quantify photo degradation potential, drug release kinetics of the sample under study by measuring UV light absorbance by the material [178].

Test for cytotoxicity—MTT assay: MTT stands for 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide assay. It is a colorimetric assay that quantifying cell viability percentage resulting from the addition of a wound healing material. This test reveals the toxic effects (indirectly biocompatibility) if any is created by the newly developed material. The cell viability is quantified by measuring absorbance at 560 nm using an ELISA reader [179].

Test for antioxidant activity—DPPH assay: DPPH (2,2-diphenyl-1-picryl-hydrazyl-hydrate) free radical scavenging assay is used for quantifying the antioxidant activity of a material. A spectrophotometer measures the absorption band at 517 nm in order to quantify the degree of discoloration created by the sample [180].

α-Glucosidase assay: α-Glucosidase is responsible for breaking down complex carbohydrates into glucose and thus inhibition of α-Glucosidase aids in delaying digestion and reducing blood glucose. α-Glucosidase Assay aids in determining the α-Glucosidase activity of the sample under study by analyzing the colorimetric product (at 405 nm) resulting from the hydrolysis of *p*-nitrophenyl-α-D-glucopyranoside [181]. The steps involved in the fabrication of BSF loaded wound healing patch is given by Fig. 8.

These BSF-based wound dressings hold significant potential for applications in soft tissue repair, particularly for chronic wounds and burns, as well as in surgical environments for sustained drug delivery. In conclusion, researches emphasizing wound healing materials from BSF and bioactive compounds could open-up new avenues in biomedical field.

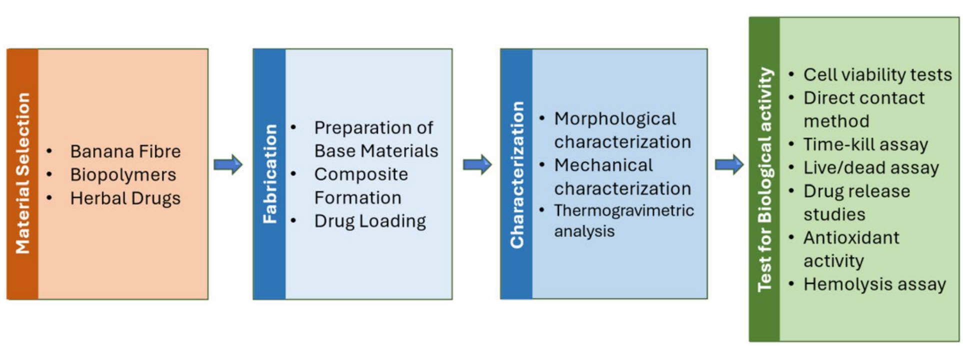


Fig. 8 Steps involved in the fabrication of BSF based wound healing patch

7 Challenges and limitations

7.1 Production scalability and processing issues of (BSF)

Banana stem fiber (BSF) is a promising sustainable biomaterial for applications in textiles, biomedicine, and composites. However, scaling up production and addressing processing challenges remain significant hurdles. These issues are tied to raw material availability, extraction methodologies, and post-processing limitations.

Raw material availability and harvesting: India, the world's largest banana producer, generates 30.5 million tons of bananas annually [182] approximately 26.0% share in the total production between 2015–17, leaving a considerable amount of pseudo-stem waste that can be utilized for BSF production. However, this raw material availability is affected by the seasonal nature of banana cultivation, leading to supply irregularities.

Fiber extraction methods: Large-scale extraction faces numerous challenges. Manual extraction, though widely used, is labor-intensive and results in inconsistent fiber quality due to variations in technique. Mechanical extraction methods, which employ specialized machinery [70], offer improved efficiency but require high initial investment, often prohibitive for small-scale producers. Alkali treatment with 2% NaOH at 95 °C is commonly employed for refining BSF by removing lignin and hemicellulose, enhancing mechanical properties. However, the process generates chemical effluents, raising environmental concerns.

Processing challenges: Advanced applications of BSF, such as in biomedical sutures and drug delivery, require precise surface modifications. For instance, BSF coated with aloe vera (AV) and gum acacia (GA) hydrogels impregnated with chloramphenicol demonstrated 87% sustained drug release over 144 h [61]. However, such processes demand advanced facilities and careful quality control. High moisture content in freshly extracted fibers also poses preservation challenges, as it promotes microbial growth. While low-energy drying methods are cost-effective, scaling these methods for industrial use remains complex [105].

Quality control and consistency: BSF's mechanical properties, such as tensile strength, vary significantly based on processing methods [107]. Variations in chemical composition, particularly cellulose and lignin content, further complicate achieving consistent product quality.

Scaling solutions: Mechanization and automation are critical to improving extraction efficiency and reducing quality inconsistencies [183]. Thus, scaling solutions is the fifth challenge. Investing in automated machinery for BSF extraction could streamline production. Collaboration with agro-industries, such as integrating extraction facilities with banana plantations, can ensure steady raw material supply while lowering transportation costs.

Sustainability and environmental impact: Inherent to every chemical treatment, maintaining sustainability and reducing environmental impact caused by effluent management from alkali treatments [114, 184] is the sixth challenge. Developing biodegradable by-products and optimizing chemical usage can mitigate environmental risks. Initiatives to minimize waste and recycle effluents can enhance BSF's eco-friendliness. A summary of the list of all challenges that hurdle the research and development of BSF-based biomaterial development is depicted in Table 6.

In conclusion, while BSF holds immense potential as a sustainable material, addressing challenges in scalability, environmental impact, and processing efficiency are vital. Technological innovations, sustainable practices, and government or industry support will be essential to unlock its full potential.

Table 6 Challenges faced in advancing BSF based biomaterial usage

Ref. No	Challenges and limitations	
[182]	Scalability and processing issues	• Supply irregularities • Seasonal nature of banana cultivation
[70]	Fiber extraction methods	• Labor—intensive, manual extraction methods, • Inconsistent fiber quality
[61, 105]	Processing challenges	• Precise surface modifications • Processes demand advanced facilities and careful quality control
[107]	Quality Control and Consistency	• Properties change with processing methods
[114, 184]	Sustainability and Environmental Impact	• Effluent management from chemical treatments

7.2 Biocompatibility and safety concerns of banana stem fiber

Banana stem fiber (BSF) is increasingly recognized for its potential in biomedical applications like suturing, wound dressings, and drug delivery systems, owing to its biocompatibility and safety. Hemolysis tests on BSF-coated sutures revealed a hemolysis rate of just 0.78%, well below the ISO standard of 5%, indicating its suitability for blood-contacting use [19]. Scanning Electron Microscopy (SEM) confirmed that BSF does not cause erythrocyte damage. Cytocompatibility, assessed via MTT assay, showed over 84% cell viability, meeting ISO standards, with BSF promoting fibroblast proliferation due to active phytochemicals like tannins and flavonoids. BSF-coated sutures and wound dressings exhibited broad-spectrum antimicrobial activity, with inhibition zones of 29 mm against *Staphylococcus aureus* and 21 mm against *Pseudomonas aeruginosa*. In vivo studies on Wistar albino rats demonstrated accelerated wound healing, reduced inflammation, and improved collagen deposition [61, 67, 162]. Toxicological assessments, following OECD guidelines, confirmed that BSF is non-toxic, with no mutagenic or carcinogenic effects. Despite the positive results achieved with BSF composites in wound healing, safety concerns with the use of BSF based biomaterials include the potential for rare allergic reactions and microbial contamination of untreated fibers. This makes ensuring biocompatibility and safety concerns to emerge as seventh hurdle. To address this, sterilization methods and antimicrobial coatings are recommended. Overall, BSF shows great promise as a safe, sustainable material for medical applications.

7.3 Regulatory and market challenges

The adoption of banana stem fiber (BSF) for industrial and biomedical applications faces several critical regulatory and market challenges. One significant regulatory obstacle is the lack of standardization regarding BSF's properties, including tensile strength and cellulose content. Studies indicate that BSF tensile strength ranges between 400 to 650 MPa, with cellulose content varying from 60 to 70%, influenced by farming and processing methods [185]. While initial biocompatibility studies show promising results such as cell viability rates around 84% and a hemolysis rate of 0.78%. Obtaining FDA or EMA approval for medical applications necessitates extensive and costly validations [186].

The processing of BSF involves the use of chemicals, generating effluents that require treatment. For small-scale operations, treatment costs range between $30,000 and $50,000, contributing to high production costs. The raw banana pseudo-stems are priced at $0.02–$0.04 USD/kg, but processing increases the cost to $0.20–$0.50 USD/kg [187]. Synthetic fibers like polyester, with greater consistency and tensile strength around 2000 MPa, provide stiff competition [2]. BSF also contends with natural fibers like flax, achieving tensile strengths up to 1035 MPa [188].

Market challenges include limited consumer awareness and a small market share, currently less than 15% for BSF. Supply chain inefficiencies, including the seasonal availability of raw materials and decentralized processing, further inflate costs. To address these challenges, establishing standardized BSF properties, investing in cost-efficient processing technologies, and improving marketing strategies are essential steps. These efforts could bolster BSF's acceptance in eco-textile applications, biodegradable composites, and medical devices [189]. Focusing on these strategies enhances the potential for BSF to secure a substantial foothold in both industrial and biomedical markets [190].

