Annals of Phytomedicine 15(1): 531-540, 2026

DOI: http://dx.doi.org/10.54085/ap.2026.15.1.46

Annals of Phytomedicine: An International Journal
http://www.ukaazpublications.com/publications/index.php

Print ISSN : 2278-9839 Online ISSN : 2393-9885

Review Article : Open Access

Microbial enzyme-assisted sustainable retting of banana (*Musa* spp.) pseudostem fibres: Advances in lignocellulosic bioprocess technologies

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Article Info

Article history
Received 9 May 2026
Revised 12 June 2026
Accepted 13 June 2026
Published Online 30 June 2026

Keywords
Banana pseudostem fibre
Biological retting
Microbial enzymes
Pectinase
Sustainable fibre processing
Circular bioeconomy

Abstract

Banana (*Musa* spp.) pseudostem, an abundant agricultural residue, represents a promising renewable resource for the production of sustainable natural fibres. However, efficient extraction and softening of banana fibre remain challenging due to the complex lignocellulosic matrix composed of cellulose, hemicellulose, pectin, and lignin. Conventional mechanical and chemical retting methods often suffer from high energy demand, environmental pollution, fibre damage, and poor process sustainability. In this context, microbial-mediated enzymatic retting has emerged as an eco-friendly and selective alternative for processing banana fibre. This review critically examines the roles of microorganisms and their enzymes, including cellulases, pectinases, hemicellulases, xylanases, and lignin-modifying enzymes, in fibre retting and softening. The mechanisms of enzymatic degradation of non-cellulosic components and their impact on fibre morphology, crystallinity, mechanical properties, and quality are discussed in detail. Recent advancements that integrate biological retting with innovative physical pretreatments, including sludge impregnation, steam explosion, microwave-assisted degumming, and ultrasonic treatment, are highlighted for their ability to enhance enzymatic accessibility, reduce processing time, and minimize chemical use. The review also compares fungal, bacterial, actinomycete, yeast, and microbial consortia-based retting systems, emphasizing their efficiency and sustainability. Overall, microbial-mediated enzymatic retting is positioned as a viable, green, and scalable strategy for transforming banana pseudostem waste into high-value fibres, supporting circular bioeconomy and sustainable material development.

1. Introduction

Growing environmental concerns and the urgent need for sustainable material solutions have driven the development and adoption of biomaterials across industries, including automotive, construction, and textiles. Heightened awareness of ecological degradation has triggered a paradigm shift from petroleum-based synthetic fibres toward biodegradable and renewable natural fibres (Rajamanickam *et al.*, 2021). Natural fibres are broadly classified into plant, animal, and mineral-based fibres, with plant fibres being the most widely utilised due to their abundance, renewability, and favourable mechanical properties. Plant-derived natural fibres are further categorised into seed, bast, leaf, core, grass, and reed fibres (Rowell, 2008). Among plant-based fibres, banana fibre has emerged as one of the strongest and most promising natural fibres, which is derived from the pseudostem of the banana plant. Banana fibre is highly resilient, biodegradable, and suitable for textile and technical applications. The banana plant produces textile-grade fibres of considerable strength and flexibility, yet remains largely underutilised. Global banana production is projected to increase at an annual rate of 1.5%, reaching approximately 135 million tonnes by 2028 (Kumari *et al.*, 2025), further highlighting the vast availability of banana biomass for value-added applications. In recent years, extensive research has focused on various natural fibres, such as coconut, jute, flax, hemp, kenaf, ramie, bamboo, napier grass, reeds, sisal, pineapple, kapok, and banana, particularly for their use as reinforcement materials in composite systems (Azman *et al.*, 2021). Despite this growing interest, banana biomass remains significantly underexploited (Arpitha *et al.*, 2023). It is estimated that nearly 114 million metric tonnes of banana waste are generated annually, with up to 60% of the total plant biomass, including pseudostems, leaves, and rachis, discarded after harvest (Acevedo *et al.*, 2021). The unmanaged decomposition of this biomass contributes substantially to greenhouse gas emissions, posing environmental challenges. The banana plant; however, represents a valuable reservoir of functional components, including fibres, cellulose, and other bioactive materials with potential applications in bioenergy, packaging, animal feed, and functional foods. The banana pseudostem is a lignocellulosic material primarily composed of cellulose embedded within a complex matrix of hemicellulose, pectin, and lignin. To enhance fibre quality, spinnability, and softness, it is essential to remove or loosen the non-cellulosic gummy constituents, thereby freeing individual cellulose bundles and improving fibre fineness and flexibility.

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Modern biological processing approaches utilise microbial cultures, such as fungi and bacteria, or their extracellular enzymes, including pectinase, cellulase, hemicellulase/xylanase, and laccase. These biological treatments operate under mild conditions, act selectively on specific components, and minimise fibre damage compared to conventional chemical methods, making them environmentally friendly and efficient alternatives for banana fibre extraction and modification (Badanayak *et al*., 2023).

