

RESEARCH PAPER

Improvement in Banana Fibre Quality through Enzymatic, Chemical and Physical Modifications

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ABSTRACT

Banana fibre is an annually renewable material that is available approximately 412.6 million tonnes each year, produced from the pseudostem of banana plant. Extracted raw fibre consists of 60–65% cellulose and the remaining 35–47% consists of pectin, hemicellulose, lignin and wax. Fibre without any modification remains inadequate for manufacturing value-added textiles. To make the fibre amenable for textile, three important modification processes namely chemical (alkali), physical (boiling or ultrasonication) and enzymatic (pectinase, xylanase, laccase) are mostly used. The advantages and disadvantages of individual process on the fibre quality enhancement along with a comparison among those processes has been summarized in details. More emphasis was given on fibre quality improvement in terms of fibre's fineness, strength, cellulose content, keeping in mind their environmental impact and scope of scalability. Mechanism of action of different types of enzymes was described on a specific substrate. Multi-enzyme system was found to yield better output, raising cellulose content to 84%, enhancing tensile strength by profoundly and reduction in fibre diameter. Hybrid process i.e., combination or sequential treatment of enzymatic and chemical processes could exhibit overall satisfactory results.

HIGHLIGHTS

- ① Enzymatic modification improved banana fibre fineness from 7.5 to 5.4 tex.
- ① Enzyme treatment reduced bundle strength marginally from 19.9 to 17.2 g/tex.
- ① Multi-enzyme treatment increased cellulose content from 54% to 84%.
- ① Enzymatic treatment reduced fibre diameter from 168 to 101 μm .
- ① Hybrid treatment achieved minimum fibre diameter of 49 μm .
- ① Enzymatic retting requires 40–60% less thermal energy than chemical processing.

Keywords: Banana fibre, Enzymatic retting, Chemical modification, Physical modification, Fibre quality

Cultivation of banana plants results in the generation large quantity of biomass i.e., approximately 412.6 million tons per year. Most of such banana biomass gets wasted, even though it contained cellulose rich good fibre that can be used for manufacturing textile, pulp & paper, composite, leather alternatives and handicraft items (Shivashankar *et al.* 2006, Chen *et al.* 2021; Samanta *et al.* 2023a; Samanta *et al.* 2023b; Basak *et al.* 2026; Chattopadhyay *et al.* 2020; Chattopadhyay *et al.* 2021a; Ray *et al.* 2012). India is one of the largest producers of banana with a

potential of approximately 1.5 million tons banana fibre, from the tentative 30 million tons of annual pseudostems production (Shivashankar *et al.* 2006). The pseudostem is consists of 20–25 concentric leaf sheath layers, arranged one top of the other layer. Fibre bundle present in the layer of pseudostem is

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rich in cellulose of 53–67%, 15–19% hemicellulose, 5–22% lignin, 3–5% pectin and waxes (Kaur *et al.* 2020, Mushtaq *et al.* 2024; Chattopadhyay *et al.* 2023). There is a significant variation among plant variety/species that could lead to banana fibre production with difference in physical, mechanical and chemical properties. For instance, the commercially cultivated banana varieties such as Poovan, Nendran, Rasthali, Karpuravalli and Robusta in India and Ambun, Kolikuttu and Atamuru in Sri Lanka yielded fibre in the range of 0.55% - 0.89%, along with difference in their chemical and physical properties (Ray *et al.* 2024; Shivashankar *et al.* 2006; Balakrishnan *et al.* 2019).

Retting, pre-treatment or fibre modification is the process of separating fibres from the non-cellulosic matrix and surrounding parenchyma tissue by break down of elastic binding agents in plant cell walls. The choice of retting/ process swiftly determines the quality of fibre obtained. Most widely practiced industrial method for retting/ pre-treatment is the chemical process, where sodium hydroxide alkali-based degumming is carried out. The process is mostly preferred due to the possibility of large-scale production, along with requirement of less time. But it could also marginally affect the cellulose polymer chains, resulting loss in fibre strength (Unal *et al.* 2022, Twebaze *et al.* 2022). Physical retting/ modification techniques using hot water, steam, ultrasonication and application irradiation technology generally lack in their efficacy, when act as single process to completely remove the non-cellulosic components from the ligno-cellulosic complex fibrous structure (Sango *et al.* 2018; Lyu *et al.* 2021). Enzymatic modification selectively removes non-cellulosic matrix under mild conditions of temperature and pH, while utilizing the substrate-specific hydrolases and oxidoreductases, thereby preserving the crystalline structure of cellulosic (Mushtaq *et al.* 2024; Jacob *et al.* 2008). Although several literatures are available in this area on individual process of fibre extraction, still there is a gap of systematic and criteria-based comparative assessment of physical, chemical and enzymatic processes, considering their advantages and disadvantages. Thus, the present paper summarizes a comparative assessment of finding in this individual area, keeping in mind the fibre strength, tenacity, cellulose%, hemi-cellulose%, lignin%, environmental impact.