8 Future perspectives

8.1 Potential advancements in banana stem fiber based biomaterials

Banana fiber-based materials hold immense promise for biomedical applications due to their biocompatibility, mechanical strength, and sustainability. Future advancements are expected to focus on innovative processing, hybridization with biomolecules, and scalability for widespread adoption. For instance, cellulose acetate nano-fibers (CANF) derived from banana pseudo-stems have demonstrated potential in drug delivery systems due to their optimized fiber diameters (< 200 nm) that mimic extracellular matrices and improve drug loading efficiency [191]. Additionally, nanotechnology integration, such as functional coatings with silver or titanium dioxide nanoparticles, chitosan (CS)/aloin nanofiber membranes (NFMs) for wound dressing can enhance antimicrobial properties and enable self-sterilization capabilities [192].

Hybrid materials incorporating banana fiber are being developed to improve cell adhesion in tissue scaffolds. Coupling with RGD peptides has shown enhanced biofunctionalization and cell-interaction properties, which are crucial for tissue engineering applications [191]. Smart biomaterials responsive to environmental triggers, such as pH or temperature, have the potential to provide targeted drug release and adaptive scaffolding, particularly when combined with polymers like chitosan or polycaprolactone for added strength, flexibility, and biodegradability [193].

Emerging applications include 3D bioprinting for creating complex tissue structures and hydroxyapatite-reinforced banana fiber composites for bone regeneration. Such composites align with sustainability goals through environmentally friendly manufacturing methods, including enzymatic retting, to reduce environmental impact [194]. Multi-layered wound dressings, advanced drug delivery systems, and medical textiles stand out as potential innovations in patient care. The eco-friendly nature and global accessibility of banana fiber position it as a transformative material in biomedical applications.

8.2 Integration of banana stem fiber-based materials with nanotechnology and bioactive compounds

The fusion of banana fiber-based materials with nanotechnology and bioactive compounds has revolutionized biomedical applications, particularly in wound healing, tissue engineering, and drug delivery. For example, banana fiber-derived cellulose acetate nano-fibers, electrospun into membranes of 200–300 nm, mimic the extracellular matrix and enhance cell adhesion and collagen synthesis. Incorporating nanoparticles such as silver (AgNPs), zinc oxide (ZnO) [195], and carbon-based materials further enhances antimicrobial activity, oxidative stress resistance, and conductivity, crucial for neural and cardiac tissue applications [196].

Bioactive materials also augment these systems. For instance, herbal extracts like nirgundi and curcumin contribute antimicrobial and anti-inflammatory benefits, while growth factors like VEGF promote angiogenesis critical for tissue repair [32, 196]. Additionally, banana fiber composites enriched with RGD peptides and collagen improve cell adhesion and mechanical strength, effectively mimicking natural tissue environments [197]. These innovations have enabled multifunctional wound dressings, osteoconductive scaffolds for bone regeneration, and responsive drug delivery systems. Smart nanomaterials, such as pH-responsive fibers, ensure targeted therapeutic release, and antimicrobial agents like CHX and antibiotics effectively combat resistant bacteria [198]. The integration of the approaches positions banana fiber as a transformative material in sustainable and advanced healthcare solutions, emphasizing its utility in next-generation biomedical applications [198].

8.3 Applications beyond antimicrobial and wound healing (e.g., drug delivery, tissue engineering)

Banana fiber-based biomaterials are gaining recognition for their diverse applications in advanced biomedical fields, including drug delivery, tissue engineering, and diagnostic technologies, owing to their biocompatibility, mechanical strength, and adaptability. In drug delivery, banana fiber composites offer controlled, localized delivery with tunable release rates. For instance, cellulose acetate nanofibers derived from banana pseudo-stems have demonstrated significant drug release capabilities, making them suitable for chronic wound therapies [67, 199]. Incorporating pH-sensitive composites further enables tailored drug release in complex wound environments [200].

In tissue engineering, banana fiber scaffolds have proven effective for bone regeneration, with tensile strengths exceeding 15 MPa, suitable for load-bearing applications. Combining these scaffolds with carbon nanotubes enhances their electrical conductivity by 2.5 times, benefiting neural and cardiac tissue engineering. Furthermore, hydrogels composed of banana fiber blended with collagen or chitosan provide supportive frameworks for skin and cartilage regeneration [201]. The application of banana fiber extends to surgical sutures, hemostatic dressings, and biodegradable implants. With tensile strengths of up to 150 MPa and an 8–12-week biodegradation period, banana fiber-based biomaterials align well with trauma care needs [202]. Modified biosensor platforms utilizing banana fiber derivatives can detect biomarkers with high sensitivity, enhancing diagnostic capabilities [203].

Banana fiber supports eco-friendly practices, reducing hospital waste by up to 30% through biodegradable composites and water filtration systems capable of removing 80% of contaminants. Emerging innovations like 3D bioprinting and stimuli-responsive systems further strengthen its position in sustainable and advanced healthcare solutions [204]. To maximize BSF potential in future, several strategies are recommended for exploration which includes,

- Conducting large-scale clinical trials to validate the efficacy and safety of banana fiber-based biomaterials.
- Developing cost-efficient extraction and processing techniques for scalability.
- Creating multifunctional platforms that combine antimicrobial, regenerative, and diagnostic features.

- Promoting accessibility in low-income regions, leveraging the widespread availability of banana pseudo-stem as raw material.
- Applications beyond antimicrobial and wound healing (e.g., drug delivery, tissue engineering)

9 Conclusion

The exploration of banana stem fiber (BSF) in biomedical applications reveals its significant potential as a sustainable and effective material for various medical uses. Natural fibers, particularly those derived from plants like banana stems, are gaining traction in the biomedical field due to their unique properties such as biodegradability, biocompatibility, and versatility. BSF stands out due to its remarkable antimicrobial activity and its ability to promote wound healing, making it a promising candidate for wound care applications.

The chemical composition, structural integrity, and mechanical properties of BSF are ideal for enhancing the durability and functionality of biomedical materials. When properly extracted and treated, BSF exhibits enhanced antimicrobial efficacy, providing effective defense against a broad spectrum of pathogens. Its potential for biodegradation and compatibility with biological systems further strengthens its role in applications that require minimal environmental impact.

The process of synthesizing BSF for biomedical purposes involves advanced techniques such as spinning, weaving, and chemical modifications, which enable the creation of fiber-based materials optimized for wound healing. Research has demonstrated that BSF, when incorporated into wound dressings, not only accelerates the healing process but also promotes tissue regeneration, thanks to its ability to retain moisture and facilitate faster granulation tissue formation. Moreover, the incorporation of bioactive compounds like phenols and flavonoids enhances the fiber's antimicrobial properties and contributes to its therapeutic effects. Studies have consistently shown that BSF-based composites outperform many synthetic alternatives, offering sustainable solutions to traditional wound care materials. Furthermore, its ability to form hybrid materials with other natural fibers or bioactive compounds opens doors for even more advanced applications, such as drug delivery systems and tissue engineering. A primary limitation with functionalized textile is their limited washing fastness which directly impacts its durability and thus, researches with respect to the incorporation of natural binders to enhance material durability will increase the usability of natural fibers as functionalized textile. Secondary challenges include scaling production, ensuring biocompatibility, and overcoming regulatory hurdles.

Despite these obstacles, the future of BSF in biomedical applications looks promising, especially with the potential for integration with nanotechnology and other bioactive materials. As research continues and innovations emerge, BSF could evolve into a multifaceted material not only for wound healing but also for broader applications in regenerative medicine, drug delivery, and tissue engineering.

In conclusion, the diverse and sustainable properties of banana stem fiber make it a compelling material in the growing field of biomedical engineering. With continued advancements in research and technology, BSF is poised to play a critical role in the development of eco-friendly and effective biomedical solutions for the future.

Author contributions The authors confirm contribution to the paper as follows: Conceptualization—Umapathi K, Hari Sriram J K, Shibu G—data curation—Sushma C, Manjupriya M, Jerone Samuvel—formal analysis—Gladson Paul E, Yogitha J, Sheik Abdullah M—investigation—Umapathi K, Hari Sriram J K,Shibu G—methodology—Umapathi K, Hari Sriram J K, Shibu G—supervision—Umaapthi K, Jayasheela M —writing—original draft—Umapathi K, Hari Sriram J K, Shibu G, Gladson Paul E—Writing—review and editing—Umapathi K, Hari Sriram J K, Manohar Ramya. All authors reviewed the results and approved the final version of the manuscript.

Funding Open access funding provided by Manipal Academy of Higher Education, Manipal.