2. Natural fibres with emphasis on banana fibre for sustainable composite applications

Natural fibres have gained significant attention as cost-effective, eco-friendly, and sustainable alternatives to synthetic reinforcements in composite fabrication (Raghunathan *et al*., 2024). Their increasing adoption is primarily driven by advantages such as low processing energy requirements, biodegradability, renewability, and low density, along with favourable mechanical properties including enhanced toughness, thermal, acoustic insulation, and improved flexural performance. These attributes make natural fibres highly suitable for environmentally responsible material development. Plant-derived natural fibres, in particular, have emerged as viable substitutes in lightweight manufacturing and engineering applications due to both economic and environmental benefits. Their lignocellulosic origin contributes to desirable characteristics such as biodegradability, recyclability, and non-abrasive behaviour. Additionally, natural fibres exhibit low density, high aspect ratio, and reduced energy consumption during processing, making them economically attractive alternatives to synthetic fibres (Mulla *et al*., 2025; Tengsuthiwat *et al*., 2024; Vigneshwaran *et al*., 2020). The performance of these fibres is largely governed by their chemical composition, which primarily includes cellulose, hemicellulose, lignin, pectin, waxes, ash, and moisture. Collectively, these constituents influence the mechanical, thermal, and durability characteristics of natural fibres. Key advantages of natural fibres include low cost, reduced density, renewability, and environmental compatibility (Hindi *et al*., 2025). Despite these benefits, natural fibres also present certain limitations, such as relatively lower mechanical strength compared to synthetic fibres, high moisture absorption, limited durability, and poor fire and thermal resistance. These drawbacks necessitate careful consideration during material selection and highlight the importance of appropriate fibre treatment, surface modification, and composite design strategies to enhance performance (Gholampour and Ozbakkaloglu, 2019). Among plant-based fibres, banana fibre is a natural bast fibre extracted from the pseudostem of the banana plant (Parameswaranpillai *et al*., 2023). It represents an abundant, cost-effective, and sustainable alternative to synthetic fibres owing to its low density, biodegradability, recyclability, and widespread availability. Chemically, banana fibre consists predominantly of cellulose (60-65%), hemicellulose (6-19%), lignin (5-10%), pectin (3-5%), and extractives (3-6%). The fibres obtained from the pseudostem are long, lustrous, and exhibit high tensile strength (Gupta *et al*., 2020). Due to their lignocellulosic structure, banana fibres demonstrate moderate stiffness and limited flexibility; however, these properties can be effectively tailored through suitable mechanical, chemical, or enzymatic treatments. Overall, the inherent strength, sustainability, and wide availability of banana fibres position them as promising materials for applications in textiles, composites, and other industrial sectors (Doshi and Karolia, 2016). The sequential stages involved in banana pseudostem processing for fibre extraction and value-added product development are depicted in Figure 1.

