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A comprehensive review on banana fibre: Extraction, degumming, and applications across industrial sectors

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Abstract
Banana fibre extracted from the pseudostem of the banana plant (Musa spp.), has gained considerable attention as a sustainable and biodegradable alternative to synthetic materials. This review explores the various extraction and degumming methods used to process banana fibre, alongside its broad range of applications in diverse industrial sectors. Traditional and mechanical extraction techniques including manual, mechanical, chemical and bilological retting are examined along with advancements various degumming processes that enhance fibre purity and performance. The integration more than one treatments especially greener methods has shown significant improvements in fibre properties, particularly in enhancing fibre-matrix adhesion for composite applications. Its high cellulose content and favourable mechanical and thermal properties make it a valuable reinforcement material in thermosetting composites, used in applications ranging from electrical casings to structural materials. In the paper industry, banana fibre contributes to the production of high-strength, long-lasting paper products including currency paper. Its potential as a biosorbent in wastewater treatment, due to its modifiable surface and high absorption capacity is also discussed. Furthermore, banana fibre is increasingly used in sustainable fashion for its aesthetic texture and environmental benefits, while offering economic opportunities to local farming communities and preserving traditional craftsmanship. This review underscores the potential of banana fibre as a versatile and eco-friendly resource, contributing to a circular bioeconomy. Emphasis is given to current innovations, material performance, and sustainable development opportunities across sectors such as construction, textiles, biomedicine, and environmental management.

Keywords: Banana fibre, sustainable alternative, extraction methods, degumming processes

Introduction
Natural fibre are gaining popularity in many industries as well due to their eco-friendly qualities and as a sustainable alternative to synthetic materials. Banana fibre, also called banana silk, is a new addition to the plant based fibre group. The fibre possesses high strength, which can be easily blended with fibres like cotton, jute or other synthetic fibre to produce blended woven fabric and textiles. Banana fibre as a natural fibre is becoming increasingly popular due to its eco-friendly qualities and as a sustainable alternative to synthetic materials. It is a ligno-cellulosic fibre, derived from the pseudostem of banana plant, and classified as a bast fibre with relatively strong mechanical properties.

The major producers of banana are mostly the tropical and subtropical countries. The total annual world production is estimated at 115.7 million tonnes of fruit. According to APEDA report 2022, India leads the global banana production accounting about 26.7% of the total production, with an annual output of about 34.9 million tons from an area of 0.88 million hectares.

Pseudostem is the major agro-waste generated after harvest, which can be effectively utilized in bulk production of fibre. About 50-60 kg of waste is generated for every 30-40 kg of banana bunch. World-wide, nearly over 1.2 billion tons/year of banana stems are left to rot. In India, with an extractable pseudostem fibre yield of 400 kg per hectare, Rs. 3000-4000 crores ($500 million) worth fibre could be extracted which is otherwise dumped as a waste after harvesting the bunches (Cecci *et al.*, 2020) [14].

The waste banana stems cannot be left in the field as they cause emission of toxic gases, such as CO_2, and also facilitate the growth of harmful microorganisms (Hussain and Tarar, 2014) [17].

The pseudostem can be used to extract fibre for textiles, and filler or structural reinforcement in composites materials. The most widely known banana plant species for its fibre is (Abaca) *Musa textilis* (Lai *et al*.,2023) [24]. It's fibre is highly important among the leaf fibre group, whereas the most common banana that is consumed by humans is a member of *Musa acuminata*, where the pseudostem is left as waste biomass after harvest. For every ton of banana fruit harvested, approximately 4 tons of biomass waste (eg., leaf, pseudostem, rotten fruit, peel, fruit-bunch-stem, rhizome, etc.) is produced. This means, for every cycle of banana fruit production, four times of biomass wastes are also produced. Also, it is estimated that one hectare of banana farm could produce approximately 220 tons of biomass wastes (Hussain and Tarar, 2014). These wastes are usually disposed of by the farmer into lakes and rivers or simply burned or left to decompose.

Characteristics features of Banana fibre

Banana fibre derived from the pseudostem of the banana plant exhibits several notable characteristics that make it a promising material for sustainable textile production. Visually, it bears a close resemblance to bamboo and ramie fibres; however, it surpasses both in terms of fineness and spinnability, offering enhanced processing capabilities for textile applications. Chemically, banana fibre is composed primarily of cellulose, hemicellulose, and lignin aligning it with other plant-based natural fibres. It is known for its high tensile strength, which contributes to its durability, while its relatively low elongation indicates limited stretchability under tension. The fibre is also lightweight, making it suitable for garments requiring comfort and ease of wear. In addition, banana fibre demonstrates excellent moisture absorption properties, promoting breathability and suitability for warm climates. From an environmental perspective, banana fibre is entirely biodegradable and thus qualifies as an eco-friendly material, contributing to efforts in sustainable development and circular fashion. Furthermore, it exhibits remarkable versatility in processing, as it can be spun using a wide range of spinning techniques, including ring spinning, open-end spinning, bast fibre spinning, and semi-worsted spinning methods. This adaptability further enhances its potential for integration into various textile manufacturing processes.