Data availability No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

References

1. Han W, Wang L, Li Q, Ma B, He C, Guo X, Nie J, Ma G. A review: current status and emerging developments on natural polymer-based electrospun fibers. Macromol Rapid Commun. 2022;43(21): e2200456. https://doi.org/10.1002/marc.202200456.
2. Tavares TD, Antunes JC, Ferreira F, Felgueiras HP. Biofunctionalization of natural fiber-reinforced biocomposites for biomedical applications. Biomolecules. 2020;10(1):148. https://doi.org/10.3390/biom10010148.
3. Zamora-Mendoza L, Gushque F, Yanez S, Jara N, Álvarez-Barreto JF, Zamora-Ledezma C, Dahoumane SA, Alexis F. Plant fibers as composite reinforcements for biomedical applications. Bioengineering. 2023;10(7):804. https://doi.org/10.3390/bioengineering10070804.
4. Singh B, Singh JP, Kaur A, Singh N. Bioactive compounds in banana and their associated health benefits—a review. Food Chem. 2016;206:1–11. https://doi.org/10.1016/j.foodchem.2016.03.033. (**ISSN 0308-8146**).
5. Ilyas RA, Aisyah HA, Nordin AH, Ngadi N, Zuhri MYM, Asyraf MRM, Sapuan SM, Zainudin ES, Sharma S, Abral H, Asrofi M, Syafri E, Sari NH, Rafidah M, Zakaria SZS, Razman MR, Majid NA, Ramli Z, Azmi A, Bangar SP, Ibrahim R. Natural-fiber-reinforced chitosan, chitosan blends and their nanocomposites for various advanced applications. Polymers (Basel). 2022;14(5):874. https://doi.org/10.3390/polym14050874.
6. Costa CG, Bom LFRP, Martins CR, da Silva CF, de Moraes MA. Chapter 9—(Bio)composites of chitin/chitosan with natural fibers. In: Gopi S, Thomas S, Pius A, editors. Handbook of chitin and chitosan. Elsevier; 2020. p. 273–98. https://doi.org/10.1016/B978-0-12-817968-0.00009-3. (**ISBN 9780128179680**).
7. Teixeira MO, Antunes JC, Felgueiras HP. Recent advances in fiber-hydrogel composites for wound healing and drug delivery systems. Antibiotics (Basel). 2021;10(3):248. https://doi.org/10.3390/antibiotics10030248.
8. Azam F, Ahmad F, Ahmad S, Zafar MS, Ulker Z. Synthesis and characterization of natural fibers reinforced alginate hydrogel fibers loaded with diclofenac sodium for wound dressings. Int J Biol Macromol. 2023;241: 124623. https://doi.org/10.1016/j.ijbiomac.2023.124623. (**ISSN 0141-8130**).
9. Bhardwaj A, Chaudhary S, Juneja S. Potential innovations of three natural fibres in medical applications. Eur J Med Plants. 2024;35(5):23–31. https://doi.org/10.9734/ejmp/2024/v35i51200.
10. Hasan KMF, Horváth PG, Alpár T. Potential natural fiber polymeric nanobiocomposites: a review. Polymers (Basel). 2020;12(5):1072. https://doi.org/10.3390/polym12051072.
11. Purnomo, et al. Potential natural fiber-reinforced composite for biomedical application. IOP Conf Ser Mater Sci Eng. 2019;494: 012018.
12. Thakker AM, Sun D. Ecological application of natural biomaterial on natural fibres. Clean Mater. 2022;3: 100038. https://doi.org/10.1016/j.clema.2021.100038. (**ISSN 2772-3976**).
13. Ghosh J, Rupanty A, Sarmin N. Study on a cationic agent-based salt-free reactive dyeing process for cotton knit fabric and comparison with a traditional dyeing process. Heliyon. 2023;9(9): 19457. https://doi.org/10.1016/j.heliyon.2023.e19457.
14. Ghosh J, Khan F, Noor T, Rupanty NS, Das SC. Union dyeing of cotton-silk blended woven fabric using Tanin bio-mordant and thyme as a colourant. Textile Leath Rev. 2024;7:303–26. https://doi.org/10.31881/TLR.2023.208.
15. Islam S, Ghosh J, Akter N. Comparative study on crease recovery finishing of silk fabric with citric acid and dimethylol dihydroxy ethylene urea (DMDHEU) as finishing agent. Int J Textile Sci. 2020;9(1):1–7. https://doi.org/10.5923/j.textile.20200901.01.
16. Ghosh J, Repon MDR, Pranta AD, Rupanty NS, Khan F, Noor T. Bioactive component integrated textiles: a promising source of medicine and healthcare. J Eng Fibers Fabrics. 2025. https://doi.org/10.1177/15589250241308561.
17. Ghosh J, Rupanty NS, Khan F, et al. Grafting modification for textile functionalization: innovations and applications. Discov Appl Sci. 2025;7:49. https://doi.org/10.1007/s42452-024-06364-5.
18. Troy E, Tilbury MA, Power AM, Wall JG. Nature-based biomaterials and their application in biomedicine. Polymers (Basel). 2021;13(19):3321. https://doi.org/10.3390/polym13193321.
19. Ghosh J, Hasan Z, Chakrabortty A. Development of antimicrobial and wound healing properties on cotton medical bandage by using the extract of eco-friendly herbs. J Inst Eng India Ser E. 2021;102:75–86. https://doi.org/10.1007/s40034-020-00199-6.
20. Ghosh J, Rupanty NS, Das SC. Application of coriander to medical cotton bandage for the development of antimicrobial and wound-healing properties. Textile Leath Rev. 2023;6:434–51. https://doi.org/10.31881/TLR.2023.113.
21. Ghosh J, Repon MR, Anas NH, et al. Development of UV protective and antimicrobial CVC fabric using colloidal zinc oxide solution with carrot and orange peel extract. SPE Polym. 2024;5(4):576–89. https://doi.org/10.1002/pls2.10144.
22. Ghosh J. Development of UV protective finished fabric using herbal synthesized colloidal solution of silver nanoparticles. J Inst Eng India Ser E. 2021;102:359–68. https://doi.org/10.1007/s40034-021-00228-y.
23. Li J, Tian X, Hua T, Jimin Fu, Koo M, Chan W, Poon T. Chitosan natural polymer material for improving antibacterial properties of textiles. ACS Appl Bio Mater. 2021;4(5):4014–38. https://doi.org/10.1021/acsabm.1c00078.
24. Shirvan AR, Shakeri M, Bashari A. 5—Recent advances in application of chitosan and its derivatives in functional finishing of textiles. In: Butola SIBS, editor. The textile institute book series, the impact and prospects of green chemistry for textile technology. Woodhead Publishing; 2019. p. 107–33. https://doi.org/10.1016/B978-0-08-102491-1.00005-8. (**ISBN 9780081024911**).
25. Mahmoud AA, Osman O, Eid K, Al Ashkar E, Okasha A, Atta D, Eid M, Aziz ZA, Fakhry A. FTIR spectroscopy of natural bio-polymers blends. Middle East J Appl Sci. 2014;4(4):816–24 (**ISSN: 2077-4613**).