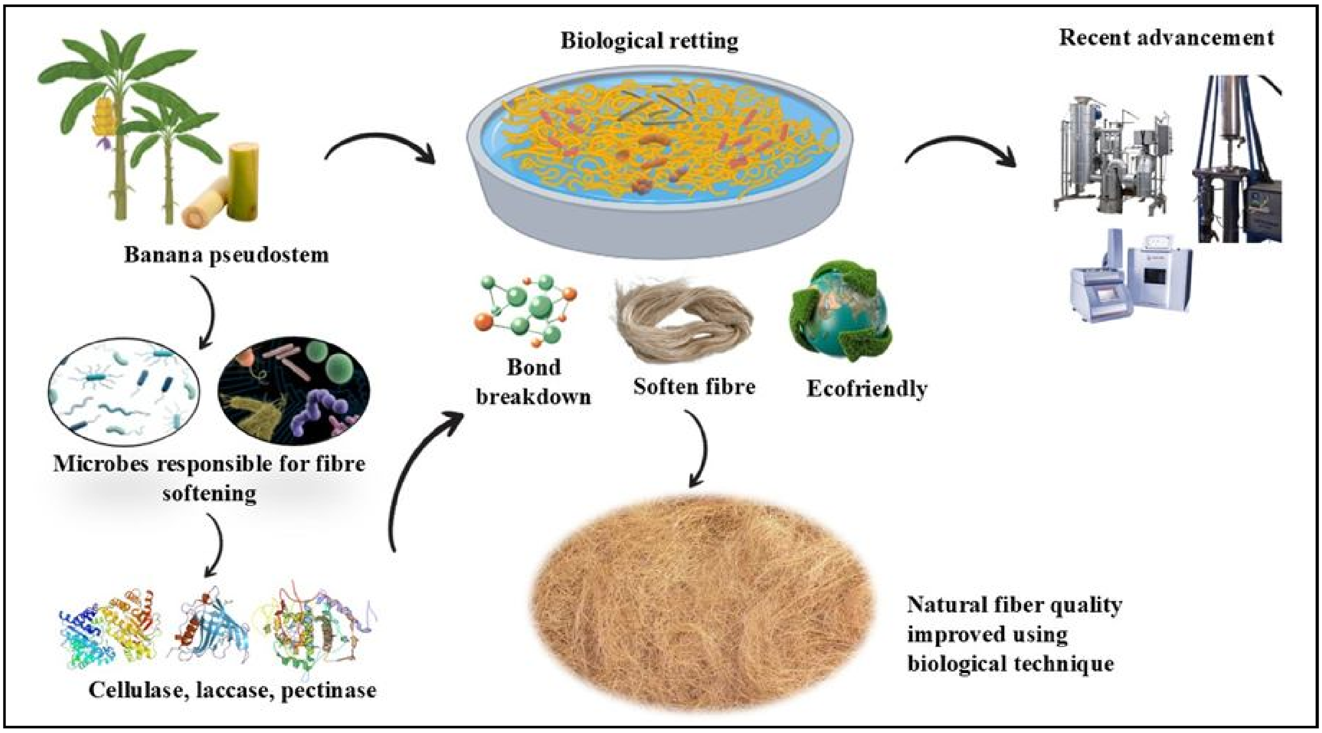

Figure 1: This figure shows banana (*Musa* spp.) pseudostem utilisation *via* biological retting. Microorganisms produce enzymes (cellulase, pectinase, laccase) that degrade cellulose, hemicellulose, lignin, and pectin, weakening fibre bonds and enabling separation (Prepared by us with the help of biorender software).

2.1 Impact of biological retting on phytochemical release and bioavailability

Banana (*Musa* spp.) pseudostem fibre obtained through biological or enzymatic retting is increasingly recognised as a sustainable lignocellulosic resource containing several valuable bioactive phytochemicals. Although, the primary constituents of processed banana fibre are cellulose, hemicellulose, and lignin, studies have reported the presence of important phytochemical compounds, including phenolic acids, flavonoids, tannins, phytosterols, and lignin-derived aromatic compounds. These bioactive constituents contribute significantly to antioxidant, antimicrobial, anti-inflammatory, and functional properties, thereby enhancing the value of banana pseudostem biomass beyond its traditional textile applications. Recent investigations have highlighted that banana pseudostem residues contain considerable quantities of total phenolics and flavonoids, making them promising sources of nutraceutical and functional biomaterials (Pillai *et al*., 2024).

Phenolic compounds represent one of the most important classes of phytochemicals identified in banana pseudostem materials. Several studies have reported the occurrence of gallic acid, ferulic acid, caffeic acid, p-coumaric acid, catechin, and epicatechin derivatives in banana by-products. These compounds function as potent antioxidants by scavenging reactive oxygen species and reducing oxidative stress. During biological retting, microbial enzymes such as laccases, cellulases, and pectinases facilitate the breakdown of lignin-carbohydrate complexes, which can release bound phenolic compounds and increase their bioavailability. Consequently, enzymatically processed fibres and retting liquors may exhibit enhanced antioxidant activity compared with untreated biomass (Hotor *et al*., 2024).

Flavonoids constitute another major group of beneficial phytochemicals associated with banana pseudostem biomass. Compounds such as quercetin, kaempferol, rutin, and myricetin have been reported in banana-derived residues and pseudostem products. These flavonoids are known for their antioxidant, antimicrobial, anti-inflammatory, and free radical scavenging activities. A recent phytochemical evaluation of banana pseudostem flour reported substantial flavonoid concentrations together with strong antioxidant potential, indicating that banana pseudostem-derived materials can serve as valuable sources of natural bioactive compounds (Yasaswini and Kamalaja, 2024).

Tannins and lignin-derived phenolic compounds are also important phytoconstituents present in banana pseudostem fibre systems. During microbial retting, partial degradation of lignin releases aromatic compounds such as vanillin, vanillic acid, syringaldehyde, and syringic acid. These compounds possess antioxidant and antimicrobial properties and may contribute to the improved functional characteristics of biologically processed fibres. The activity of ligninolytic microorganisms and enzymes, particularly laccase and manganese peroxidase, plays a crucial role in this depolymerisation process and in the generation of valuable phenolic metabolites (Hotor *et al*., 2024).

In addition to phenolics and flavonoids, banana pseudostem biomass contains phytosterols such as β-sitosterol, stigmasterol, and campesterol, which have been associated with cholesterol-lowering and anti-inflammatory effects. Furthermore, the fibre matrix itself is rich in cellulose, hemicellulose, residual pectin, and dietary fibre fractions that exhibit prebiotic and gut health-promoting properties. Recent reviews have emphasised that the valorisation of banana pseudostem waste can simultaneously support sustainable fibre production and the recovery of high-value bioactive compounds for food, pharmaceutical, and biomedical applications (Hotor *et al*., 2024).

3. Different methods of banana fibre extraction

The extraction of banana fibre is a critical step that significantly influences fibre quality, yield, and downstream applications and remains one of the major challenges in banana fibre processing. Several extraction techniques have been developed, including manual (hand-driven), mechanical, chemical, and biological methods. Each method differs in terms of efficiency, fibre quality, environmental impact, and suitability for large-scale production. While manual extraction is simple and cost-effective, mechanical methods offer higher productivity, whereas chemical and enzymatic approaches improve fibre surface and mechanical properties. Among these, microbial and enzymatic degumming methods are considered environmentally safe and sustainable alternatives (Badanayak *et al*., 2023; Paramasivam *et al*., 2020; Ezeamaku *et al*., 2022).