One of its key advantages is the abundant and cost-effective availability of raw material, as banana plants are widely cultivated in many tropical and subtropical regions. This economic accessibility supports its use in a variety of applications. The fibre's versatility allows it to be utilized in the production of diversified products, ranging from textiles and handicrafts to absorbent materials and components for the automotive industry. Its wide applicability not only enhances its commercial value but also contributes significantly to socio-economic development. In particular, the cultivation, extraction, and processing of banana fibre offer considerable employment opportunities in rural areas. It holds special potential for empowering women through Self-Help Groups (SHGs), promoting inclusive growth and community-level entrepreneurship. As a result, banana fibre presents both environmental and socio-economic benefits, reinforcing its value in sustainable industrial practices.

Varietal variation in fibre recovery

Banana fibre is a natural and eco-friendly material, making it an attractive alternative to synthetic fibres in the pursuit of sustainable development. The genomic characteristics of a banana variety significantly influence its potential for biomass production, particularly in terms of fibre yield. Studies have shown that the proportion of extractable pseudostem and the corresponding fibre yield differ between cultivar types. In dessert cultivars, the extractable pseudostem constitutes approximately 46.4% of the plant, with a fibre yield of about 0.53%, whereas culinary varieties demonstrate higher values with 55.2% extractable pseudostem and a fibre yield of 0.78%. Preethi and Murthy (2011) [38], using a semi-automatic fibre extraction machine, evaluated fibre recovery across several banana cultivars including Nendran, Monthan, Poovan, and Grand Naine. Their findings indicated that Poovan exhibited the highest fibre recovery rate at 2.71%, followed by Nendran (2.30%) and Monthan (2.20%). Grand Naine, by contrast, showed the lowest recovery rate, with only 0.80% fibre yield. These results underscore the influence of varietal differences on the efficiency of fibre extraction and overall biomass utilization.

Fibre yield in banana cultivars is influenced by several anatomical and physiological factors, including the number and weight of fibre-extractable sheaths, the weight of the non-extractable inner core, and the moisture content present in the leaf sheaths. A study conducted by Asish (2021) [7] investigated fibre yield and quality across various banana cultivars and revealed notable differences. Among the cultivars examined, Pisang Lilin and Kunnan exhibited the lowest fibre yield per sheath, with values of 3.24 g and 3.38 g respectively. In contrast, the highest fibre yield was recorded in the Chenkadali cultivar at 11.31 g per sheath. The study also found a positive correlation between the weight of individual sheaths and the fibre yield they produced. Generally, the middle sheath layers contributed more significantly to fibre yield compared to the outer and inner layers. However, Chenkadali presented an exception to this trend, with its outer sheath layers yielding more fibre than the middle layers. These findings highlight the importance of both cultivar selection and sheath morphology in optimizing fibre extraction from banana plants.

Extraction of banana pseudostem fibre

Extraction is the process of separating the fibre from the pseudostem sheaths. Extraction processes of banana fibre were performed by different methods that include mechanical extraction, chemical, microbial, and enzymatic retting. Each method has its advantages and disadvantages in the contexts of the yield, quality, and properties of fibre bundles obtained (Balda *et al*. 2021) [8]

Physical method: Banana fibre extracted manually is regarded as superior in quality compared to fibres obtained through other methods. In the manual extraction process, each leaf sheath is detached from the pseudostem and sliced into strips measuring 6-10 cm in width. Using a steel blade, the sheath's flesh is scraped away, and after multiple scrapings, the fibre is collected (Aravindakshan and Pushkaran, 1996) [5]. In the Philippines, two hand extraction techniques are employed. The Bacnis method involves separating the sheaths from the pseudostem externally, then crushing them and removing the fibre by cutting away the pulpy section and pulling it from the strip. The Loenit method uses a stripping knife to separate the fibre, where the plant flesh is scraped off the sheath with the knife (Ray *et al*., 2013) [41].

Mechanical extraction: The raspador machine is a banana decorticator designed for extracting fibre. It features a scraping plate positioned in front of a drum equipped with a carbon steel angle blade. Leaf sheaths are placed between the drum and rollers and then pulled back. A simple stripping process using a steel blade removes all adhering particles to yield clean fibre. With the raspador machine, it is possible to produce 5 kg of dry fibre in a day, whereas a skilled individual using manual extraction can only obtain 150 to 200 g of dry fibre (Gopinath, 2005) [15].