26. Arik B, Seventekin N. Evaluation of antibacterial and structural properties of cotton fabric coated by chitosan/titania and chitosan/silica hybrid sol-gel coatings. Tekstil ve Konfeksiyon. 2011;21:107–15.
27. Freitas AS, Oliveira R, Ribeiro A, Almeida-Aguiar C. Biofunctional textiles: antioxidant and antibacterial finishings of cotton with propolis and honey. Int J Mol Sci. 2024;25(15):8034. https://doi.org/10.3390/ijms25158034.
28. Ghayempour S, Montazer M. Tragacanth nanocapsules containing Chamomile extract prepared through sono-assisted W/O/W microemulsion and UV cured on cotton fabric. Carbohyd Polym. 2017;170:234–40. https://doi.org/10.1016/j.carbpol.2017.04.088. (**ISSN 0144-8617**).
29. Mihailiasa M, Caldera F, Li J, Peila R, Ferri A, Trotta F. Preparation of functionalized cotton fabrics by means of melatonin loaded β-cyclodextrin nanosponges. Carbohyd Polym. 2016;142:24–30. https://doi.org/10.1016/j.carbpol.2016.01.024. (**ISSN 0144-8617**).
30. Massella D, Argenziano M, Ferri A, Guan J, Giraud S, Cavalli R, Barresi AA, Salaün F. Bio-functional textiles: combining pharmaceutical nanocarriers with fibrous materials for innovative dermatological therapies. Pharmaceutics. 2019;11(8):403. https://doi.org/10.3390/pharmaceutics11080403.
31. Lee S, Park S. Optimizing washing conditions for smart fabrics: a comprehensive study. RSC Adv. 2024;14:40098–116. https://doi.org/10.1039/D4RA07365G.
32. Barman M, Rahman S, Joshi N, Sarma N, Bharadwaj P, Thakur D, Devi R, Chowdhury D, Hurren C, Rajkhowa R. Banana fibre-chitosan-guar gum composite as an alternative wound healing material. Int J Biol Macromol. 2024;259: 129653. https://doi.org/10.1016/j.ijbiomac.2024.129653. (**ISSN 0141-8130**).
33. Mostafa HS. Banana plant as a source of valuable antimicrobial compounds and its current applications in the food sector. J Food Sci. 2021;86:3778–97. https://doi.org/10.1111/1750-3841.15854.
34. https://www.fao.org/markets-and-trade/commodities/bananas/en/
35. https://nhb.gov.in/report_files/banana/BANANA.htm
36. Britannica T. Editors of Encyclopaedia. Banana. Encyclopedia Britannica; 2024. https://www.britannica.com/plant/banana-plant.
37. Britannica T. Editors of Encyclopaedia. Abaca. Encyclopedia Britannica; 2014. https://www.britannica.com/plant/abaca
38. Subagyo A, Chafidz A. Banana pseudo-stem fiber: preparation, characteristics, and applications. IntechOpen; 2020. https://doi.org/10.5772/intechopen.82204.
39. Jyothirmayi N, Rao NM. Banana medicinal uses. J Med Sci Technol. 2015;4(2):152–60.
40. Kumar KPS, Bhowmik D, Duraivel S, Manivannan U. Traditional and medicinal uses of banana. J Pharmacogn Phytochem. 2012;1:51–63.
41. Afzal MF, Khalid W, Akram S, Khalid MA, Zubair M, Kauser S, et al. Bioactive profile and functional food applications of banana in food sectors and health: a review. Int J Food Prop. 2022;25(1):2286–300. https://doi.org/10.1080/10942912.2022.2130940.
42. Zaini HM, Roslan J, Saallah S, Munsu E, Sulaiman NS, Pindi W. Banana peels as a bioactive ingredient and its potential application in the food industry. J Funct Foods. 2022;92: 105054. https://doi.org/10.1016/j.jff.2022.105054. (**ISSN 1756-466, ISSN 0141-8130**).
43. Balda S, Sharma A, Capalash N, Sharma P. Banana fiber: a natural and sustainable bioresource for eco-friendly applications. Clean Technol Environ Policy. 2021. https://doi.org/10.1007/s10098-021-02041-y.
44. Singh S, Naik N, Sooriyaperakasam N, Iyer T, Agarwal C, Tirupathi J, Al Abdali M. A comprehensive review of banana fiber-reinforced composites: properties, processing and applications. J Comput Mech Manag. 2022. https://doi.org/10.57159/gadl.jcmm.1.2.23011.
45. Dejene BK. False banana (Enset Ventricosum) fibers: an emerging natural fiber with distinct properties, promising potentials, challenges and future prospects–a critical review. J Nat Fibers. 2024. https://doi.org/10.1080/15440478.2024.2311303.
46. Rahman M, Nipa ST, Rima SZ, et al. Pseudo-stem banana fiber as a potential low-cost adsorbent to remove methylene blue from synthetic wastewater. Appl Water Sci. 2022;12:242. https://doi.org/10.1007/s13201-022-01769-2.
47. Begum H, Haque A, Islam M, Hasan M, Ahmed S, Razzak M, Khan R. Analysis of the adsorption of toxic chromium (VI) by untreated and chitosan treated banana and areca fiber. J Textile Sci Technol. 2020;6:81–106. https://doi.org/10.4236/jtst.2020.62007.
48. Gore MA, Akolekar D. Evaluation of banana leaf dressing for partial thickness burn wounds. Burns. 2003;29(5):487–92. https://doi.org/10.1016/s0305-4179(03)00050-0.
49. Mushtaq B, Nawab Y, Ahmad S, Ahmad F. An eco-friendly enzymatic treatment to prepare spinnable banana fibers as an alternative to cotton for textile applications. Int J Biol Macromol. 2024;278: 134630. https://doi.org/10.1016/j.ijbiomac.2024.134630. (**ISSN 0141-8130**).
50. Elfaleh I, Abbassi F, Habibi M, Ahmad F, Guedri M, Nasri M, Garnier C. A comprehensive review of natural fibers and their composites: an eco-friendly alternative to conventional materials. Results Eng. 2023;19: 101271. https://doi.org/10.1016/j.rineng.2023.101271. (**ISSN 2590-1230**).
51. Kumar V, Chakraborty P, Janghu P, Umesh M, Sarojini S, Pasrija R, Kaur K, Lakkaboyana SK, Sugumar V, Nandhagopal M, Sivalingam AM. Potential of banana based cellulose materials for advanced applications: a review on properties and technical challenges. Carbohydr Polym Technol Appl. 2023;6: 100366. https://doi.org/10.1016/j.carpta.2023.100366. (**ISSN 2666-8939**).
52. Kabir MM, Wang H, Lau KT, Cardona F. Chemical treatments on plant-based natural fibre reinforced polymer composites: an overview. Compos B Eng. 2012;43(7):2883–92. https://doi.org/10.1016/j.compositesb.2012.04.053. (**ISSN 1359-8368**).
53. Hasan R, Aktar N, Kabir SMT, Honi U, Halim A, Islam R, Sarker MDH, Haque MS, Alam MM, Islam MS. Pectinolytic bacterial consortia reduce jute retting period and improve fibre quality. Sci Rep. 2020;10(1):5174. https://doi.org/10.1038/s41598-020-61898-z.
54. Xu S, Xiong C, Tan W, Zhang Y. Microstructural, thermal, and tensile characterization of banana pseudo-stem fibers obtained with mechanical, chemical, and enzyme extraction. BioRes. 2015;10(2):3724–35.
55. Twebaze C, Zhang M, Zhuang X, Kimani M, Zheng G, Wang Z. Banana Fiber degumming by alkali treatment and ultrasonic methods. J Nat Fibers. 2022. https://doi.org/10.1080/15440478.2022.2079581.
56. Zhang M, Liu Q, Twebaze CB, Zhuang X, Kimani M, Zheng G, Wang Z, Zhao J, Zhu R, Wang R. The effect of activated water degumming technique on alkali-pretreated banana fiber. BioResources. 2022;17(4):6775–88.
57. Gomes CV, Araújo JC, Chaves DM, Fangueiro R, Ferreira DP. Improving textile circular economy through banana fibers from the leaves central rib: effect of different extraction methods. Food Bioprod Process. 2024;146:195–204. https://doi.org/10.1016/j.fbp.2024.06.002. (**ISSN 0960-3085**).
58. Adamu BF. Extraction of Ethiopian Kusha fiber from Ethiopian Kusha Plant by different methods and characterization of its morphological and mechanical properties. Results Mater. 2021. https://doi.org/10.1016/j.rinma.2021.100238.

59. Motaleb KZMA, Mizan RA, Milaˇ sius R. Development and characterization of eco-sustainable banana fiber nonwoven material: surface treatment, water absorbency and mechanical properties (Sep). Cellulose. 2020;27(14):7889–900. https://doi.org/10.1007/s10570-020-03343-y.
60. Gupta US, Dhamarikar M, Dharkar A, Chaturvedi S, Tiwari S, Namdeo R. Surface modification of banana fiber: a review. Mater Today Proc. 2021;43(Part 2):904–15. https://doi.org/10.1016/j.matpr.2020.07.217.
61. Kalita H, Hazarika A, Kandimalla R, Kalita S, Devi R. Development of banana (*Musa balbisiana*) pseudo stem fiber as a surgical bio-tool to avert post-operative wound infections. RSC Adv. 2018;8(64):36791–801. https://doi.org/10.1039/C8RA04470H.
62. Alonso E, Pothan LA, Ferreira A, Cordeiro N. Surface modification of banana fibers using organosilanes: an IGC insight. Cellulose. 2019;26(6):3643–54. https://doi.org/10.1007/s10570-019-02329-9.
63. Arifuzzaman Khan GM, Alam Shams MS, Kabir MR, Gafur MA, Terano M, Alam MS. Influence of chemical treatment on the properties of banana stem fiber and banana stem fiber/coir hybrid fiber reinforced maleic anhydride grafted polypropylene/low-density polyethylene composites. J Appl Polym Sci. 2013;128:1020–9. https://doi.org/10.1002/app.38197.
64. Abraham E, Deepa B, Pothan LA, Jacob M, Thomas S, Cvelbar U, Anandjiwala R. Extraction of nanocellulose fibrils from lignocellulosic fibres: a novel approach. Carbohyd Polym. 2011;86(4):1468–75. https://doi.org/10.1016/j.carbpol.2011.06.034. (**ISSN 0144-8617**).
65. Zinge C, Kandasubramanian B. Nanocellulose based biodegradable polymers. Eur Polymer J. 2020;133: 109758. https://doi.org/10.1016/j.eurpolymj.2020.109758. (**ISSN 0014-3057**).
66. Patel BH, Panchal DP, Chaudhari SB. Per-acetic acid effect on separation of banana fiber and their dyeing with natural dyes. Discov Mater. 2024;4:24. https://doi.org/10.1007/s43939-024-00086-6.
67. Shrestha P, Sadiq MB, Anal AK. Development of antibacterial biocomposites reinforced with cellulose nanocrystals derived from banana pseudostem. Carbohydr Polym Technol Appl. 2021;2: 100112. https://doi.org/10.1016/j.carpta.2021.100112. (**ISSN 2666-8939**).
68. Sachcha IH, Paddar K, Minar MM, Rahman L, Hasan SMK, Akhtaruzzaman M, Billah MT, Yasmin S. Development of eco-friendly biofilms by utilizing microcrystalline cellulose extract from banana pseudo-stem. Heliyon. 2024;10(7): e29070. https://doi.org/10.1016/j.heliyon.2024.e29070. (**ISSN 2405-8440**).
69. Macaspag CM, Caya JE, Leaño JL Jr. Biocompatible and antimicrobial cellulose acetate nanofiber membrane from banana (*Musa acuminata* X Balbisiana) pseudostem fibers for wound healing and tissue engineering.|EBSCOhost. https://openurl.ebsco.com/contentitem/10.35812%2Fcellulosechemtechnol.2023.57.70?sid=ebsco:plink:crawler&id=ebsco:10.35812%2Fcellulosechemtechnol.2023.57.70. Accessed 2 Dec 2024.
70. Soraisham LD, Gogoi N, Mishra L, Basu G. Extraction and evaluation of properties of indian banana fibre (*Musa domestica* Var. Balbisiana, BB Group) and its processing with ramie. J Nat Fibers. 2022. https://doi.org/10.1080/15440478.2021.1897728.
71. Wang J, Wang D, Mao Q, Chen J. Fabric insert injection molding for the preparation of ultra-high molecular weight polyethylene/high-density polyethylene two-component self-reinforced composites. Polymers. 2022;14(20): Art. No. 20. https://doi.org/10.3390/polym14204384.
72. http://www.ae.iitkgp.ac.in/ebooks/chapter1.html.
73. Khalid MY, Al Rashid A, Arif ZU, Ahmed W, Arshad H, Zaidi AA. Natural fiber reinforced composites: sustainable materials for emerging applications. Results Eng. 2021;11: 100263. https://doi.org/10.1016/j.rineng.2021.100263. (**ISSN 2590-1230**).
74. Narayanan V, Elayaperumal A. Banana fiber reinforced polymer composites—a review. J Reinf Plast Compos. 2010;29:2387–96. https://doi.org/10.1177/0731684409360578.
75. Kusuma SSW, et al. Manufacturing of natural fiber-reinforced recycled polymer–a systematic literature review. J Phys Conf Ser. 2021. https://doi.org/10.1088/1742-6596/1808/1/012005.
76. Raji M, Abdellaoui H, Essabir H, Kakou C-A, Bouhfid R, Qaiss AEK. Prediction of the cyclic durability of woven-hybrid composites. In: Durability and life prediction in biocomposites, fibre-reinforced composites and hybrid composites. Elsevier; 2019. p. 27–62. https://doi.org/10.1016/B978-0-08-102290-0.00003-9.
77. Sathish T, Palani K, Natrayan L, Merneedi A, De Poures MV, Singaravelu DK. Synthesis and characterization of polypropylene/ramie fiber with hemp fiber and coir fiber natural biopolymer composite for biomedical application. Int J Polym Sci. 2021;2021:1–8. https://doi.org/10.1155/2021/2462873.
78. Elkington M, Bloom D, Ward C, Chatzimichali A, Potter K. Hand layup: understanding the manual process. Adv Manuf Polym Compos Sci. 2015;1:138–51.
79. Mahmud S, Hasan KMF, Jahid MA, Mohiuddin K, Zhang R, Zhu J. Comprehensive review on plant fiber-reinforced polymeric biocomposites. J Mater Sci. 2021;56:7231–64.
80. Hofmann M, Machado M, Shahid A, Dourado F, Garrido M, Bordado JC, Correia JR. Pultruded carbon fibre reinforced polymer strips produced with a novel bio-based thermoset polyester for structural strengthening. Compos Sci Technol. 2023;234: 109936. https://doi.org/10.1016/j.compscitech.2023.109936. (**ISSN 0266-3538**).
81. Vijaya Kumar N, Banapurmath NR, Ganachari SV, Sajjan AM, Patil AY. Feasibility studies on bio composites using PLA and Epoxy for structural applications. IOP Conf Ser Mater Sci Eng. 2021;1070: 012048.
82. Vasu VK, Anand PB, Nagaraja S, Ammarullah MI. Mechanical and fracture property optimization of graphene-SiO2-reinforced epoxy-PLA nanocomposites for biomedical applications. Results Chem. 2025;13: 102040. https://doi.org/10.1016/j.rechem.2025.102040. (**ISSN 2211-7156**).
83. Hamad QA, Oleiwi JK, Abdulrahman SA. Tensile properties of laminated composite prosthetic socket reinforced by different fibers. Mater Today Proc. 2023;80:2353–9. https://doi.org/10.1016/j.matpr.2021.06.348. (**ISSN 2214-7853**).
84. Campbell AI, Sexton S, Schaschke CJ, Kinsman H, McLaughlin B, Boyle M. Prosthetic limb sockets from plant-based composite materials. Prosthet Orthot Int. 2012;36(2):181–9. https://doi.org/10.1177/0309364611434568. (**Epub 2012 Feb 3**).
85. Awad S, Siakeng R, Khalaf EM, Mahmoud MH, Fouad H, Jawaid M, Sain M. Evaluation of characterisation efficiency of natural fibre-reinforced polylactic acid biocomposites for 3D printing applications. Sustain Mater Technol. 2023;36: e00620. https://doi.org/10.1016/j.susmat.2023.e00620. (**ISSN 2214-9937**).
86. Macha IJ, Muna MM, Magere JL. In vitro study and characterization of cotton fabric PLA composite as a slow antibiotic delivery device for biomedical applications. J Drug Deliv Sci Technol. 2018;43:172–7.
87. Kramar A, González-Benito FJ. Cellulose-based nanofibers processing techniques and methods based on bottom-up approach—a review. Polymers. 2022;14(2):286. https://doi.org/10.3390/polym14020286.