3.1 Hand-driven fibre extraction method

Manual or hand-driven fibre extraction is the oldest and most traditional method, commonly practised in rural and village settings. This method involves the use of simple, sharp tools such as knives, blades, or improvised cutting instruments to scrape fibres from the banana pseudostem. Although, highly labour-intensive and time-consuming, manual extraction yields relatively clean and high-quality fibres with minimal surface damage and fewer impurities. Despite its advantages in fibre quality, manual extraction produces only a limited quantity of fibre, typically around 4 kg per day, making it unsuitable for large-scale or industrial applications. The high labour requirement and low productivity significantly limit its commercial feasibility (Ganan *et al*., 2004).

3.2 Mechanical fibre extraction method

Mechanical extraction is widely adopted for large-scale banana fibre production due to its higher efficiency and reduced processing time. Long fibres are commonly extracted using a decorticator, a versatile machine originally designed for bast and leaf fibres such as ramie and banana (Basak *et al*., 2015). While the basic operating principle of decorticators remains consistent, variations in design exist depending on the manufacturer and the fibre type being processed (Jayaprabha *et al*., 2011; Parameswaranpillai *et al*., 2023). In this method, freshly harvested banana pseudostem sheaths are manually separated and fed into the decorticator. The machine typically consists of a high-speed rotating drum that mechanically beats the sheaths, removing non-fibrous material and separating fibre bundles. The extracted fibres are subsequently combed using metallic combs to remove residual pseudostem matter, followed by washing and drying. A substantial proportion of the pseudostem is converted into long fibres during this process (Uma *et al*., 2005). Mechanical extraction offers significantly higher productivity, yielding approximately 20-30 kg of fibre per day compared to manual methods (Jagadeesh *et al*., 2021). However, the intense hammering action can cause fibre damage, reducing fibre integrity at higher operating speeds. In contrast, manually extracted fibres retain superior mechanical characteristics, such as higher cellulose content and lower microfibrillar angle, which are largely preserved during hand extraction (Mohamed *et al*., 2023). Optimal operational conditions are critical for maximising fibre yield and quality. Studies have shown that extraction at moderate rotating speeds (around 650 rpm) provides the highest fibre yield within a relatively short extraction time. Although, higher speeds (750-850 rpm) further reduce processing time, they result in lower fibre recovery due to increased fibre breakage. Overall, mechanical extraction at optimised speeds offers a clear advantage over manual extraction in terms of productivity and efficiency (Sheikh *et al*., 2016). It is also important to note that decortication must be performed immediately after harvesting, as dried pseudostem sheaths cannot be processed effectively. Additionally, most decorticators operate in batch mode, allowing only one sheath to be processed at a time.

3.3 Chemical fibre extraction method

Chemical extraction methods primarily involve alkali treatment to remove non-cellulosic components and improve fibre surface characteristics. Sodium hydroxide (NaOH) is the most commonly used alkali, as it effectively reduces fibre roughness and enhances mechanical performance. Other chemical agents such as protease, pectinase, sulphuric acid, hydrogen peroxide, and sodium citrate have also been explored for fibre extraction and modification (Sheikh *et al*., 2016, and Raghunathan *et al*., 2023). In a typical chemical extraction process, raw banana fibres are treated with 6% NaOH solution for 24 h, followed by neutralisation with dilute acetic acid, washing until neutral pH is achieved, and sun drying for approximately 72 h. Compared to untreated fibres, alkali-treated fibres exhibit reduced diameter (from 0.233 to 0.189 mm), increased density (from 1.23 to 1.35 g/cc), and significantly improved mechanical properties. Notable enhancements include higher tensile strength (266 to 487 MPa), Young's modulus (19.3 to 28.7 GPa), and elongation at break (6.5% to 10.1%), while fibre length remains largely unchanged (30-50 mm). These improvements indicate that alkali treatment enhances fibre strength, stiffness, and flexibility (Nensok *et al*., 2021). Despite these benefits, chemical extraction has several limitations. The process is time-consuming, often requiring 35-40 days to obtain high-quality fibres, and is associated with high costs and significant chemical waste generation. These drawbacks limit its environmental sustainability and large-scale applicability (Sheikh *et al*., 2016).

3.4 Biological method of banana fibre extraction and softening

Biological fibre extraction, also referred to as microbial or enzymatic retting, is an environmentally benign and sustainable alternative to conventional mechanical and chemical extraction methods. This approach employs selected microorganisms or their extracellular enzymes to selectively degrade non-cellulosic binding components in the banana pseudostem under mild processing conditions, thereby facilitating fibre separation while preserving fibre integrity (Jacob *et al*., 2006; Badanayak *et al*., 2023). Several microorganisms, including *Aspergillus niger*, *Trichoderma* spp., and *Bacillus* spp., are widely used for banana fibre softening and retting (Vellaichamy *et al*., 2017; Patel *et al*., 2022). These microbes produce key lignocellulolytic enzymes such as pectinase, cellulase, hemicellulase, and laccase, which collectively loosen fibre bundles, remove gummy substances, and enhance fibre flexibility, fineness, and surface smoothness (Badanayak *et al*., 2023). Unlike chemical methods, microbial and enzyme-assisted extraction avoids harsh reagents, reduces fibre damage, and minimises environmental pollution. In microbial retting, banana pseudostems are submerged in water inoculated with microbial consortia and incubated for a minimum of seven days. During this period, microorganisms secrete multiple enzymes that degrade pectin, hemicellulose, and partially degrade lignin, enabling the release of individual fibres. Biological treatment has been reported to improve fibre uniformity, gloss, and overall quality, while also increasing fibre yield (Patel *et al*., 2022). The molecular structure of cellulose, lignin, and pectin is represented in Figures 2, 3, and 4