With the growing environmental concerns associated with synthetic polymer and fibres, coupled with increasing awareness regarding biodegradable products, have significantly enhanced the interest in the utilization of various plant fibres for development of eco-friendly and biodegradable textile products. Conventionally utilized natural fibres such as cotton, silk, wool, jute, flax, and ramie could not fulfil the growing demand for natural fibres for applications in textile, composite, packaging and other industrial areas. Consequently, researchers have focused on exploring the alternative natural fibres, derived from the agricultural biomasses and underutilized plant resources. In this context, fibre extracted from the banana pseudostem has immense potential for textile and other industrial applications (Chattopadhyay *et al.* 2020; Samanta *et al.* 2026). Banana fibre possesses several advantageous viz., high tensile strength, light in weight, low elongation, biodegradability, good moisture absorption capacity, thermal resistance and relatively good mechanical performance. Due to these properties, banana fibre has gained importance for the production of apparel textiles, home furnishing materials, technical textiles, handmade paper, ropes, mats, bags, decorative articles, handicrafts and composite materials (Samanta *et al.* 2023a). Despite of these advantages, raw banana fibre exhibits certain inherent limitations that restrict its direct application in fine textiles. Those limitations are fibre coarseness, stiffness and rigid, due to the presence of appreciable amounts of lignin, hemicellulose, pectin, waxes and gummy substances. Thus, the fibre requires suitable physical, chemical, and biochemical interventions to improve its fineness, softness and flexibility for value added textile applications. In the present work, banana fibre was modified using xylanase rich enzyme to make the fibre fine and flexible, keeping in mind its value-added textile applications.

FIBRE MODIFICATION

Chemical process

Chemical modification employs the use of 5-10% sodium hydroxide, hydrogen peroxide, sodium carbonate, or combinations of these chemicals to break down the non-cellulosic substances, present in the ligno-cellulosic fibrous structure. A similar non-cellulosic composition is also found in other



plant fibres like jute, flax, nettle, ramie and hemp (Samanta *et al.* 2023c; Chattopadhyay *et al.* 2022; Chattopadhyay *et al.* 2021b). Chemical retting operates at the molecular scale to saponify and/or chemically decompose the ester linkages created due to plant cell wall maturation involving pectin and hemicellulose acetyl groups, split the β -ether bonds within the lignin-carbohydrate complex and eliminate waxy substances from the outer surface of the fibre. Low-temperature peracetic acid bleaching of banana fibre was carried out in mild alkaline condition with an aim of improving the fibre quality and whiteness index above 70, while retaining the majority of raw fibre properties like strength and weight (Chattopadhyay *et al.* 2023). Peracetic acid treatment on banana fibre may be considered as an effective and environmentally friendly bleaching process for banana fibre.

Physical process

Physical processes include water retting, mechanical fibrillation, steam treatment and ultrasonic-assisted modification. Such approaches help fibre-to-fibre separation through mechanical disruption, thermal energy induced separation and cavitation-induced breakdown of non-cellulosic counterpart, thereby reducing the adhesion between cellulose fibres and with surrounding matrix (Unal *et al.* 2022; Twebaze *et al.* 2022). Hot-water immersion at 90-100 °C can partially dissolve the pectin and low-molecular-weight waxes from the fibre's surface due to action of thermal energy, leading to better fibre separation than mechanical separation. But thermal energy/treatment alone could not completely break down the covalent cross-links of hemicellulose-lignin-cellulose (Sango *et al.* 2018). Use of ultrasound energy aids in the localized cavitation bubbles at the fibre-liquid interface that generates high-pressure microjets, once collapsed. This process mechanically break down the surface gum deposits, while facilitating chemical penetration. The combination of ultrasonic and alkali pre-treatment processes was more effective for reducing fibre diameter over the only alkali-based fibre modification (Twebaze *et al.* 2022). However, ultrasonic energy as a solitary physical process has not been much effective for adequate removal of matrix to obtain quality fibre. Other irradiations techniques viz., gamma, microwave and plasma have been assessed in

similar bast-fibres to selectively disrupt amorphous hemicellulose bonds (Lyu *et al.* 2021). Physical methods are more accurately viewed, as it aids instead of main retting process of banana fibre.