88. Surendran G, Sherje AP. Cellulose nanofibers and composites: an insight into basics and biomedical applications. J Drug Deliv Sci Technol. 2022;75: 103601. https://doi.org/10.1016/j.jddst.2022.103601. (**ISSN 1773-2247**).
89. Cherian BM, Pothan LA, Nguyen-Chung T, Mennig G, Kottaisamy M, Thomas S. A novel method for the synthesis of cellulose nanofibril whiskers from banana fibers and characterization. J Agric Food Chem. 2008;56(14):5617–27. https://doi.org/10.1021/jf8003674.
90. Kumar R, Kumari S, Surah SS, Rai B, Kumar R, Sirohi S, Kumar G. A simple approach for the isolation of cellulose nanofibers from banana fibers. Mater Res Expr. 2019;6: 105601. https://doi.org/10.1088/2053-1591/ab3511.
91. Merais MS, Khairuddin N, Salehudin MH, Mobin Siddique MB, Lepun P, Chuong WS. Preparation and characterization of cellulose nanofibers from banana pseudostem by acid hydrolysis: physico-chemical and thermal properties. Membranes. 2022;12(5):451. https://doi.org/10.3390/membranes12050451.
92. Meng F, Wang G, Du X, Wang Z, Xu S, Zhang Y. Extraction and characterization of cellulose nanofibers and nanocrystals from liquefied banana pseudo-stem residue. Compos Part B Eng. 2019;160:341–7. https://doi.org/10.1016/j.compositesb.2018.08.048. (**ISSN 1359-8368, ISSN 1773-2247**).
93. Nascimento REA, Carvalheira M, Crespo JG, Neves LA. Extraction and characterization of cellulose obtained from banana plant pseudostem. Clean Technologies. 2023;5(3):1028–43. https://doi.org/10.3390/cleantechnol5030052.
94. Anusiya G, Jaiganesh R. A review on fabrication methods of nanofibers and a special focus on application of cellulose nanofibers. Carbohydr Polym Technol Appl. 2022;4: 100262. https://doi.org/10.1016/j.carpta.2022.100262. (**ISSN 2666-8939**).
95. Sadat-Shojai M, Asadnia M, Zarei-fard N, et al. Electrospinning of liquefied banana stem residue in conjugation with hydroxyapatite nanocrystals: towards new scaffolds for bone tissue engineering. Cellulose. 2022;29:4039–56. https://doi.org/10.1007/s10570-022-04542-5.
96. Alghoraibi I, Alomari S. Different methods for nanofiber design and fabrication. In: Barhoum A, Bechelany M, Makhlouf A, editors. Handbook of nanofibers. Cham: Springer; 2019. https://doi.org/10.1007/978-3-319-53655-2_11.
97. Namvar F, Jawaid M, Md Tahir P, Mohamad R, Azizi S, Khodavandi A, Rahman HS, Nayeri MD. Potential use of plant fibres and their composites for biomedical applications. BioRes. 2014;9(3):5688–706.
98. Karimah A, Ridho MR, Munawar SS, Adi DS, Ismadi, Damayanti R, Subiyanto B, Fatriasari W, Fudholi A. A review on natural fibers for development of eco-friendly bio-composite: characteristics, and utilizations. J Mater Res Technol. 2021;13:2442–58. https://doi.org/10.1016/j.jmrt.2021.06.014. (**ISSN 2238-7854**).
99. Sujita S, Sari NH. The greatness of the characteristics fiber pseudo stem outer layer of Musa acuminata origin lombok Indonesia as reinforcing polyester composite. East Eur J Enterp Technol. 2022;4(12):38–43. https://doi.org/10.15587/1729-4061.2022.261921.
100. Kun L, Fu S, Huaiyu Z, Yao Z, Lucia L. Analysis of the chemical composition and morphological structure of banana psudo-stem. BioResources. 2010. https://doi.org/10.15376/biores.5.2.576-585.
101. Oyewo T, et al. Physico-chemical, thermal and micro-structural characterization of four common banana pseudo-stem fiber cultivars in Nigeria. J Nat Fibers. 2023;20(1):2167031. https://doi.org/10.1080/15440478.2023.2167031.
102. Badanayak P, Jose S, Bose G. Banana pseudostem fiber: a critical review on fiber extraction, characterization, and surface modification. J Nat Fibers. 2023. https://doi.org/10.1080/15440478.2023.2168821.
103. Chengoué M, Tchotang T, Fokam CB, Kenmeugne B. 'Influence of extractions techniques on the physico-mechanical properties of banana pseudo-stem fibers. J Mater Environ Sci. 2020;11(7):1121–8.
104. Ramesh M, Palanikumar K, Hemachandra Reddy K. Plant fibre based bio-composites: sustainable and renewable green materials. Renew Sustain Energy Rev. 2017;79:558–84. https://doi.org/10.1016/j.rser.2017.05.094. (**ISSN 1364-0321**).
105. De Oliveira GQ, De Nascimento RA, Costa JF, Santana EB, Costa CML, Ribeiro NFDP. Drying of banana pseudo-stem fibers: evaluation of kinetic models, effective diffusivity, thermodynamic properties, and structural characterization. J Nat Fibers. 2022;19(10):3654–67. https://doi.org/10.1080/15440478.2020.1848717.
106. Nguyen TA, Nguyen TH. Study on mechanical properties of banana fiber-reinforced materials poly (lactic acid) composites. Int J Chem Eng. 2022;2022(1):8485038. https://doi.org/10.1155/2022/8485038.
107. Mumthas CSI, Wickramasinghe GLD, Gunasekera US. Effect of physical, chemical and biological extraction methods on the physical behaviour of banana pseudo-stem fibres: Based on fibres extracted from five common Sri Lankan cultivars. J Eng Fibers Fabr. 2019;14:1558925019865697. https://doi.org/10.1177/1558925019865697.
108. Sharma S, Wadhwa N. Characterization of Banana Fibers Extracted with Pectinase from *Staphylococcus sciuri*. Curr Appl Sci Technol. 2023. https://doi.org/10.55003/cast.2023.05.23.010.
109. Cecci RRR, Passos AA, De Aguiar Neto TC, Silva LA. Banana pseudostem fibers characterization and comparison with reported data on jute and sisal fibers. SN Appl Sci. 2020;2(1):20. https://doi.org/10.1007/s42452-019-1790-8.
110. Ruangnarong C, Khojitmate S, Srivorradatphisan S, Panyathikun N, Chonsakorn S. Evaluation of mechanically extracted banana fibers from pseudostem layers: a sustainable textile raw material. Heliyon. 2024;10(21): e39880. https://doi.org/10.1016/j.heliyon.2024.e39880. (**ISSN 2405-8440**).
111. Norman MKE, Hashim MY. Tensile strength of single banana fibers (SBFs) improved by novel alkaline treatment. IOP Conf Ser Mater Sci Eng. 2022;1244: 012001.
112. Hassan MZ, Sapuan SM, Roslan SA, Aziz SA, Sarip S. Optimization of tensile behavior of banana pseudo-stem (*Musa acuminate*) fiber reinforced epoxy composites using response surface methodology. J Mater Res Technol. 2019;8(4):3517–28. https://doi.org/10.1016/j.jmrt.2019.06.026.
113. Patel BY, Patel HK. Retting of banana pseudostem fibre using *Bacillus* strains to get excellent mechanical properties as biomaterial in textile & fiber industry. Heliyon. 2022;8(9): e10652. https://doi.org/10.1016/j.heliyon.2022.e10652.
114. Shukla N, Devnani GL. Characterization of untreated and alkalitreated banana fiber, a potential reinforcement in bio-composites. Rasayan J Chem. 2023;16(03):1473–7. https://doi.org/10.31788/RJC.2023.1638461.
115. Sreenivasan VS, Ravindran D, Manikandan V, Narayanasamy R. Mechanical properties of randomly oriented short *Sansevieria cylindrica* fibre/polyester composites. Mater Des. 2011;32(4):2444–55. https://doi.org/10.1016/j.matdes.2010.11.042.
116. Barreto AC, Costa MM, Sombra AS, Rosa DS, Nascimento RF, Mazzetto SE, Fechine PB. Chemically modified banana fiber: structure, dielectrical properties and biodegradability. J Polym Environ. 2010;18:523–31. https://doi.org/10.1007/s10924-010-0216-x.