3.4.1 Role of cellulolytic enzymes from microorganisms in fibre softening

Cellulose-degrading microorganisms play an important role in controlled fibre softening. Cellulases hydrolyse β-1,4-glycosidic linkages in cellulose, enabling partial loosening of fibre structure without excessive degradation. These enzymes are produced by diverse bacteria, fungi, and actinomycetes, including *Bacillus* spp., *Cellulomonas* spp., *Streptomyces* spp., *Ruminococcus* spp., *Clostridium* spp., *Pseudomonas* spp., and *Staphylococcus* spp. (Bhatia *et al*., 2024). Cellulolytic bacteria can be broadly classified into three physiological groups: (i) aerobic Gram-positive bacteria such as *Cellulomonas* and *Thermobifida*; (ii) aerobic gliding bacteria such as *Cytophaga* and *Sporocytophaga*; and (iii) anaerobic fermentative bacteria, mainly Gram-positive genera such as *Clostridium* and *Ruminococcus*, along with a few Gram-negative types such as *Fibrobacter* and *Acetivibrio* (Bhati *et al*., 2020) In enzymatic hydrolysis, endoglucanases and exoglucanases act synergistically to depolymerise cellulose into cello-oligosaccharides, which are subsequently converted into glucose by β-glucosidase (Sindhu *et al*., 2015) Controlled cellulase activity is crucial in banana fibre processing to prevent excessive fibre weakening.

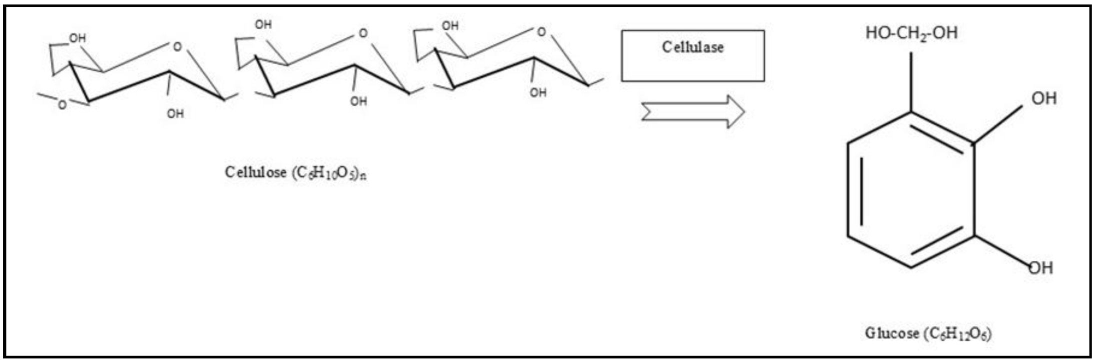

Figure 2: Enzymatic hydrolysis of cellulose.

3.4.2 Microbial degradation of lignin during fibre processing

Lignin is a highly complex, cross-linked aromatic polymer that binds cellulose and hemicellulose, imparting rigidity and resistance to degradation in banana fibres. Structurally, lignin is composed of three primary monolignols: p-coumaryl alcohol, coniferyl alcohol, and sinapyl alcohol, forming a three-dimensional phenolic network (Vanholme *et al*., 2008). Due to its recalcitrant nature, lignin limits fibre accessibility and processing efficiency. Various microorganisms, particularly bacteria and fungi, are capable of lignin degradation through specialized oxidative enzyme systems (Atiwesh *et al*., 2021; Weng *et al*., 2021). Ligninolytic bacteria such as *Streptomyces*, *Sphingomonas*, *Rhodococcus*, *Nocardia*, and *Comamonas* species produce extracellular peroxidases that partially degrade lignin during lignocellulose processing (Raj *et al*., 2006; Yadav *et al*., 2022; Datta *et al*., 2017). Fungal lignin degradation has been more extensively studied and is considered more efficient than bacterial degradation. White-rot, brown-rot, and soft-rot fungi secrete powerful ligninolytic enzymes, including laccases and peroxidases, which modify or depolymerise lignin. Species belonging to Ascomycetes (*e.g., Trichoderma reesei*) (Ferrari *et al*., 2021; Zhu *et al*., 2017) and Basidiomycetes (*e.g., Phanerochaete chrysosporium*) are particularly effective in lignin transformation during fibre retting (Martínez *et al*., 2005; Janusz *et al*., 2017; Zhou *et al*., 2025)