Enzymatic process

1. Xylanase / Hemicellulase

The β -(1,4)-linked D-xylo-oligosaccharides are hydrolysed by action of xylanase from the β -(1,4)-D-xylose backbone of glucuronoxylan. The process takes place in an endo manner i.e., through hydrolysis of the main chains, generating xylooligosaccharides that are capable of diffusing out of the fibre. Main structural alteration is the disruption of interfacial hydrogen bonds between the xylan and the cellulose microfibril hydroxyls that weakens the cross-linking strength, which imparts rigidity to the matrix as well as adhesiveness to the fibre bundles. Secondary structural modifications involve the elimination of flaky scales apparent as a residue that is oriented perpendicular to the fibre's axis, thereby improving moisture transport along with reduction in fibre friction (Kaur *et al.* 2020; Lyu *et al.* 2021). Simultaneous application of xylanase and pectinase in a bio-scouring process of fibre at pH 8.5, temperature of 50 °C for 60 min resulted in 8.6% reduction in fibre yellowness index, coupled with a significant enhancement in water-absorbing capacity (Kaur *et al.* 2020). Mushtaq *et al.* stated a Taguchi ANOVA analysis, revealing that hemicellulase (5% owf) was the most statistically significant for cellulose proportion and hemicellulose content, thus confirming the intended hydrolysis of hemicellulose may be the main factor for enhancing composition (Mushtaq *et al.* 2024). Sample treated with enzymes sequentially showed a xylan decrease by 61.9% (Jana *et al.* 2024).

MATERIALS AND METHODS

Raw banana fibre was subjected to scouring treatment in the presence of mild alkaline solution using sodium carbonate (Na_2CO_3) and soap. Then the scoured fibre was treated with 2% o.w.f. xylanase rich enzyme along with little pectinolytic activity. Fibre fineness before and after the treatment was determined using standard gravimetric cut-and-weigh method, keeping the fibre cut length of 5 cm. Then its weight was taken

in a digital microbalance and result is expressed in 'tex' unit. Bundle-strength of banana fibre was evaluated in electronic fibre bundle strength tester and result is expressed in g/tex. The X-ray diffraction (XRD) analysis was performed to study the structural parameter of raw and modified fibres using X-ray diffractometer. Fibre surface features of the raw and enzyme modified samples were also analysed under scanning electron microscope (Model: SNE-3200M). Colour parameters of raw and modified fibres were analysed in terms of whiteness index (WI), yellowness index (YI), colour strength (K/S), lightness-darkness (L^*), red-green (a^*), yellow-blue (b^*), chroma (C^*) and hue angle (H^*) using computerized colour matching system. Fourier-transform infrared spectroscopy (FTIR) in ATR mode was performed to study the change in chemical properties.

RESULTS AND DISCUSSION

It was well known that banana fibre contains lot of surface impurities that needs to be removed for better efficacy of enzyme processing in the successive processing. The raw banana fibre contains 59.2% cellulose, 19.6% hemicellulose and 9.2% lignin (Chattopadhyay *et al.* 2023). A pre-treatment like mild scouring in mild alkaline condition could reduce certain percentage of fat & wax, hemi-cellulose and lignin that could facilitate in ease of enzyme action. Fibre was enzyme treated after the scoring operation and Table 1 shows the improvement in fibre properties.

Table 1: Fibre fineness and strength before and after modification

Sampel details	Bundle strength (g/tex)	Fineness (tex)
Raw banana fibre	19.9	7.5
Enzyme treated banana fibre	17.2	5.4

From the table 1, it can be seen that raw banana fibre is quire coarser in nature and its fineness can be improved due to scouring followed by enzyme treatments. As far as fibre's bundle strength is concerned, it decreases marginally by 13.5%. Such a decrease in strength and improvement in fibre fineness might have happened due to partial removal of non-cellulosic component from the fibre surface. Fig. 1 shows the picture of raw and enzyme

treated banana fibres. The colour attributes in these fibres were measured in computerized colour matching system and data are tabulated in Table 2.