The Banana fibre extractor, developed by the Central Tobacco Research Institute in Rajahmundry, is another fibre extraction machine. It includes a rotating drum with horizontal bars that have blunt edges and can produce up to 25 kg of fibre daily, compared to 500 g by hand extraction. Although the mechanical method of fibre extraction is fast, it has the drawback of producing fibres with limited bundle length, which is highly valued in the textile industry. As an alternative, the biological retting method can be employed.

According to Pitimaneeyakul (2009) [36], manual fibre extraction requires a skilled person and is time-consuming. The biological method results in fibres that are darker in color, which is a disadvantage for biological retting. The mechanical method yields a similar amount of fibre as biological extraction, and these fibres have a good light color. However, the length of banana fibres is affected in the mechanical method, with only 25-30% of the fibres produced being long enough for use in yarn spinning.

Chemical extraction: Chemical extraction utilizes substances such as alkali, hypochlorite, mild acids, and hydrogen peroxide. Initially, the fibre is boiled in an alkali solution to remove gummy substances like arabans and xylan, which are primary components of gum, and then it is rinsed with water to neutralize it. The bleaching of the fibre is carried out using either hydrogen peroxide or hypochlorite, followed by another water rinse. Occasionally, oxalic acid and sulfuric acid, along with detergents, are employed in the chemical extraction process. Additionally, other chemicals like stearic acid, potassium permanganate, and benzoyl chloride have been used. (Arifuzzaman Khan *et al*., 2013) [6]. The quality of fibres obtained through chemical extraction is influenced by factors such as the duration of treatment, type of chemicals, the temperature, and the concentration employed (Vardhini *et al*., 2016) 48[]. The chemicals used in this process pose environmental challenges, as the waste produced contains high levels of COD, BOD, halogenated compounds, and lignin derivatives. Consequently, it is essential to treat this waste before it is discharged into the environment to reduce its detrimental effects, which also increases operational expenses. (Mumthas *et al*., 2019) [29].

Biological extraction: Biological retting of banana fibre refers to the process of separating fibre bundles by partially digesting the binding material. This process involves two main steps: initially water is absorbed into the fibre matrix, causing it to swell followed by either aerobic or anaerobic microbial activity. The biological method employs microbes or enzymes to extract fibre from the banana pseudostem. This method is advantageous because it is specific, selective, and operates under mild conditions without usage of chemicals. It can be conducted both aerobically and anaerobically (Jacob and Prema, 2008) [20]. Traditional method of biological extraction utilizes environmental microbes to eliminate lignin, hemicellulose and pectin. Pseudostem sheaths are immersed in water with environmental microbes (e.g., *Bacillus*, *Fusarium lateritium*, *Clostridium*, and *Rhizomucor pusillus*) for several days to remove these non-cellulosic components. Akubueze *et al*. (2015) [3] documented biological extraction using a bacterial consortium of *Bacillus subtilis*, *B. licheniformis*, *B. cereus*, and *B. polymyxa*. A significant limitation of these methods is the extended duration required for treatment.

Brindha *et al*. (2019) [13] investigated various methods (mechanical, microbial, chemical, and enzymatic) for extracting cellulosic fibre from the Poovan variety. They examined the flexural and tensile properties of the fibre to assess its suitability for different applications. Among the retting processes, the use of natural microorganisms present in groundwater facilitated effective retting by the 18th day, while treatment with *A. niger* required 22 days for satisfactory results. In the absence of additional nitrogen and carbon sources, natural microbes utilized the pseudostem biomass as substrates for growth, potentially accelerating the retting process. SEM analysis, tensile and flexural properties confirmed that chemical retting with sodium hydroxide produced fibre samples with a low tex value (6.4), making them more suitable for the textile industry. Microbially retted fibre is better suited for fibre reinforcement composites due to its higher lignin content.

Among the various techniques for extracting banana fibre (mechanical, chemical, and biological)the mechanical method is regarded as efficient, producing approximately 20-30 kg of fibre per day, in contrast to manual extraction which yielded about 4 kg (Uma *et al*., 2005). Despite its productivity, this method is less effective at eliminating the gummy substances that adhere to the fibre surface. The chemical method, which typically employs alkali or synthetic detergents facilitates better gum removal but adversely affects the physical properties of fibre, including surface fibrillation, brightness, and tensile strength. Additionally, it poses significant environmental concerns due to chemical waste discharge (Ahirwar *et al*., 2019) [1]. In comparison, biological methods such as retting yield higher-quality fibres with minimal damage; however, it is labor-intensive, water-intensive, and time-consuming method (Jacob & Prema, 2008) [20]. Therefore, degumming is essential following fibre extraction which involves the breaking of peptide bonds through enzymatic, chemical, or hydrolytic catalysis by solubilization or dispersion to remove rough and hard polysaccharides embedded in the fibre matrix (Kim *et al*., 2016) [22].