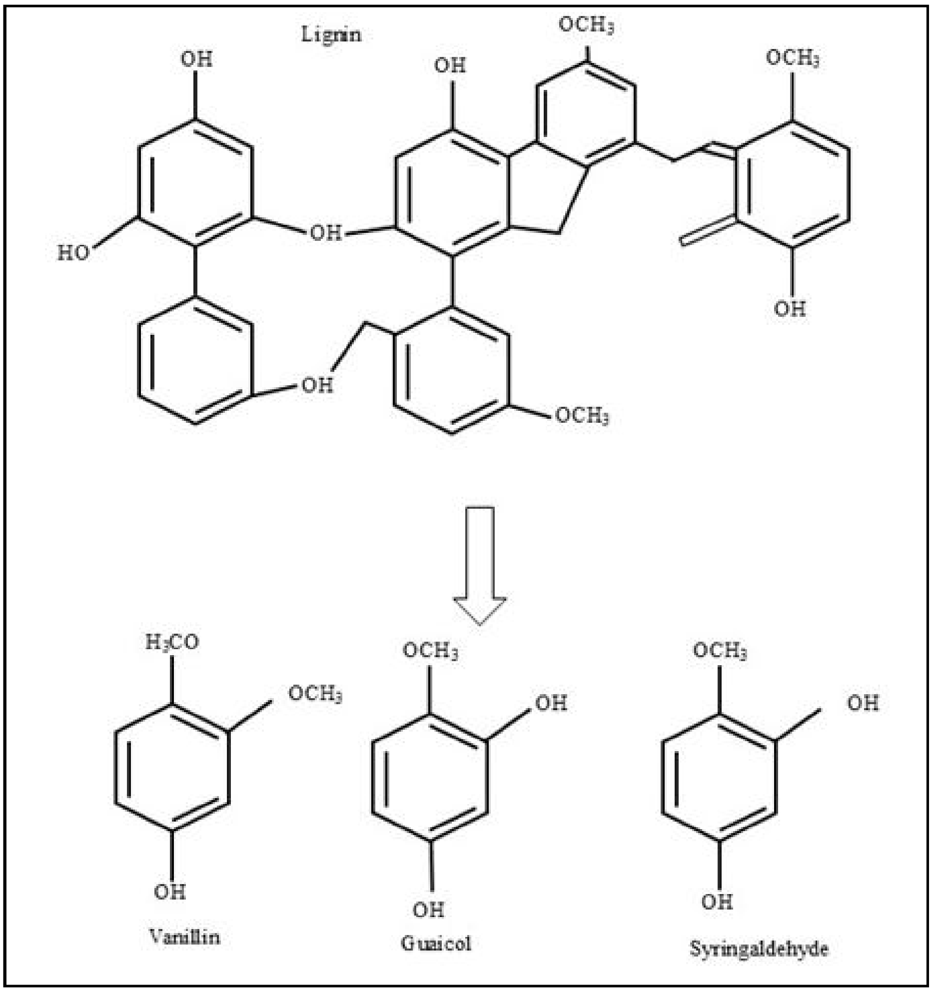

Figure 3: Enzymatic hydrolysis of lignin.

3.4.3 Enzymatic degradation of pectin in banana fibre retting

Pectin acts as a cementing material that binds fibre bundles in the banana pseudostem. It is a complex polysaccharide predominantly present in plant cell walls, especially in dicotyledonous plants (Yuksel *et al*., 2024a; Yuksel *et al*., 2024b). Due to its structural complexity and variability, enzymatic degradation is preferred over chemical methods for selective pectin removal (Khattab *et al*., 2022). Microbial pectinases play a critical role in banana fibre biosoftening by depolymerising pectin under mild conditions, thereby facilitating fibre separation and improving flexibility and surface smoothness. Common pectinolytic microorganisms include *Bacillus* spp., *Aspergillus niger*, *Aspergillus awamori*, *Penicillium restrictum*, *Mucor piriformis*, and yeast-like species such as *Dioszegia* spp., *Phenoliferia glacialis*, and *Tetracladium* spp. (Carrasco *et al*., 2019; Weng *et al*.,2021 and Haile *et al*.,2022)

The microbial-mediated enzymatic retting offers a controlled, eco-friendly, and efficient strategy for banana fibre extraction and softening, producing fibres with improved flexibility, uniformity, and quality while minimising environmental impact. Microbial-mediated enzymes involved in banana fibre softening and retting, the target fibre components, the specific enzymes responsible for degradation, the major microbial groups, and the representative microorganisms employed are represented (Table 1). Collectively, these microbial-enzymatic systems enable the selective degradation of binding materials, improve fibre softness and flexibility, and enhance overall fibre quality in an environmentally sustainable manner.

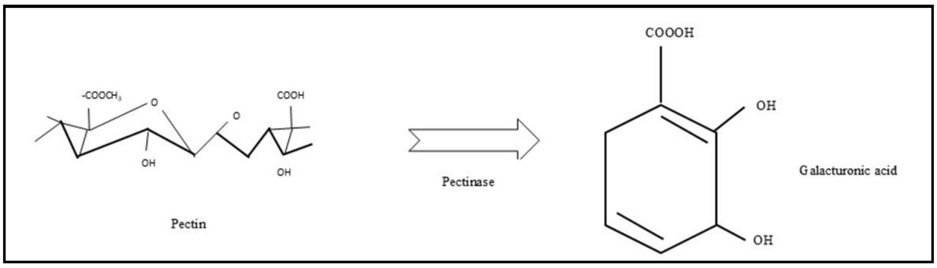

Figure 4: Enzymatic hydrolysis of pectin.