Fig. 1: Pictures of raw and enzyme treated banana fibres

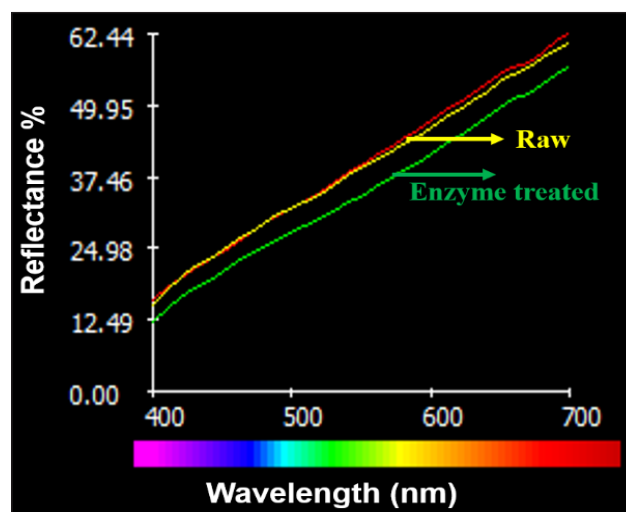
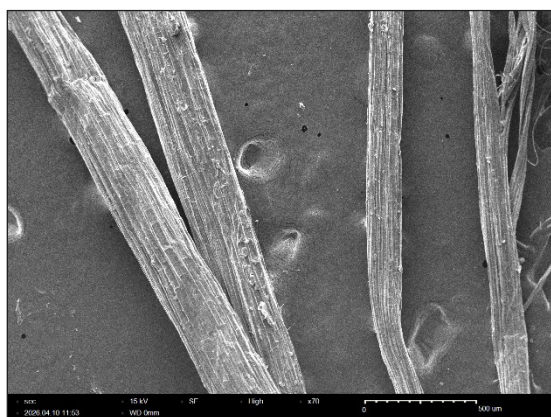


Fig. 2: Colour spectra of raw and enzyme treated banana fibres

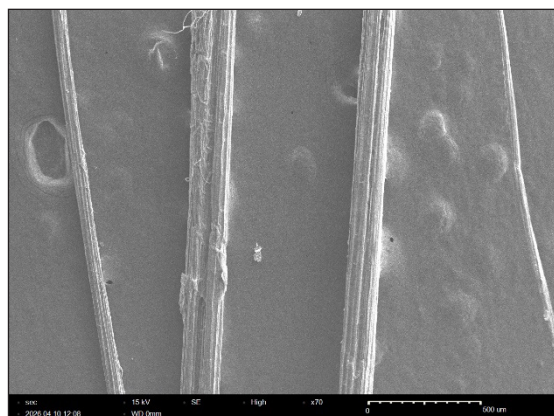
Enzyme treatment results in noticeable reduction in whiteness of the fibre, evidenced by decreases in whiteness index (WI) and L^* values. This also can be noted from the little increase in yellowness index (YI) and a^* values, due to little reddish chromophoric group. The decrease in WI and L^* , along with increase in YI values have increased the colour strength (K/S) in the enzyme treated sample. The increase in K/S indicates enhanced light absorption by the treated fibre. Such changes can occur due to partial alternation in the percentage of lignin, phenolic compounds, or other natural pigments, in the scoured and enzyme treated sample.

Table 2: Different colour parameters in the banana fibres

Colour parameters	Raw fibre	Enzyme treated fibre
WI	57	53
YI	51	53
L*	70	65
a*	5.8	6.1
b*	21	21
C*	22	21
K/S	1.60	2.10



(a)

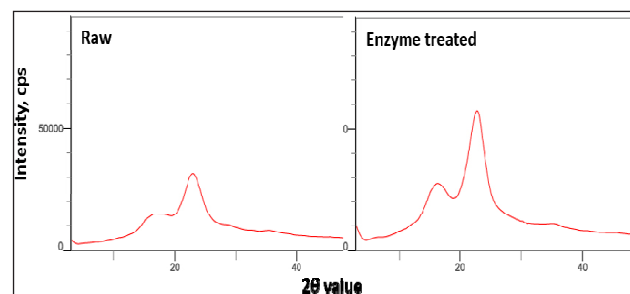
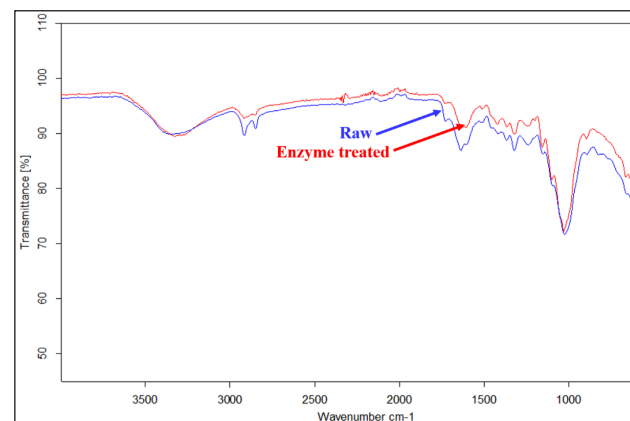