Degumming

Degumming refers to the process of separating fibre from the bark composite matrix, a crucial step in bast fibre extraction. In practical applications, degumming typically involves a combination of two or more methods: chemical, physical, or biological to enhance the quality of the extracted fibre. A variety of agents can be employed in the degumming process, including alkali, steam, microwave irradiation, ultrasonic waves, and enzymes, each contributing differently to the effectiveness of gum removal and the preservation of fibre integrity.

Alkali degumming: To remove waxes, the fibre samples are boiled in water, emulsified with a detergent for an hour, and then dried at 80 °C for a further hour. The fibre is then degummed by exposing it to sodium hydroxide (NaOH) at approximately 5% concentrations for three hours at 95 °C. After 30 minutes of neutralizing the alkali in the fibre with 1% hydrochloric acid (HCl), the fibre is rinsed once more with excess water to get rid of any remaining chemical. Finally, the fibre is dried for an hour at 80 °C in an oven.

The chemical, thermal, and morphological characteristics of untreated and NaOH-treated banana fibre were examined by Parre *et al*. (2020) [35]. The fibre's surface was smoothed and non-cellulosic materials and other contaminants were effectively eliminated by a 5% NaOH treatment. Better fibre matrix interface, fibre bonding, and wetting properties resulted from this. Because the waxy layers and other contaminants are removed from the surface, it also appears to increase the banana fibre's resilience to heat. Advantages of alkali degumming

The processing and treatment of banana fibre are essential steps in optimizing its functional characteristics for diverse applications. A key outcome of these treatments is the effective removal of non-cellulosic substances and surface contaminants, resulting in a smoother and more refined fibre texture. This modification enhances the fibre-matrix interfacial interaction, thereby improving bonding strength and wettability—critical parameters in the performance of fibre-reinforced composites. Furthermore, the process leads to the substantial reduction of lignin and hemicellulose content, effectively increasing the cellulose concentration and structural uniformity of the fibre. The development of robust hydrogen bonding within the treated fibre matrix further contributes to superior mechanical properties, including increased tensile strength and durability. Additionally, the elimination of waxy coatings and residual impurities significantly boosts the thermal resistance of the fibre, rendering it more suitable for applications that demand thermal stability. Overall, these enhancements collectively elevate the structural integrity and functional efficacy of banana fibre, particularly in the development of bio-composites and other high-performance sustainable materials.

Steam explosion

To obtain high-quality banana fibre, the procedure consists of slicing banana stems and leaves, and then performing a steam explosion on them, followed by rinsing and bleaching. The invention's preparation technique is pollution-free since water steam is utilized as the medium in the steam explosion process without the addition of chemical reagents. Over 90% of the pectin and hemicellulose in banana stems and leaves are broken down by the steam explosion process, which also breaks down some lignin and totally separates the fibre bundles from extraneous materials.

While the rinsing procedure can remove various tissues besides the fibre, the steam explosion method tears the banana fibre into the loose structure, which helps with bleaching, oil feeding, and loosening the fibre and enhances its quality. The invention offers a novel method for preparing banana fibre that can improve fibre yield and quality while lowering the cost of degumming and preventing environmental damage from conventional degumming techniques. (Behera *et al*., 2014) [10].

In a study conducted by Sheng *et al*. (2014) [44] the fibre was subjected to steam explosion at 800 °C. By using FTIR, XRD, and chemical composition, the hydrolysis of the lignin and hemicelluloses was verified. When compared to the raw fibre, the treated fibre's surface morphology changed according to the SEM examination. The thermal analysis demonstrated an improvement in the treated fibre's thermal stability.

Microwave assisted degumming

In the process of microwave extraction, before being heated in a microwave, bast fibre must be soaked in water to create moisture molecules inside the gum structure. Consequently, the moisture is evenly dispersed throughout the stem's cell walls. Moisture absorbs microwaves strongly and transforms them into heat as it is a polar molecule with a large dielectric loss. Gums and cellulose exhibit minimal absorption sensitivity to microwaves and have a low dielectric loss. (Li *et al*., 2020) [25].