117. Das D, Hussain S, Ghosh AK, Pal AK. Studies on cellulose nanocrystals extracted from *Musa sapientum*: Structural and bonding aspects. Cellulose Chem Technol. 2018;52(910):729–39.
118. Parre A, Karthikeyan B, Balaji A, Udhayasankar R. Investigation of chemical, thermal and morphological properties of untreated and NaOH treated banana fiber. Mater Today Proc. 2020;22:347–52. https://doi.org/10.1016/j.matpr.2019.06.655.
119. Hoque M, Janaswamy S. Biodegradable packaging films from banana peel fiber. Sustain Chem Pharm. 2024;37: 101400. https://doi.org/10.1016/j.scp.2023.101400. (**ISSN 2352-5541**).
120. Saragih SW, Hardiyanti R, Mahendra IP. Antimicrobial activity of cellulose nanofiberbased hydrogels from abacá banana pseudo-stem fibre. Rasayan J Chem. 2021;14:578–83. https://doi.org/10.31788/RJC.2021.1415883.
121. Prasetyo WE, et al. Effect of silanized-chitosan on flammability, mechanical, water absorption and biodegradability properties of pseudo-stem banana fiber and montmorillonite filled waste polypropylene biocomposite. IOP Conf Ser Mater Sci Eng. 2017;172: 012063. https://doi.org/10.1088/1757-899X/172/1/012063.
122. Hunt M, Torres M, Bachar-Wikstrom E, et al. Cellular and molecular roles of reactive oxygen species in wound healing. Commun Biol. 2024;7:1534. https://doi.org/10.1038/s42003-024-07219-w.
123. Caldwell MD. Bacteria and antibiotics in wound healing. Surg Clin N Am. 2020;100(4):757–76. https://doi.org/10.1016/j.suc.2020.05.007.
124. Cushnie TPT, Lamb AJ. Antimicrobial activity of flavonoids. Int J Antimicrob Agents. 2005;26(5):343–56. https://doi.org/10.1016/j.ijantimicag.2005.09.002.
125. De Rossi L, Rocchetti G, Lucini L, Rebecchi A. Antimicrobial potential of polyphenols: mechanisms of action and microbial responses—a narrative review. Antioxidants. 2025;14(2):200. https://doi.org/10.3390/antiox14020200.
126. Bhoyar SD, Malhotra K, Madke B. Dressing materials: a comprehensive review. J Cutan Aesthet Surg. 2023;16(2):81–9. https://doi.org/10.4103/JCAS.JCAS_163_22.
127. Parikh DV, Calamari TA, Sawhney APS, et al. Woven and nonwoven medical/surgical materials. Int Nonwovens J. 1999. https://doi.org/10.1177/1558925099OS-800117.
128. Alamgir ANM. Fibers, surgical dressings, and bandages of natural origin. In: Therapeutic use of medicinal plants and their extracts: Volume 1. Progress in drug research, vol. 73. Cham: Springer; 2017. https://doi.org/10.1007/978-3-319-63862-1_8.
129. Le Y, Anand SC, Horrocks AR. Recent developments in fibres and materials for wound management. Special issue: IJFTR. 1997;22(4):337–47.
130. Gao C, Zhang L, Wang J, Jin M, Tang Q, Chen Z, Cheng Y, Yang R, Zhao G. Electrospun nanofibers promote wound healing: theories, techniques and perspectives. J Mater Chem B. 2021. https://doi.org/10.1039/D1TB00067E.
131. Antunes JC, Domingues JM, Miranda CS, Silva AFG, Homem NC, Amorim MTP, Felgueiras HP. Bioactivity of chitosan-based particles loaded with plant-derived extracts for biomedical applications: emphasis on antimicrobial fiber-based systems. Mar Drugs. 2021;19(7):359. https://doi.org/10.3390/md19070359.
132. Zhang M, Guo N, Sun Y, Shao J, Liu Q, Zhuang X, Twebaze CB. Nanocellulose aerogels from banana pseudo-stem as a wound dressing. Ind Crops Prod. 2023;194: 116383. https://doi.org/10.1016/j.indcrop.2023.116383. (**ISSN 0926-6690**).
133. Patel DK, Dutta SD, Lim K-T. Nanocellulose-based polymer hybrids and their emerging applications in biomedical engineering and water purification. RSC Adv. 2019;9(33):19143–62. https://doi.org/10.1039/C9RA03261D.
134. Kibungu C, Kondiah PPD, Kumar P, Choonara YE. This review recent advances in chitosan and alginate-based hydrogels for wound healing application. Front Mater. 2021;8: 681960. https://doi.org/10.3389/fmats.2021.681960.
135. Pal S, Nisi R, Stoppa M, Licciulli A. Silver-functionalized bacterial cellulose as antibacterial membrane for wound-healing applications. ACS Omega. 2017;2(7):3632–9. https://doi.org/10.1021/acsomega.7b00442.
136. Hussain M, Suo H, Xie Y, Wang K, Wang H, Hou Z, Gao Y, Zhang L, Tao J, Jiang H, Zhu J. Dopamine-substituted multidomain peptide hydrogel with inherent antimicrobial activity and antioxidant capability for infected wound healing. ACS Appl Mater Interfaces. 2021;13(25):29380–91. https://doi.org/10.1021/acsami.1c07656.
137. Kong Y, Tang X, Zhao Y, Chen X, Yao Ke, Zhang L, Han Qi, Zhang L, Ling J, Wang Y, Yang Y. Degradable tough chitosan dressing for skin wound recovery. Nanotechnol Rev. 2020;9(1):1576–85. https://doi.org/10.1515/ntrev-2020-0105.
138. Yousefi M, Ghahremanzadeh R, Nejadmoghaddam MR, Samadi FY, Najafzadeh S, Fatideh FM, Mohammadi Z, Minai-Tehrani A. Nanofabrication of chitosan-based dressing to treat the infected wounds: in vitro and in vivo evaluations. Future Sci OA. 2024;10(1):FAO921. https://doi.org/10.2144/fsoa-2023-0077.
139. Chen S, Wang H, Yajuan Su, John JV, McCarthy A, Wong SL, Xie J. Mesenchymal stem cell-laden, personalized 3D scaffolds with controlled structure and fiber alignment promote diabetic wound healing. Acta Biomater. 2020;108:153–67. https://doi.org/10.1016/j.actbio.2020.03.035. (**ISSN 1742-7061**).
140. Rasheed U, Kiani MN, Butt MS, Saeed H, Hanif R, Anwar S. Fabrication and biocompatibility of neem/chitosan coated silk sutures for infection control and wound healing. J King Saud Univ Sci. 2024;36(10): 103435. https://doi.org/10.1016/j.jksus.2024.103435. (**ISSN 1018-3647**).
141. Ghasemzadeh Rahbardar M, Hosseinzadeh H. Therapeutic effects of rosemary (*Rosmarinus officinalis* L.) and its active constituents on nervous system disorders. Iran J Basic Med Sci. 2020;23(9):1100–12. https://doi.org/10.22038/ijbms.2020.45269.10541.
142. Sharma S, Devi M, Parmar K, Thakur N, Jeet K. Vitex Negundo: medicinal values, biological activities, and phytopharmacological actions. Int J Novel Res Dev. 2023; 8(4).
143. Felgueiras HP, Teixeira MA, Tavares TD, Amorim MTP. New method to produce poly(vinyl alcohol)/cellulose acetate films with improved antibacterial action. Mater Today Proc. 2020;31(Supplement 2):S269–72. https://doi.org/10.1016/j.matpr.2019.12.100.
144. Alborzi Z, Izadi-Vasafi H, Ghayoumi F. Wound dressings based on chitosan and gelatin containing starch, sesame oil and banana peel powder for the treatment of skin burn wounds. J Polym Res. 2021. https://doi.org/10.1007/s10965-021-02427-y.
145. Thandavamoorthy R, Devarajan Y, Kaliappan N. Antimicrobial, function, and crystalline analysis on the cellulose fibre extracted from the banana tree trunks. Sci Rep. 2023;13:15301. https://doi.org/10.1038/s41598-023-42160-8.
146. Gupta G, Saxena S, Baranwal M, Reddy MS. In vitro evaluation of bioactive properties of banana sap. Biologia (Bratisl). 2022;77(10):2989–3000. https://doi.org/10.1007/s11756-022-01159-8. (**Epub 2022 Jul 4**).
147. Gayathry KS, John JA. Physical, functional and bioactive properties of microencapsulated powders from banana pseudostem and inflorescence extracts. Food Prod Process and Nutr. 2024;6:74. https://doi.org/10.1186/s43014-024-00251-7.