Table 1: Microbial-mediated enzymes used for the banana softening/retting process

Target fibre components	Enzyme involved for softening /retting	Microbial group	Microorganism (s)	References involved
Cellulose and pectin	Cellulase and pectinase	Fungi	*Aspergillus niger*	Manjusha *et al.*, 2023
Cellulose, pectin, and lignin	Cellulase, pectinase, and laccase	Fungi	*Aspergillus niger*	Vellaichamy *et al.*, 2017
Cellulose	Cellulase	Bacteria	*Staphylococcus sciuri*	Sharma *et al.*, 2021
Cellulose and lignin	Cellulase and laccase	Bacteria	*Bacillus aryabhattai, Bacillus licheniformis, and Bacillus Subtilis*	Patel *et al.*, 2022
Cellulose	Endoxylanase	Fungi	*Thermomyces lanuginosus*	Hindi *et al.*, 2025
Cellulose	Cellulase	Actinomycetes	*Thermobifida halotolerans*	Yang *et al.*, 2004
Hemi cellulose,	Hemicellulases,			
pectin, and lignin	pectinases, and laccases	Consortium (Bacteria)	*Bacillus cereus, B. licheniformis, B. subtilis, and B. polymyxa*	Balda *et al.*, 2021
Hemicellulose and Pectin	Xylanase and Pectinase	Actinomycetes	*Actinomadura* spp., *Streptomyces* spp., and *Streptomyces lydicus*	Sathya *et al.*, 2012; Mukhtar *et al.*, 2017 and Jacob *et al.*, 2006
Lignin	Laccase	Fungi	*Aspergillus niger, Penicillium citrinum, Fusarium oxysporum*	Sarma *et al.*, 2025
Pectin and xylane	Pectinase and xylanase	Bacteria	*Enterobacter cloacae*	Subash *et al.*, 2022
Pectin	Pectinase	Endophytic	*Exiguobacterium acetylicum, Exiguobac-*	Sharma *et al.*, 2021
		bacteria	*terium indicum*	
Pectin	Pectinase	Fungi	*Phoma herbarum, Aspergillus niger, Penicillium purpurogenum*	Sarma *et al.*, 2025
Pectin	Polygalacturonase	Fungi	*Aspergillus niger*	Hindi *et al.*, 2025
Pectin	Pectinase	Yeast	*Yarrowia phangngaensis*	Ezeh *et al.*, 2023
Pectin	Polygalacturonase	Actinomycetes	*Streptomyces lydicus*	Jacob *et al.*, 2006
Pectin	Polygalacturonase	Bacteria	*Thalassospira frigidphilosprofundus*	Rekha *et al.*, 2013

4. Recent advances in banana fibre softening and degumming

Recent years have witnessed substantial progress in the development of fibre softening and degumming technologies for banana pseudostem fibres, aimed at improving fibre flexibility, spinnability, and end-use performance. Conventional approaches such as mechanical, chemical, enzymatic, and microbiological methods have been widely explored, each offering specific benefits and limitations. Mechanical extraction methods, although simple and cost-effective, often leave behind residual non-cellulosic components that adversely affect fibre quality. Chemical pretreatments, including alkali and acid delignification, are effective in removing lignin and hemicellulose; however, they are energy-intensive and generate environmentally hazardous effluents (Manjusha *et al.*, 2023). Enzymatic delignification provides greater selectivity and minimises cellulose damage, but its industrial applicability is constrained by high enzyme costs, limited stability, and scalability issues (Shirkavand *et al*., 2015). In this context, microbial-mediated enzymatic softening has emerged as one of the most promising recent advancements and a viable future alternative for sustainable banana fibre processing. Microbial systems offer a controlled and eco-friendly approach by selectively degrading non-cellulosic binding components under mild conditions, thereby preserving cellulose integrity while enhancing fibre softness and mechanical properties. Beneficial microorganisms such as *Bacillus subtilis* are widely used for their ability to secrete synergistic enzyme systems, including cellulases, pectinases, hemicellulases, and lignin-modifying enzymes, which effectively remove pectin, lignin, and hemicellulose from the fibre surface (Liang *et al*., 2025).