The mechanical and morphology of microwave treated and untreated fibre were investigated by Imoisili *et al*. (2018) [18]. The results of studies on mechanical (tensile) qualities showed that microwave radiation at 550 W power might increase the fibre's modulus and tensile strength. Analysis using a scanning electron microscope (SEM) revealed that the fibre's surface roughness improved and that uniform surface roughness had been attained.

Ultrasonic treatment

Ultrasonic treatment utilizes a sound wave with a frequency higher than 20,000 Hz transferring in the form of mechanical vibrations (Bang and Suslick, 2010) [9]. The alternating appearance of positive and negative pressure during transmission in the water-fibre matrix can result in the generation of numerous tiny bubbles. The bubbles expand rapidly before exploding under extreme pressure and heat. This process is referred as sonic cavitation. At the fibre interface, acoustic cavitation takes place, which promotes the transmission of liquor. Chemicals will find it simpler to reach and degrade the gum as a result of the movement. Twebaze *et al*. (2022) [47] found that a combination of alkali pre-treatment and ultra-sonication improved the banana fibre quality. Vascular bundle individualization was clearly apparent which led to better fibrillation. The notable fibrillation that occurred by ultra-sonication also contributed to the achievement of a 19.36 μm fibre diameter, 31.12 cN/dtex breaking strength, and 9.38% breaking elongation. According to fibre component analysis and XRD, the ultrasonication method also increased the cellulose content to 72.78% and the crystallinity index to 60.19%. The characteristics of the alkali-pretreated fibre were enhanced by the ultrasonic technique. This modified fibre was used to make yarn and for various purposes in the textile industry. Banana pseudostem could therefore substitute synthetic fibre, lessen the planting pressure of conventional fibre, and diversify natural fibre textile goods.

Enzymatic degumming

Microbial and enzymatic degumming methods are safe and environmentally friendly, with minor damage to lignocellulosic fibre. Different enzymes such as pectinase, laccase, cellulase hemi-cellulase can be employed for enzymatic treatment. Exclusion of thickly coated sticky material around fibre using enzymes is in high demand. The effect of enzymatic degumming of extracted banana fibre were reported by Paramasivam *et al*. (2022) [34]. Better grade fibre was produced by treating machine-extracted banana fibre with enzymes under ideal conditions. In comparison to other degumming techniques, the laccase enzyme demonstrated an effective role in enhancing the fibre's surface quality through improved stiffness. The market value of the pseudostem waste produced by using them for different industrial applications will grow as well as a result.

Applications

After the banana fruit is harvested, the pseudostem typically turns into biomass waste, posing a significant disposal challenge due to its volume. To address this issue, researchers have begun extracting fibres and other materials from the stem to create various value-added products. Among the most prevalent products made from banana pseudostem fibre today are ropes and cordage. The fibre's resistance to seawater and its natural buoyancy have created a demand for it in the production of shipping cables. Additionally, this fibre is utilized in making fishing nets, other types of cordage, mats, packaging materials, sheets, and more.

Additionally, in the Edo period of Japan (1600-1868), banana pseudostem fibre was used to make traditional dresses such as kimono and kamishimo. This fibre is usually used due to its light weight and comfort. In addition, banana pseudostem fibre is employed in the creation of items like cushion covers, bags, tablecloths, curtains, and more. There are also several potential applications for banana fibre, including its use as a natural absorbent, in arts and crafts, as string thread, in paper cardboard, tea bags, high-quality textiles and fabrics, currency note paper, and various other products. The potential of banana fibre as a natural absorbent is promising, particularly for absorbing oil spills in oil refineries. It can also serve as an absorbent for colored wastewater from textile industry dyes. Both bananas and banana pseudostems contain pathogenesis proteins, which have antimicrobial properties. Furthermore, numerous research studies have documented the use of banana pseudostem fibre in the production of polymer/fibre composites.

Textile and handicrafts industry

Banana fibre known for its stiffness and high tensile strength is an excellent material for textiles, yarn, and handicrafts. Historically, banana fibre has been utilized in India for textile production, as evidenced by ancient texts like the Ramayana, where characters such as Sita and Rama are described wearing "Naravastra" garments made from this fibre. In countries like the Philippines and Japan, banana fibre is extensively used in the commercial production of shirts, dresses, and household items. This fibre is versatile, finding applications in creating various value-added products and handicrafts, including table mats, wall hangings, bags, curtains, ropes, clothing, and home furnishings. Its lightweight and comfortable nature makes it a popular choice for summer apparel (Pappu *et al*., 2015) [33]. Research has explored the enzymatic degumming of banana fibre to enhance its smoothness for yarn and fabric production. A study by Soraisham *et al*. (2022) [45] found that bleaching banana fibre improved its spinnability. Enzymes like lignin peroxidase and polygalacturonase from *Aspergillus niger* have been used to enhance the surface smoothness and fibre strength for textile applications (Vellaichamy and Gaonkar, 2017) [50]. Ortega *et al*. (2016) [31] employed a combination of pectinase, polygalacturonase (Biopectinase K) and hemicellulase (Biopectinase M01) to produce textile-grade banana fibre.

