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Research article

Retting of banana pseudostem fibre using *Bacillus* strains to get excellent mechanical properties as biomaterial in textile & fiber industry

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ABSTRACT

Banana pseduostem (BP) fibre, sometimes known as banana fibre, is a new natural fibre with potential commercial applications in the textile and fibre industries. Softening these fibres might enhance their mechanical qualities, allowing them to be used in more textile applications. The current research looks at the softening of banana fibres (*Musa paradisiaca* L) utilising a variety of chemical (NaOH & HCl) and bacterial treatments. Physical (Hygroscopicity, Density, Linear density), chemical (cellulose, Hemi-cellulose and Lignin) and mechanical parameters (Peak load, Breaking Elongation, Tenacity) of the treated fibres were measured as per normal technique with raw banana fibres. The tenacity (g/tex) of microbial treated (*Bacillus licheniformis)* (7 days) fibre was found to be greater, at 6.33, but the average peak elongation (%) of (*Bacillus Subtilis)* was found to be higher, at 8.2. The lignin % of untreated Banana fibres (15.98%) was reduced in fibres treated with 5N of NaOH (10.75%), 5N HCl (8.73%), *Bacillus aryabhattai* (11.4%), *Bacillus licheniformis* (12.54%) and *Bacillus Subtilis* (13.56%). In contrast to raw banana fibre, the mechanical qualities of treated fibres showed incremental results. Finally, the study found that treating banana fibre with NaOH, HCl and *Bacillus* sp. had a substantial impact on the physiochemical parameters. SEM and FTIR methods were used to validate the efficiency of the bacterial treatment.

1. Introduction

The primary concern that prompted the development of biomaterials and their application in the automobile and other industries is "environmental friendliness." Increased awareness of environmental issues has prompted a paradigm shift away from synthetic fibres and toward biodegradable natural fibres (Rajamanickam et al., 2021). Natural fibres are a flattering and appealing option for synthetic fibres because to their renewability, recyclability, economic effectiveness, and environmental friendliness. The requirement of fibrous materials in textile and technology applications has been increasing at an above-average rate for a few years. For example, according to (Björquist 2017) Global fibre consumption is anticipated to increase from 87 MT in 2014 to 240 MT in 2050, in which 100 MT demand was already achieved in 2016 (Kosan et al., 2020). This significantly higher increase in fibre demand cannot be met by increasing cotton production because of the limited availability of farmlands which also in favour of escalating food security. Furthermore, the increasing synthetic fibre production or genetically modified crops are alternative approach to meet the increasing demand of fibre other less-than-desirable cultivation techniques (Gloy et al., 2021) (see Table 1).

Bananas are presently cultivated in 129 different nations throughout the globe. It is the fourth-largest steady food crop in the planet. The global banana fruit production is 26.2 million, with India accounting for 14.7% of that with 7.1 lakh hectares of banana crop producing land. *Musa paradisiaca* is a *Musa* species. Bananas are part of the Musaceae plant family. A perennial herb that resembles a tree, the banana plant is a kind of perennial herb. After cultivation, the parent plant's aerial portions die down to the ground (Elanthikkal et al., 2010). Billions of tonnes of stems and leaves are discarded each year. These wastes can be used as fibre sources, reducing the need for synthetic fibres. Because of their high specific strength, lightweight, and extended life, synthetic fibres are often utilized as reinforcing components in polymeric composites. They do, however, have substantial disadvantages, such as massive cost, non-biodegradability, and high power consumption, which can lead to pollution, itchiness, and erosion process equipment, among other things (Manimaran et al., 2018). Banana fibre is stronger, more resilient to environmental factors like temperature and moisture, and it has a better

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Table: 1. Weight Losses of Banana Fibers treated with 5N HCl and 5N NaOH.

S. No	Concentration of HCL	Weight before Treatment(g)	Weight after Treatment(g)	Weight loss (%)	Conditions (%)
1	Raw Banana (Fiber)	20	25	00	Temp = 35 °C Time = 24 h
2	5 N HCL	20	15.00	25%	
3	5N NaOH	20	17.00	15%	

efficiency of reinforcing. Banana fibres are becoming more popular on international markets as a result of the expensive cost of synthetic fibres like glass, carbon, and plastics as well as the health risks caused by asbestos fibres (Diarsa and Gupte 2021).