148. Saravanan K, Aradhya SM. Polyphenols of pseudostem of different banana cultivars and their antioxidant activities. J Agric Food Chem. 2011;59(8):3613–23. https://doi.org/10.1021/jf103835z.
149. Bhattacharjee S, Singh A. Antioxidant and LC-MS screening of banana pseudostem. AgriRxiv. 2024. https://doi.org/10.31220/agriRxiv.2024.00254.
150. Purnama RC, Primadiamanti A. Phytochemical screening and spectrum profile of functional group from Banana (*Musa paradisiaca* L.) stem waste extract using Fourier-transform Infrared (FTIR) Spectroscopy method. J Phys Conf Ser. 2021;1882(1): 012106. https://doi.org/10.1088/1742-6596/1882/1/012106.
151. Harith SS, Yasim NHM, Harun A, Omar W, Atikah WS, Musa MS. Phytochemical screening, antifungal and antibacterial activities of Musa acuminata plant. Malay J Anal Sci. 2018;22:452–7. https://doi.org/10.17576/mjas-2018-2203-11.
152. Amanah NK, Mashudi S, Munawaroh S, Azzarin AW, Karimah FN, Gunawan F. Exploring the efficacy of *Musa cavendish* stem extract (Mucase) as a novel wound dressing: a comparative study with sofratulle®. Cureus. 2024;16(2): e54411. https://doi.org/10.7759/cureus.54411.
153. Shamsudin NF, Ahmed QU, Mahmood S, Ali Shah SA, Khatib A, Mukhtar S, Alsharif MA, Parveen H, Zakaria ZA. Antibacterial effects of flavonoids and their structure-activity relationship study: a comparative interpretation. Molecules. 2022;27(4):1149. https://doi.org/10.3390/molecules27041149.
154. Yan K, Xu F, Wei W, Yang C, Wang D, Shi X. Electrochemical synthesis of chitosan/silver nanoparticles multilayer hydrogel coating with pH-dependent controlled release capability and antibacterial property. Colloids Surf B. 2021;202: 111711.
155. Kalavathi R, Vijayakumar S, Vidhya E. Silver nanoparticles derived from *Clerodendrum inerme* L. using biosynthesis: an infection curing and enhancing the feasibility of various cell proliferation efficiencies. Vegetos. 2024. https://doi.org/10.1007/s42535-024-00979-0.
156. Dejene BK. Biosynthesized ZnO nanoparticle-functionalized fabrics for antibacterial and biocompatibility evaluations in medical applications: a critical review. Mater Today Chem. 2024;42: 102421. https://doi.org/10.1016/j.mtchem.2024.102421. (**ISSN 2468-5194**).
157. Dejene BK. Exploring the potential of ZnO nanoparticle-treated fibers in advancing natural fiber reinforced composites: a review. J Nat Fibers. 2024. https://doi.org/10.1080/15440478.2024.2311304.
158. Kudzin MH, Boguń M, Mrozińska Z, Kaczmarek A. Physical properties, chemical analysis, and evaluation of antimicrobial response of new polylactide/alginate/copper composite materials. Mar Drugs. 2020;18(12):660. https://doi.org/10.3390/md18120660.
159. Harini K, Ramya K, Sukumar M. Extraction of nano cellulose fibers from the banana peel and bract for production of acetyl and lauroyl cellulose. Carbohyd Polym. 2018;201:329–39. https://doi.org/10.1016/j.carbpol.2018.08.081. (**ISSN 0144-8617**).
160. Zaini HM, Saallah S, Roslan J, Sulaiman NS, Munsu E, Wahab NA, Pindi W. Banana biomass waste: a prospective nanocellulose source and its potential application in food industry—a review. Heliyon. 2023;9(8): e18734. https://doi.org/10.1016/j.heliyon.2023.e18734. (**ISSN 2405-8440**).
161. Diarsa M, Gupte A. Preparation, characterization and its potential applications in isoniazid drug delivery of porous microcrystalline cellulose from banana pseudostem fibers. 3 Biotech. 2021;11(7):334. https://doi.org/10.1007/s13205-021-02838-0. (**Epub 2021 Jun 15**).
162. Vajpayee M, Singh M, Ledwani L, Prakash R, Nema SK. Investigation of antimicrobial activity of DBD air plasma-treated banana fabric coated with natural leaf extracts. ACS Omega. 2020;5(30):19034–49. https://doi.org/10.1021/acsomega.0c02380.
163. Nilavukkarasi M, Vijayakumar S, Prathip Kumar S. Biological synthesis and characterization of silver nanoparticles with Capparis zeylanica L leaf extract for potent antimicrobial and anti proliferation efficiency. Mater Sci Energy Technol. 2020;3:371–6. https://doi.org/10.1016/j.mset.2020.02.008. (**ISSN 2589-2991**).
164. Amutha K, Selvakumari U. Wound healing activity of methanolic stem extract of Musa paradisiaca Linn. (Banana) in Wistar albino rats. Int Wound J. 2016;13(5):763–7. https://doi.org/10.1111/iwj.12371. (**Epub 2014 Sep 16**).
165. Shahidi F, Yeo JD. Insoluble-bound phenolics in food. Molecules. 2016;21(9):1216. https://doi.org/10.3390/molecules21091216.
166. Shahidi F, Hossain A. Importance of insoluble-bound phenolics to the antioxidant potential is dictated by source material. Antioxidants (Basel). 2023;12(1):203. https://doi.org/10.3390/antiox12010203.
167. Rocchetti G, Gregorio RP, Lorenzo JM, Barba FJ, Oliveira PG, Prieto MA, Simal-Gandara J, Mosele JI, Motilva M-J, Tomas M, Patrone V, Capanoglu E, Lucini L. Functional implications of bound phenolic compounds and phenolics–food interaction: a review. Compr Rev Food Sci Food Saf. 2022;21:811–42. https://doi.org/10.1111/1541-4337.12921.
168. Su D, Zhang R, Hou F, et al. Comparison of the free and bound phenolic profiles and cellular antioxidant activities of litchi pulp extracts from different solvents. BMC Complement Altern Med. 2014;14:9. https://doi.org/10.1186/1472-6882-14-9.
169. Seneviratne DM, et al. A low-cost, antimicrobial aloe-alginate hydrogel film containing Australian First Nations remedy 'lemon myrtle oil' (*Backhousia citriodora*)—potential for incorporation into wound dressings. Heliyon. 2024;10(18): e37516.
170. Onyema CT, Ofor CE, Okudo VC, Ogbuagu AS. Phytochemical and antimicrobial analysis of banana pseudo stem (*Musa acuminata*). J Pharm Res Int. 2016;10(1):1–9. https://doi.org/10.9734/BJPR/2016/22593.
171. Pereira R, Carvalho A, Vaz DC, Gil MH, Mendes A, Bártolo P. Development of novel alginate-based hydrogel films for wound healing applications. Int J Biol Macromol. 2013;52:221–30. https://doi.org/10.1016/j.ijbiomac.2012.09.031. (**Epub 2012 Oct 8**).
172. Prathipkumar S, Vijayakumar S, Alsalhi MS, et al. Biogenic-mediated silver nanoparticles using heneicosane and their enhanced antimicrobial, antiproliferative, sensing capability and photocatalytic potential. Appl Nanosci. 2023;13:5839–49. https://doi.org/10.1007/s13204-023-02787-5.
173. Zhou W, Apkarian R, Wang ZL, Joy D. Fundamentals of Scanning electron microscopy (SEM). In: Zhou W, Wang ZL, editors. Scanning microscopy for nanotechnology. New York: Springer; 2006. https://doi.org/10.1007/978-0-387-39620-0_1.
174. Anon. X-ray diffraction (XRD) basics and application; 2022. https://chem.libretexts.org/@go/page/148442. Accessed 5 Apr 2025.
175. Smith BC. Fundamentals of fourier transform infrared spectroscopy. 2nd ed. CRC Press; 2011. https://doi.org/10.1201/b10777.
176. Bowler PG, Duerden BI, Armstrong DG. Wound microbiology and associated approaches to wound management. Clin Microbiol Rev. 2001;14(2):244–69. https://doi.org/10.1128/CMR.14.2.244-269.2001.
177. Hossain TJ. Methods for screening and evaluation of antimicrobial activity: a review of protocols, advantages, and limitations. Eur J Microbiol Immunol (Bp). 2024;14(2):97–115. https://doi.org/10.1556/1886.2024.00035.
178. Suba S, Vijayakumar S, Nilavukkarasi M, Vidhya E, Punitha VN. Eco synthesized silver nanoparticles as a next generation of nanoproduct in multidisciplinary applications. Environ Chem Ecotoxicol. 2022;4:13–9. https://doi.org/10.1016/j.enceco.2021.11.001. (**ISSN 2590-1826**).