The enzymatic treatment of banana fibre has shown promising results in enhancing its textile properties. These improvements include increased surface smoothness, strength, and spinnability, making the fibre more suitable for yarn and cloth production. Further research in this area could lead to the development of more efficient and sustainable processes for utilizing banana fibre in the textile industry.

Pacakaging material

With the growing global demand for biodegradable packaging solutions, banana fibre has emerged as a promising, sustainable, and eco-friendly alternative to conventional synthetic materials. Due to its natural composition including cellulose, hemicellulose, pectin, and lignin banana fibre offers enhanced ultraviolet protection (UPF) and weather resistance, as these components function as natural UV absorbers. Additionally, its higher moisture content contributes to the natural preservation of food products. In a study by Manickam and Kandhavadivu (2022) [26], a nonwoven packaging material was developed using banana fibre through the needle punching technique. This material was evaluated for its effectiveness in preserving perishable fruits and vegetables. The findings indicated that the banana fibre-based packaging extended the shelf life of nearly all tested produce by approximately 1 to 5 days, highlighting its potential suitability for use in the international export of fresh agricultural products.

Sathasivam *et al*. (2010) [43] prepared composite films composed of banana pseudostem fibre and polyvinyl alcohol (PVA) and evaluated for their physical properties. The study demonstrated that increasing the fibre content enhanced the physical performance of film while simultaneously reducing their swelling capacity compared to pure PVA films. Based on these findings, the authors proposed that such fibre-reinforced composite films hold potential as sustainable alternatives to conventional food packaging materials.

Medicinal use

Recently the development of biodegradable polymers has garnered considerable attention within materials science, particularly due to their ecological benefits and potential biomedical applications. In this context, Kalita *et al*. (2018) [21] explored the innovative use of banana pseudostem (*Musa balbisiana*) to fabricate a novel suture biomaterial. Addressing the critical need for infection-resistant surgical materials, the researchers developed an advanced antimicrobial releasing suture by integrating therapeutic agents such as chloramphenicol, clotrimazole, and specific growth factors into banana fibre using a hydrogel-based delivery system.

The resulting surface modified suture exhibited high tensile strength and favorable physicochemical properties aligned with the requirements of an ideal biomedical suture. It demonstrated excellent biocompatibility and sustained drug release capabilities for up to 144 hours. Moreover, the suture showed notable antimicrobial activity against common pathogenic microorganisms, including *Staphylococcus aureus*, *Escherichia coli*, and *Candida* *albicans*, under both *in vitro* and *in vivo* conditions. In addition to its biomedical efficacy, the eco-friendly nature and straightforward fabrication process of this banana fibre-based suture make it a promising candidate for sustainable medical applications.

Paper and pulp industry

Banana fibre has demonstrated significant potential as a raw material for paper production due to its high cellulose content and comparatively lower levels of hemicellulose and lignin when compared to other non-wood sources. This unique composition makes it suitable for manufacturing various types of paper, including currency paper, cheque paper, writing paper, and anti-grease paper. Remarkably, paper produced from banana fibre is known to have a shelf life exceeding 100 years and is currently utilized in the production of Japanese Yen notes. In efforts to promote sustainable packaging, plastic wrapping materials can also be replaced with banana fibre-based wrapping paper. A study by Ramdhonee and Jeetah (2017) [40] evaluated the applicability of banana fibre for wrapping paper production and found that paper made entirely from banana fibre exhibited superior absorbency and abrasion resistance.

Furthermore, the incorporation of 20% wastepaper into banana fibre enhanced key mechanical properties, including tensile strength and burst index, making it suitable for high-quality paper products. A patent has been granted for the development of both premium-grade paper and currency paper derived from banana fibre. The adoption of enzyme-assisted, eco-friendly production methods has also attracted research interest. Notably, xylanase enzymes derived from *Bacillus subtilis* (Manimaran & Vatsala, 2007) [27] and *Aspergillus oryzae* (Pratibha *et al*., 2017) [37] have been employed in the bio-bleaching of banana fibre pulp, resulting in marked improvements in the optical and mechanical properties of the final product. This enzymatic treatment helps reduce the need for harsh chemicals traditionally used in pulp bleaching, thereby minimizing environmental pollution. Additionally, the fine and long fibres of banana contribute to the smooth texture and high durability of the finished paper. These qualities make banana fibre-based paper not only sustainable but also competitive with conventional paper in terms of performance and longevity.