4.1 Advances in lignocellulosic bioprocess technologies

Recent studies have further demonstrated the potential of enzyme-assisted microbial consortia and sludge-based retting systems, which utilise naturally occurring microbial communities rich in lignocellulolytic activities. Activated sludge retting, described as a "waste-to-treat-waste" bioprocess, enables the synergistic degradation of hemicellulose and lignin without the need for additional chemical inputs, thereby reducing energy consumption and effluent generation (Harsanyi *et al*., 2025). Optimisation studies using statistical designs such as Box-Behnken have reported significant improvements in fibre tensile strength, elasticity, and elongation. Structural and thermal analyses (Scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), Thermogravimetric analysis and differential thermogravimetry (TGA-DTG) confirmed efficient removal of non-cellulosic materials and enhanced cellulose crystallinity, supporting the suitability of biologically softened fibres for applications in bio-composites, packaging, geotextiles, and speciality papers (Liang *et al*., 2025). Although, scale-up through continuous-flow systems appears feasible, further research on microbial community dynamics and process control is required for consistent industrial implementation. Alongside biological methods, several green physical pretreatment techniques have gained attention as complementary or alternative fibre softening strategies. Steam explosion is a chemical-free process in which chopped banana stems and leaves are subjected to high-pressure steam followed by rapid decompression. This technique effectively removes more than 90% of pectin and hemicellulose, partially disrupts lignin, and enables clean fibre bundle separation without environmental pollution (Behera *et al*., 2014). The loosened fibre structure enhances subsequent bleaching, oiling, and softening steps, resulting in improved fibre yield and quality.

Microwave-assisted degumming represents another emerging physical-thermal pretreatment method. In this approach, pre-soaked fibres absorb microwave energy through polar water molecules, leading to selective internal heating. This localised heating promotes fibre swelling and efficient disruption of gum components while minimising damage to the cellulose structure (Li *et al*., 2020). Similarly, ultrasonic-assisted treatment employs high-frequency sound waves to generate cavitation at the fibre surface, enhancing liquid penetration and chemical accessibility. When combined with mild alkali pretreatment, ultrasonication significantly accelerates gum removal, improves fibre fibrillation, and promotes individualisation of vascular bundles, thereby refining fibre quality (Bang *et al*., 2010; Twebaze *et al*., 2022; Akhila *et al*., 2025; and Rana *et al*., 2023). While physical and hybrid methods contribute to process intensification, microbial-mediated enzymatic softening stands out as the most sustainable and future-ready approach for processing banana fibre. Ongoing advances in enzyme engineering, microbial consortia design, and process optimisation are expected to overcome existing limitations related to cost and scalability. As environmental regulations become stricter and demand for green materials increases, biologically driven fibre softening is poised to play a central role in next-generation banana fibre valorisation.

5. Conclusion

Recent advances in banana fibre retting and softening have highlighted the significant potential of innovative green pretreatment technologies, including sludge impregnation, steam explosion, microwave-assisted degumming, and ultrasonic treatment. These physical pretreatment strategies effectively disrupt the lignin-pectin matrix and loosen fibre bundles, thereby enhancing fibre accessibility and improving the efficiency of subsequent microbial and enzymatic retting processes. When integrated with targeted microbial consortia and enzyme-specific formulations, these approaches facilitate the selective removal of non-cellulosic components while preserving cellulose integrity. Consequently, such integrated systems substantially reduce chemical consumption, wastewater toxicity, and energy requirements compared with conventional chemical retting methods, making them highly promising for sustainable and environmentally responsible industrial applications.

Looking forward, advances in lignocellulosic bioprocess technologies are expected to significantly transform banana fibre retting by enabling more efficient, sustainable, and environmentally friendly processing strategies. The integration of microbial-mediated enzymatic retting with eco-friendly physical pretreatments and advanced bioprocessing approaches offers considerable potential for improving lignin and hemicellulose removal while preserving fibre quality. Future research should focus on optimising bioprocess parameters, enhancing the stability and catalytic efficiency of microbial strains and enzyme formulations, developing cost-effective multi-enzyme systems, and integrating process intensification strategies for industrial-scale applications. Furthermore, innovations in synthetic biology, metabolic engineering, systems biology, and engineered microbial consortia are expected to facilitate the development of highly efficient lignocellulose-degrading platforms. Comprehensive techno-economic analyses and life-cycle assessments will also be essential for evaluating the commercial viability, scalability, and environmental sustainability of these next-generation lignocellulosic bioprocess technologies in banana fibre processing.

Overall, the strategic utilisation of banana pseudostem waste through advanced green retting technologies presents significant opportunities for both academia and industry. Continued interdisciplinary research and industry-academia collaboration will be instrumental in unlocking the full potential of banana fibre, enabling its transition from an underutilised agricultural residue to a high-value, sustainable material supporting circular and climate-smart manufacturing systems.

Acknowledgements

Authors are thankful and acknowledge researchers of the original research works whose publications are cited in the present review, and also acknowledge the Biorender.com tool to customise the figure of banana (*Musa* spp.) pseudostem utilisation *via* biological retting.

We did receive funds from the State Government (DBT GOI INDIA, Award Number: No.BT/PR51773/NER/95/2111/2024|Recipient: Sabarinathan.K.G.) to conduct this study.

Conflict of interest

The authors declare no conflicts of interest relevant to this article.

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Citation **Harini Andavar, K.G. Sabarinathan, K.Kumutha, M. Gomathy, C. Ravindran, T. Susikokila and Jayapratha Chokkalingam (2026). Microbial enzyme-assisted sustainable retting of banana (*Musa* spp.) pseudostem fibres: Advances in lignocellulosic bioprocess technologies. Ann. Phytomed., 15(1):531-540, http://dx.doi.org/10.54085/ap.2026.15.1.46.**