(b)

Fig. 3: SEM micrographs of raw (a) and enzyme treated (b) fibres

From the Fig. 3, it can be seen that raw banana fibre at 70X magnification exhibits lot of surface deposition due to the presence of non-cellulosic materials. After the scouring and enzyme treatment in the presence of soap and alkali, and enzyme solutions, fibre diameter reduces. At the same time, fibre becomes cleaner also. Both the fibres look like cylindrical/rod like shape along with attributes

of multi-cellular structure. Fig. 4 shows the XRD curves of raw and enzyme treated banana fibres. Both the samples show the major diffraction peak at $22.5 - 23^\circ$ 2θ value. This is the main peak of crystalline cellulose I. Peak height in case of enzyme treated sample increases possibly due to removal of non-cellulosic material. Figure 5 shows the FTIR spectra of the raw and enzyme modified banana fibres. It shows that the major peaks as well as their peak position remain same in the both the samples. However, there is a small change in their peak intensity. Peaks at 1600 cm^{-1} and 1510 cm^{-1} (aromatic C=C stretching and skeletal vibrations from lignin) decline a little, confirming lignin reduction, in case of modified fibre. In both raw and enzyme treated banana fibres, -OH stretching vibration is appeared at around 3350 cm^{-1} , indicating presence of moisture in the natural fibres. It is one of the intense peaks due to strong hydrogen bonds in banana fibre, as far as presence of moisture and hydroxyl groups are concerned. The CH_2 stretching vibration is observed at 2918 cm^{-1} , which is due to $-\text{CH}_2\text{OH}$ group of cellulose and hemicellulose polymers. This peak reduced notably due to partial removal of hemicellulose by action of alkali and enzyme.

**Fig. 4:** XRD spectra of raw and enzyme treated banana fibres**Fig. 5:** FTIR spectra of raw and enzyme treated banana fibres

2. Pectinase/ polygalacturonase

Enzyme process consists of utilizing the biocatalysts, either solo or in a combination of different enzymes on the non-cellulosic polymeric matrix via hydrolysis and/or oxidation under mild processing conditions i.e., temperature of 45-60 °C, pH of 4.5-8.5, fibre to water/liquor ratio of 1:25-1:50, as discussed below in details. In the middle lamella zone of plant cell walls, heteropolysaccharides primarily comprise long chains of α -(1,4)-linked D-galacturonic acid units (homogalacturonans), allowing these polysaccharides to bond the fibres together. Consequently, pectinases enzymes like endopolygalacturonase can break down the α -(1,4)-glycosidic bonds, found in the homogalacturonan molecule's backbone in a random manner. Consequently, such hydrolytic reaction leads to the swift depolymerization of pectic network, causing the middle lamella to potentially lose its cohesive ability. It facilitates cells to be easily separated from each other by using slight mechanical action. The macroscopic evidence of pectinase activity includes a reduction in the number of bundles and in stiffness due to the removal of pectin-calcium cross-linking. The process could also enhance in fibre flexibility and whiteness value (Kaur *et al.* 2020). Activity of polygalacturonase could breakdown the bundle cohesion due to the hydrolysis of homogalacturonan (Jacob *et al.* 2008). Successive research supports that the observed bundle separation was primarily due to the application of pectinase from the specified species at different concentration levels (*Aspergillus niger* 7.0-7.5 U/mL; *Phoma herbarum*; and *Enterobacter cloacae* PMC04) (Mushtaq *et al.* 2024; Paramasivam *et al.* 2022). Employing the pectinase in xylano-pectinolytic bio-scouring (4.8 IU pectinase, pH 8.5, 50 °C, 60 min) resulted in enhancement of 13% whiteness and 16% brightness of the fabric, due to removal of surface gum residue (Kaur *et al.* 2020).