The versatility of banana fibre in paper production extends beyond currency and wrapping materials, with potential applications in various industries. Its eco-friendly nature and durability make it an attractive alternative to traditional wood-based paper products. Ongoing research into enzymatic treatments, such as those using xylanase from different microbial sources, continues to improve the quality and efficiency of banana fibre paper production.

Absorbent of oil and chemical dyes

An attempt is made by Teli and Valia (2013) [46], to provide an efficient and easily deployable method for oil spill cleanup and oil recovery, acetylated banana fibre has been investigated as a sustainable sorbent material. The acetylation process significantly enhanced the oil sorption capacity of the banana fibre, surpassing that of conventional synthetic sorbents such as polypropylene, as well as unmodified natural fibres. These findings suggest that oil sorbents derived from biodegradable banana fibre represent a promising alternative to non-biodegradable synthetic materials for environmental remediation applications, particularly in oil spill management.

In the work conducted by Rahman *et al*. (2022) [39], pseudostem banana (*Musa acuminata*) (PBF) fibre was utilized as a potential low-cost natural adsorbent to uptake methylene blue (MB) dye from synthetic wastewater by batch adsorption process. Various adsorption parameters such as initial dye concentration, solution pH, contact time, and adsorbent dosage were optimized to maximize the removal efficiency of methylene blue (MB) using banana pseudostem fibre-based adsorbents (PBF/MB). The results indicated that an increase in the initial dye concentration led to a decrease in the percentage of dye removal from the aqueous solution. In contrast, the adsorption efficiency improved with longer contact time and higher adsorbent dosages, demonstrating the significance of these factors in enhancing dye separation performance.

The utilization as a biosorbent can be further expanded as a feedstock in wastewater treatment. Chemical modification on banana fibre enhanced the surface area and biosorption capacity which resulted in the higher percentage removal of color and metal ions (Rosli and Jalil, 2022) [42]. This improvement is primarily due to the removal of non-cellulosic components (such as lignin, hemicellulose, and waxes) and the introduction or exposure of reactive sites like hydroxyl, carboxyl, and amino groups on the fibre surface. These functional groups have a high affinity for binding with pollutants such as dyes and heavy metal ions through mechanisms like ion exchange, complexation, and hydrogen bonding. Additionally, increasing the surface area provides more active sites for adsorption, allowing for greater interaction between the biosorbent and contaminants in the wastewater. As a result, chemically modified banana fibre exhibits significantly improved biosorption capacity, leading to a higher percentage removal of colorants and toxic metal ions such as lead, cadmium, and chromium. This makes it a cost-effective, eco-friendly, and efficient material for wastewater purification applications.

Banana fibre reinforced composites as thermoset plastic appliances

Fibre-reinforced thermosetting composites offer significant advantages due to the reinforcement materials enhancing both the strength and toughness of the plastic matrix. In a study conducted by Neelamana *et al*. (2013) [30], the morphological and surface characteristics of banana fibres (BFs) in macrofibrillated, microfibrillated, and nanostructured forms were examined to assess their influence on the mechanical performance of phenol formaldehyde (PF) composites. The results demonstrated a notable improvement in thermal stability from macrofibres to nanofibres, confirming the superior thermal resistance of the nanostructured form. Additionally, mechanical properties such as tensile strength, flexural strength, and impact strength of the BF-reinforced PF composites showed significant enhancement, with even small quantities of banana-derived cellulose nanofibres contributing to substantial improvements in these metrics.

Further research by Benítez *et al*. (2013) [11] indicated that treating banana fibres with sodium hydroxide under saturation pressure conditions can enhance thermal stability without considerably altering mechanical behaviour. Moreover, comparative analyses by Vijaya *et al*. (2013) [51] revealed that banana fibre composites possess superior flexural and impact strength compared to hybrid composites made from banana and flax fibres. These enhanced properties highlight the suitability of banana fibre-reinforced thermosetting composites for high-performance applications, including in the manufacturing of electrical equipment casings such as voltage stabilizers, projectors, and mirror housings where mechanical strength and thermal durability are essential.

Banana fibre-reinforced materials for constructions

The effect of banana fibre length on the mechanical performance of Green Compressed Earthen Blocks (GCEBs) was examined by Mostafa and Uddin (2015) [28], providing valuable insights into how fibre reinforcement can influence the compressive and flexural strength of earthen construction materials. The study highlighted that various factors including soil composition, fibre content, chemical stabilization using ordinary Portland cement, compaction effort and curing conditions collectively affect the mechanical strength of GCEBs. Among the tested samples, blocks reinforced with 50 mm banana fibres exhibited superior flexural and compressive strength compared to both unreinforced blocks and those reinforced with 25 mm fibres. Additionally, the presence of fibre within the matrix was found to delay and prevent sudden failure during the modulus of rupture test, indicating an enhancement in structural integrity due to fibre reinforcement.