179. van Meerloo J, Kaspers GJ, Cloos J. Cell sensitivity assays: the MTT assay. Methods Mol Biol. 2011;731:237–45. https://doi.org/10.1007/978-1-61779-080-5_20.
180. Baliyan S, Mukherjee R, Priyadarshini A, Vibhuti A, Gupta A, Pandey RP, Chang CM. Determination of antioxidants by DPPH radical scavenging activity and quantitative phytochemical analysis of *Ficus religiosa*. Molecules. 2022;27(4):1326. https://doi.org/10.3390/molecules27041326.
181. Eertmans F, Bogaert V, Van Poecke T, Puype B. An improved neutral a-glucosidase assay for assessment of epididymal function-validation and comparison to the WHO method. Diagnostics (Basel). 2014;4(1):1–11. https://doi.org/10.3390/diagnostics4010001.
182. Evans E, Ballen F, Siddiq M, Ahmed J, Lobo G. Banana production, global trade, consumption trends, postharvest handling, and processing; 2020. https://doi.org/10.1002/9781119528265.ch1
183. Okieimen FE, Bakare IP. Short communication: alkaline surface modification of banana stem fibres. Niger J Chem Res. 2007;11(1):37–42. https://doi.org/10.4314/njcr.v11i1.35631.
184. Gebremaryam G, Shahapurkar K, Chenrayan V, Althoey F, Hadidi H, Soudagar ME, Tirth V, Algahtani A, Al-Mughanam T, Alghtani A, Ananda MHC. Influence of layering pattern, fibre architecture, and alkalization on physical, mechanical, and morphological behaviour of banana fibre epoxy composites. Int J Polym Sci. 2023. https://doi.org/10.1155/2023/6023056.
185. Ilyas RA, Zuhri MYM, Norrrahim MNF, Misenan MSM, Jenol MA, Samsudin SA, Nurazzi NM, Asyraf MRM, Supian ABM, Bangar SP, et al. Natural fiber-reinforced polycaprolactone green and hybrid biocomposites for various advanced applications. Polymers. 2022;14(1):182. https://doi.org/10.3390/polym14010182.
186. Prasad A, Kandasubramanian B. Fused deposition processing polycaprolactone of composites for biomedical applications. Polym Plast Technol Mater. 2019;58:1–34. https://doi.org/10.1080/25740881.2018.1563117.
187. Amara C, El Mahdi A, Medimagh R, Khwaldia K. Nanocellulose-based composites for packaging applications. Curr Opin Green Sustain Chem. 2021;31: 100512. https://doi.org/10.1016/j.cogsc.2021.100512. (**ISSN 2452-2236**).
188. Lala SD, Deoghare AB, Chatterjee S. Effect of reinforcements on polymer matrix bio-composites—an overview. Sci Eng Compos Mater. 2018;25(6):1039–58. https://doi.org/10.1515/secm-2017-0281.
189. Gregory DA, et al. Bacterial cellulose: a smart biomaterial with diverse applications. Mater Sci Eng R Rep. 2021;145: 100623. https://doi.org/10.1016/j.mser.2021.100623.
190. Klemm D, Cranston ED, Fischer D, Gama M, Kedzior SA, Kralisch D, Kramer F, Kondo T, Lindström T, Nietzsche S, Petzold-Welcke K, Rauchfuß F. Nanocellulose as a natural source for groundbreaking applications in materials science: today's state. Mater Today. 2018;21(7):720–48. https://doi.org/10.1016/j.mattod.2018.02.001. (**ISSN 1369-7021**).
191. Rojas J, Bedoya M, Ciro Y, Poletto M, Junior HLO. Current trends in the production of cellulose nanoparticles and nanocomposites for biomedical applications. In: Cellulose—fundamental aspects and current trends. IntechOpen; 2015. https://doi.org/10.5772/61334.
192. Yin J, Xu L, Ahmed A. Batch preparation and characterization of electrospun porous polylactic acid-based nanofiber membranes for antibacterial wound dressing. Adv Fiber Mater. 2022;4(4):832–44. https://doi.org/10.1007/s42765-022-00141-y.
193. Kashid S, Joshi K. Biopolymer-based nanomaterials: synthesis, characterization, and applications. In: Innovations in green nanoscience and nanotechnology. CRC Press; 2022. p. 15–59. https://doi.org/10.1201/9781003319153-3.
194. Hasnain MS, Nayak AK. 7—Nanocomposites for improved orthopedic and bone tissue engineering applications. In: Inamuddin AMA, Mohammad A, editors. Woodhead Publishing series in biomaterials, applications of nanocomposite materials in orthopedics. Woodhead Publishing; 2019. p. 145–77. https://doi.org/10.1016/B978-0-12-813740-6.00008-9. (**ISBN 9780128137406**).
195. Falsafi SR, Topuz F, Bajer D, Mohebi Z, Shafieiuon M, Heydari H, Rawal S, Sathiyaseelan A, Wang MH, Khursheed R, Enayati MH, Rostamabadi H. Metal nanoparticles and carbohydrate polymers team up to improve biomedical outcomes. Biomed Pharmacother. 2023;168: 115695. https://doi.org/10.1016/j.biopha.2023.115695.
196. Iqubal MK, Saleem S, Iqubal A, Chaudhuri A, Pottoo FH, Ali J, Baboota S. Natural, synthetic and their combinatorial nanocarriers based drug delivery system in the treatment paradigm for wound healing via dermal targeting. Curr Pharm Des. 2020;26(36):4551–68. https://doi.org/10.2174/1381612826666200612164511.
197. Randhawa A, Dutta SD, Ganguly K, Patil TV, Patel DK, Lim KT. A review of properties of nanocellulose, its synthesis, and potential in biomedical applications. Appl Sci. 2022;12(14): Art. no. 14. https://doi.org/10.3390/app12147090.
198. D'Amora U, Dacrory S, Hasanin MS, Longo A, Soriente A, Kamel S, Raucci MG, Ambrosio L, Scialla S. Advances in the physico-chemical, antimicrobial and angiogenic properties of graphene-oxide/cellulose nanocomposites for wound healing. Pharmaceutics. 2023;15(2):338. https://doi.org/10.3390/pharmaceutics15020338.
199. Baptista IF, Borges J. Cellulose-based bioelectronic devices. In: Cellulose—medical, pharmaceutical and electronic applications. IntechOpen; 2013. https://doi.org/10.5772/56721.
200. Ali SN, Arafat MT. 7—Cellulose-based biocomposites. In: Hoque ME, Sharif A, Jawaid M, editors. Woodhead Publishing series in biomaterials, green biocomposites for biomedical engineering. Woodhead Publishing; 2021. p. 135–95. https://doi.org/10.1016/B978-0-12-821553-1.00017-X. (**ISBN 9780128215531**).
201. Abdul Khalil HPS, Adnan AS, Yahya EB, Olaiya NG, Safrida S, Hossain MS, Balakrishnan V, Gopakumar DA, Abdullah CK, Oyekanmi AA, et al. A review on plant cellulose nanofibre-based aerogels for biomedical applications. Polymers. 2020;12(8):1759. https://doi.org/10.3390/polym12081759.
202. Oprea M, Voicu SI. Recent advances in composites based on cellulose derivatives for biomedical applications. Carbohyd Polym. 2020;247: 116683. https://doi.org/10.1016/j.carbpol.2020.116683. (**ISSN 0144-8617**).
203. Hasanin MS, Saied HE, Kamel S. Polysaccharides based biosensors for medical applications: prospective and future aspects. Starch Stärke. 2023;75(11–12):2300037. https://doi.org/10.1002/star.202300037.
204. Chandel N, Jain K, Jain A, Raj T, Patel A, Yang Y-H, Bhatia S. The versatile world of cellulose-based materials in healthcare: from production to applications. Ind Crops Prod. 2023;201: 116929. https://doi.org/10.1016/j.indcrop.2023.116929.