3. Laccase

Laccase is a multicopper oxidase enzyme with four copper ion binding sites and an active site to facilitate one-electron oxidations of the phenolic components of lignin (syringyl, guaiacyl, and p-hydroxyphenyl). Laccases generate phenoxyl radicals that could break down the polymer chain either by direct cleavage or by forming covalent

bonds. When it is available at low concentrations to serve as a mediator, the full oxidizing potential of laccases is also utilized to oxidize the non-phenolic components of lignin, thereby HBT significantly enhances the enzymatically oxidized quantity of lignin. At the fibre-surface, laccase activity eliminates the dark, hydrophobic lignin layer from the top layer of the fibre, which subsequently reduces the water contact angle along with improvement in surface wettability. It also removes the chromatic conjugated phenolic compounds responsible for the typical yellow/ brown colour of banana fibre. Such surface oxidation neither impacts the cell wall on surface area, nor results in pit formation or lumen collapse. It results in generating a smooth/ micro-grooved surface topology, as observed under the scanning-electron microscope (SEM) (Vardhini and Murugan, 2016).). Laccase treatment with 3 - 5% owf, 5 U/mL, 1 mM HBT achieves around 29% lignin removal. A mixture of three distinct enzymes has also been attempted, where laccase leads to overall lignin reduction by 52.3%.

4. Endoglucanase (Bio-polishing)

Endoglucanase selectively breaks down the disordered amorphous region cellulose of the fibre that are mostly projected from the surface of yarn or fabric in the form of fibrillar fuzz. Such outward projected fibrous fuzz are produced due to mechanical action, which enhances the inter-fibres friction, downgrades fabric quality and adversely affects the skin-comfort. Used under the condition of $\leq 1-2$ IU/mL or $< 0.5\%$ owf for less than 6 h, endoglucanase carries out the bio-polishing action by cutting surface microfibrils, without entering the crystalline phase of cellulose of fibre, which part is unreachable for the enzyme (Mushtaq *et al.* 2024, Balakrishnan *et al.* 2019). The process leads to overall textural reduction in terms of surface roughness, while ensuring the improvement in tactile feel and effective reduction of fibre diameter owing to microfibril removal, rather than bulk bundle separation. Application of controlled enzymes with the conditions of 5% owf, 55 °C, pH 2.5-3.5 and M:Lr- 1:50 decreased the fibre diameter from 168 to 101 μm , while achieving a 19% rise in single-fibre strength from 2.7 to 3.3 gf (Balakrishnan *et al.* 2019). Moderate bio-polishing enhances surface features without damaging the cellulose fibrillar structure.



5. Modification with multi-enzymes

Multi-enzyme systems utilize the biochemical compatibility of four types enzyme as mentioned earlier. Pectinase breaks down the pectin matrix of the middle lamella, facilitating cell separation. Xylanase/ hemi-cellulase eliminates the hemi-cellulosic network linking cellulose microfibrils. Laccase oxidises and eliminates the hydrophobic surface layer of lignin. Controlled endoglucanase bio-polishes any remaining surface fibrils. When implemented in succession or as a mixture formulation, these actions accomplish through non-cellulosic matrix elimination, which is not possible to accomplish using a single enzyme system. Mushtaq *et al.* utilized a Taguchi L9 orthogonal array to methodically enhance four-enzyme combinations (hemicellulase, laccase, amylase, pectinase) at 50 °C, pH 5 for 2 hours (Mushtaq *et al.* 2024). Two combinations of enzyme namely Type 1 hemicellulase 5%, laccase 5%, amylase 3% and Type 2 hemicellulase 5%, laccase 3%, pectinase 5% mixture were used that could increase cellulose percentage to 84% and 83% respectively, from their initial value of 54%. Type 2, enzyme combination improves single-fibre strength from 49 to 148 cN/tex and decreases the fibre linear density from 5.8 to 1.8 tex (Mushtaq *et al.* 2024). A sequence of pectinase, xylanase and laccase treatment could result in reductions of 74% pectin, 62% xylan and 52% lignin, i.e., the highest overall matrix removal (Jana *et al.* 2024). Combined bio-scouring using xylano-pectinolytic enzymes resulted in 13.3% enhancement in fibre whiteness and 16.1% brightness (Kaur *et al.* 2020). ANOVA result validates that hemicellulase and laccase are the two most statistically important factors for overall quality enhancement of fibre (Mushtaq *et al.* 2024). Table 3 shows the effect of

different enzymes on fibre properties.