In a related investigation, Kumar *et al*. (2008) [23] chemically modified banana fibres using alkali treatment and characterized them through techniques such as Fourier Transform Infrared (FTIR) spectroscopy, Scanning Electron Microscopy (SEM), Thermogravimetric Analysis (TGA), and Wide-Angle X-ray Diffraction (WXRD). The treated fibres were then used to develop composites with soy protein isolate (SPI) as the matrix, and their mechanical performance was evaluated based on fibre content and the nature of the matrix specifically, the use of plasticized SPI. The results demonstrated that alkali treatment significantly improved fibre-matrix adhesion and mechanical properties of the composites. These improvements suggest that banana fibre-reinforced SPI composites possess promising potential for application in the construction sector, offering a biodegradable and sustainable alternative to conventional building materials.

Banana fibre composites for automotive and transportation applications

Banana fibre has emerged as a promising reinforcement material for automotive applications, particularly in the production of car tires. Owing to its high tensile strength, low density, and biodegradability, banana fibre is being explored by manufacturers as a sustainable alternative to conventional synthetic reinforcements. Its lightweight nature and mechanical robustness make it suitable for reducing the overall weight of automotive components while maintaining structural integrity, thereby aligning with industry trends toward eco-friendly and sustainable materials. (Boopalan *et al*., 2013) [12]. Natural fibre-reinforced fibre metal laminate for automotive components may reduce vehicle weight and subsequently reduce the overall vehicle CO_2 gas emissions (Ishak *et al*., 2016) [19]. Thus, the use of natural fibre is improving rapidly due to the fact that the field of application is improved day by day especially in automotive industries.

Making tea bags: By incorporating banana fibre, manufacturers can create environmentally friendly and compostable tea bags, highlighting its versatility and sustainability for various applications as part of banana fibre uses. The fibre is crafted into a mesh-like material that permits water to pass through while keeping the tea leaves contained. This alternative to conventional tea bags made from paper or plastic is eco-friendlier and sustainable. (Ali and Karale, 2022)

Other applications

Banana pseudostem has several other uses, such as serving as a dye absorbent, a heavy metal absorber, a biofertilizer, and a substrate for growing mushrooms (Padam *et al*., 2014) [32]. The sap, which is the liquid derived from the banana pseudostem, can function as a color mordant, a liquid fertilizer, and a nutrient spray solution for fruit and vegetable crops. Additionally, the scutcher waste produced during fibre extraction can be utilized as vermicompost and organic fertilizer. (Akinyemi and Dai, 2020) [2].

The growing global emphasis on sustainability has led to an increased demand for eco-friendly materials, including banana fibre, as consumers and brands alike become more environmentally conscious. This shift has opened new avenues in various industries, particularly in fashion, where the distinctive texture and aesthetic qualities of banana fibre provide opportunities for innovative design. Designers are increasingly exploring blends of natural fibres and incorporating banana fibre into their collections to create distinctive, sustainable fashion products. Moreover, the production of banana fibre presents meaningful opportunities for collaboration with local communities in banana-growing regions. By engaging these communities in fibre extraction and processing, the industry not only supports sustainable economic development but also contributes to the preservation of traditional textile techniques, fostering both cultural heritage and environmentally responsible practices.

Conclusion

After the harvest of banana bunch, the pseudostem is often discarded, yet it serves as a rich source of high-quality fibre. The method used to extract the fibre significantly influences both its quality and quantity. Utilizing banana fibre for various industrial purposes opens up new avenues for academic and industrial exploration of its potential uses. The fibre content and strength are crucial factors that determine its suitability for specific applications. Due to its high cellulose and low lignin content, banana fibre is particularly well-suited for the pulp and paper industry, which is known for its environmental impact. Additionally, banana fibre have excellent absorption and strength properties make it a promising alternative to plastic in the production of sanitary pads, which are currently significant pollutants. Thus, banana fibre presents an eco-friendly and cost-effective substitute for synthetic fibres. However, the main challenges in commercializing banana fibre involve the efficient and environmentally friendly extraction of quality fibre from the pseudostem on a large scale. Most research is currently confined to laboratory settings, necessitating further development for industrial application. Future areas for banana fibre exploration include eco-friendly, plastic-free N, PPE kits,95-type masks sustainable clothing, carry bags, mattresses, carpets, art and craft design. Its potential use in capsule coatings for medicinal research also need further investigation.

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