FIBRE QUALITY PARAMETERS

Strength and fineness

Fibre diameter is the primary feature for determining the spinnability of a fibre in terms of its conversion into yarn and production of fineness count yarn. A particular type of plant variety produced machine extracted fibre of 168 µm (Balakrishnan *et al.* 2019). Diameters of banana fibre is found to reduce to 120–150 µm, after the boiling and to 101 µm for enzymatic modification. Diameter could be further reduced to below 100 µm through a combination of enzyme, and hydrogen peroxide and sodium hydroxide (H₂O₂/ NaOH) treatments (Sango *et al.* 2018). In another fibre type, diameter of 101 µm was noted with enzymatic treatment and 49 µm in case hybrid treatment (Balakrishnan *et al.* 2019). Tenacity of a fibre gives an indication of efficacy of fibre modification. It was seen that fibre tenacity decreases after the chemical modification in the presence of alkali. Alterations in physical boiling, maintains the tenacity, yet no enhancement were achieved due to insufficient matrix elimination. The best combination of enzymatic formulation consisting of hemicellulose 5%, laccase 3% and pectinase 5% could increase the tenacity value to 148 cN/tex, due to elimination of non-load bearing matrix component (Mushtaq *et al.* 2024). Anaerobic biological retting of the Nendran variety yielded 61 g/tex, surpassing the results obtained by methods A and B, which recorded 35 g/tex and 36 g/tex, respectively (Shivashankar *et al.* 2006), indicating utilizing the enzymes in a unique manner.

Table 3: Effect of different enzymes on fibre properties (Kaur *et al.* 2020; Jacob *et al.* 2008; Jana *et al.* 2024; Vardhini and Murugan, 2016; Mushtaq *et al.* 2024; Balakrishnan *et al.* 2019)

Enzyme	Process conditions	Fibre properties
Pectinase / Polygalacturonase	4.8–7.5 U/mL; pH 5–8.5; 50–55 °C; 60–120 min	Bundle separation; increase in 13.3% whiteness and 16.1% brightness
Hemicellulase (multi)	5% owf; 50 °C; pH 5; 120 min	Hemicellulose decreases from 22% to 3.6%
Laccase	5 U/mL; 1 mM HBT; 3–5% owf	Lignin decreases by 52.3; whiteness increases
Endoglucanase (controlled)	≤1–2 IU/mL or <0.5% owf; 55 °C; ≤6 h	Fibre diameter reduced from 168 to 101 µ and biopolishing effect
Pectinase + Xylanase	4.8 IU pectinase + 15 IU xylanase; pH 8.5; 50 °C; 60 min	Increase in whiteness by 13.3% and brightness by 16.1%

Crystal structure and surface morphology

The X-ray diffraction (XRD) analysis reveals that enzymatic modification could preserve the cellulose I crystal structure, with appearance of diffraction peaks at 2θ value of 15.3° (I_{01}) and 22.6° (I_{02}), in all the enzyme treated samples (Mushtaq *et al.* 2024, Jana *et al.* 2024). The enhancement in the crystal index (CrI) after enzymatic treatment is likely due to elimination of non-cellulosic amorphous materials, leading to relatively higher crystalline phase that signifies no structural rearrangement (Jana *et al.* 2024). The rise in CrI contributes to the observed enhancement in tenacity. Chemical modification with the elevated NaOH levels leads to the mercerization of cellulose and its transformation from I to II structure, causing a reduction in original crystallinity (Unal *et al.* 2022). Moderate temperature during the physical treatment could maintain the structure of cellulose and enhance the CrI (Sango *et al.* 2018). Enzyme-treated fibre exhibits the depletion of bands related to pectin, hemicellulose and lignin, as confirmed by FTIR analysis (Mushtaq *et al.* 2024). SEM offers the most distinct visual differentiation among the retting methods. Enzymatically processed fibre (S9-B) shows smooth, consistent, micro-grooved surfaces without pitting, lumen collapse or longitudinal cracks formation (Mushtaq *et al.* 2024). The application of 10% NaOH resulted in uneven cell-wall erosion, visible fractured cell cross-sections and collapse lumen (Twebaze *et al.* 2022). Physical boiling alone resulted in visible interfibrillar gum remnants and bundle adhesion layers (Sango *et al.* 2018). Enzyme-chemical combination yielded the best surface diameter of $49\text{ }\mu\text{m}$ due to the elimination of hemicellulose and lignin binding agents, while maintaining fibre cell boundaries (Balakrishnan *et al.* 2019). Due to enzyme treatment, hemicellulose, lignin and pectin was found to reduce from 22 to 3.6%, from 15.2 to 3.5% and from 3–5 to <0.5%, respectively while cellulose percentage increased from 4.2 to 84.3 (Mushtaq *et al.* 2024; Jana *et al.* 2024).

Environmental aspect

Chemical modification (retting) is presently the sole method that has been instigated on industrial scale for processing banana fibre, due to availability of chemicals at a reasonable price and possibility of scale up (Unal *et al.* 2022). Chemical modification

mostly operated at higher temperature of 60–95 °C with or without need of pressure arrangement, where more thermal energy per kilogram of fibre is required in comparison to enzyme process, carried out at lower temperature of around 50 °C (Twebaze *et al.* 2022). Economics of chemical modification is relatively advantageous due to needs to less expensive common chemicals, but the process lacks from the generation and management of effluent. This is due to unreacted alkali liquor remained in the process bath along with presence of disintegrated lignin, hemi-cellulosic and pectin byproducts. Wastewater has a pH exceeding 10 may be categorized as hazardous that needs neutralization by suitable disposal protocol (Unal *et al.* 2022; De Prez *et al.* 2018). Biological-oxygen-demand (BOD) and chemical-oxygen-demand (COD) of the spent textile alkali liquors are typically higher than those of enzyme-based processed liquor, which merely needs any pH adjustment (Mushtaq *et al.* 2024). Clean water effluent generated from the physical modification/retting has low dissolved load. However, this method is the least demanding among the three alternatives, as it could not produce desired quality fibre (Lyu *et al.* 2021). Enzymatic retting at 45–60 °C needs approximately 40–60% less thermal energy compared to high-temperature chemical processing. Ultrasonication insisted physical modification requires high specific-energy electrical input (power density 20–60 W/cm²) with somewhat less reagents (Lyu *et al.* 2021). Physical retting methods ensure the safest environment, but it lacks in term of scalability (Sango *et al.* 2018; Lyu *et al.* 2021). Enzymatic retting incurs higher expenses owing to cost of enzyme and needs of a device to maintain the specified range of temperature, but possesses benefits of lower effluent generation (Mushtaq *et al.* 2024; De Prez *et al.* 2018). Enzymatic process also needs facility like a stable and controlled enzyme supply (2–8 °C) system, maintaining the pH and temperature during the processing (Mushtaq *et al.* 2024). A phased hybrid approach is the most suitable system for extracting fibres in industrial settings. Fibre fineness of 49 μm (5.6 tex) and single fibre strengths of 62 gf was produced through the application of 5% pectinase at 55 °C for 120 min, followed by hydrogen peroxide (H₂O₂) bleaching (Balakrishnan *et al.* 2019). Hybrid method enables a significant reduction in chemical dosage by enzymatically pre-treatment of the fibre.



Table 4: Comparative statement and environmental aspects of different processes (Mushtaq *et al.* 2024; Unal *et al.* 2022; Twebaze *et al.* 2022; Sango *et al.* 2018; Lyu *et al.* 2021; Jacob *et al.* 2008; Kaur *et al.* 2020)

Different parameters	Enzyme process	Chemical process	Physical process
Chemical/ reagents requirement	Pectinase, xylanase, laccase	NaOH, Na ₂ CO ₃ , H ₂ O ₂	Water, heat, ultrasound
Tentative operating temperature (°C)	45–60	80–140	80–100
Process time (h)	2–6	0.5–2	2–4
Process pH	4.5–8.5	10–14	6–8
COD/BOD load	Very low	High	Low

Table 4 summarizes the conditions of the three processes of fibre modification.

GENERATIVE AI DECLARATION

The author(s) confirm that there was no use of artificial intelligence (AI)-assisted technology for assisting in the writing or editing of the manuscript, and no images were manipulated using AI. The authors developed and verified all scientific content, data analysis, interpretation of results, and conclusions. The authors take full responsibility for the accuracy, integrity, and originality of the work presented, and no AI tool was listed as an author

CONCLUSION

The present paper summarizes the physical, chemical and enzymatic routes of modification of banana fibre along with their comparative advantages and limitations. As natural fibres vary from location to location, type of plant variety and age of the plant, quantitative value of various parameters of fibre may be compared as relative to each other. A single process could not offer the best results across all the desirable criteria need for its application in value-added textile. A process needs to be selected, keeping in mind the quality required and quantity of fibre to be modified, while also providing attention on the environmental footprint and economic involvement. Based on currently available studies, enzymatic retting may be produce the most balanced results in all aspects, as far as fibre strength, improvement in fibre-fineness and chemical composition are concerned. Chemical process is only the current requisite process for large scale industrial modification/retting of fibre that offers faster processing with low operation cost, although it poses a notable effluent generation. Physical modification seems to be safer and free from chemicals involvement, but it is inadequate as far as production of desire fibre quality is concerned

for high-value application. Hybrid process emerges as a promising route of fibre modification for achieving quality fibre, fostering the advantage of both the processes. Banana fibre treatment in the presence of xylanase rich enzyme could improve the fibre fineness and colour attribute of sample, with a little decrease in fibre mechanical strength.

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