Banana fibres are very absorbent, airy, quick-drying, and tensile-strengthening. The tensile strength of the fibre was determined in part by the matrix in which the cells were placed. Banana pseudo stem fibre is a lignocellulosic substance mostly made up of polysaccharides, with cellulose (50%) interwoven with hemicelluloses (30%), lignin (18%), pectin (5%), water soluble material (3%), fat (3%), and ash (5%) (Mohiuddin et al., 2014). The banana creates a lot of lignocellulosic waste, which is a type of cellulosic waste (Manimaran et al., 2018). Due to its crystalline nature and ß-4 linked D-glucan chained structure, cellulose is the principal source of high efficiency in plant fibres. The Young's modulus of crystalline cellulose is similar to that of Kevlar, and it is probably extremely durable. Hemicellulose has an amorphous structure due to its short and branching chains with pedant side groups. Lignin is a three-dimensional copolymer that contributes to the stiffness of plant fibre cells. Natural fibre has been given the designation lignocellulosic fibre since it is mostly made up of cellulose, hemicellulose, and lignin. Natural fibres are noted for their mechanical strength and acoustic qualities, as well as being lightweight and cost-effective, making them more appealing than synthetic fibre materials (Gupta et al., 2021). Agricultural waste sinks in the land, causing further environmental problems in banana-growing areas. Chemical examination of banana pseudo-stem fibre reveals a high holocellulose content and low lignin content when compared to other non-wood fibre resources. It is difficult to spin fibre with a lignin % of 20–30% in textile processes. As a result, lignin must be removed by the degumming process (Vardhini et al., 2016).

Softened banana fibres can be utilized as fortification in polymer mixtures, packing, automobiles, interiors, and loading containers. Banana fibres are removed using a variety of techniques, including mechanical, chemical, and biological processes. The process of extracting non-fibrous plant tissues and other reinforcing material from fibre bundles is known as extraction (decortication). In comparison to the time-consuming manual method, mechanical extraction can recover 15–20 kg of banana fibre every day (Väisänen et al., 2017). Chemicals such Sodium hydroxide (NaOH), Ammonium oxalate $(NH_4)_2C_2O_4$, or Sodium sulphite (Na_2SO_3) are employed in the chemical extraction of banana fibre to remove non-fibrous extraneous elements. For fibre extraction in biological treatment, microbial enzymatic retting is utilized. In microbial retting, the pseudostem is suspended for at least seven days in water containing microbial consortia and characterized for the synthesis of several lignocellulolytic enzymes that are employed for fibre extraction. Biological treatment resulted in a larger fibre output and better fibre quality due to increased evenness and shine in the fibre. Mechanical extraction, on the other hand, is commonly used due to its superior capacity and productivity.

Many studies have been conducted so far to characterize banana fibre in order to use it in various fiber-based sectors such as textiles, automobiles, pulp and paper, and so on. Despite the fact that they are utilized in the textile and pulp sectors, the lignin makes hurdle on the end product's quality of fibre. As a result, companies have adopted a variety of chemical treatments to remove lignin content. However, the widespread use of these chemicals has resulted in a hazardous wastewater disposal problem, as well as a significant expense and risk to employees. As a result, safer and more ecologically friendly procedures are needed to degrade lignin of the fibre, which improves the fiber's quality. The microorganisms were utilized to eliminate the lignin content of fibre through the development of lignocellulolytic enzymes for this bio-softening process. Given his expertise, the current research attempted to improve and compare the performance of chemical and biological treatments for softening banana fibre.

2. Materials and methods

2.1. Collection of banana fiber

The banana pseudo stem fibre was provided by Gujarat's Navsari Agriculture University. The fibre was extracted from the banana pseudo using either a human extractor or a semi-automated Raspador machine with a drum speed of 700–800 rpm. A scraping plate sits in front of a 14-inch-diameter drum with a 12-inch-long carbon steel angle blade on the Raspador machine. The leaf sheaths were fed into the machine one after one. The fibres were rinsed properly in water to eliminate any dirt or pulp that had become entangled, and then dried. The fibres were then combed through a swarm of massive nails pounded into a piece of wood. The fibres were collected and straightened.

2.2. Biological treatment of banana fiber

The 2 g of sterilized banana fibres cut into 30cm lengths were utilized for biological treatment. The three lignocellulolytic pure Bacterial strain cultures, *Bacillus aryabhattai*, *Bacillus licheniformis,* and *Bacillus Subtilis* were isolated from agriculture waste rotting. The samples were collected from decaying BP trash in a sample jar. From each site, 5 g of sample was collected and ground into fine powder. It was placed into 100 ml of pH 7 Bushnell Haas medium (BHM) for enrichment. After 07 days, 1 mL of this culture solution was transferred to fresh BHM media for the next 07 days and the process was repeated five times the potential microbes were screened for greater laccase (Bandounas et al., 2011), and cellulase (Kasana et al., 2008) enzyme activity on the relevant agar plate. Furthermore, the potential isolate was screened using their morphological and biochemical characteristics using Bergey's manual classification. The cultures were grown in Luria Bertani (LB)broth for 24 h at 37 °C in a shaking environment. The cultures were kept at 37 °C in LB agar slant. In biological treatment, cultures of *Bacillus aryabhattai*, *Bacillus licheniformis* and *Bacillus Subtilis* were treated at for softening of banana Fibers. The 5 ml inoculums of *Bacillus aryabhattai, Bacillus licheniformis,* and *Bacillus Subtilis* were inoculated separately into a 100 ml flask of mineral medium (pH 6.0 + 0.5% glucose) and incubated at 30 °C for 24 h with 150 rpm shaking condition. With the help of sterile forceps, 1 g of banana fiber was transferred aseptically into flask. The flaks were then incubated at room temperature for 72 h under stationary conditions. After treatment, the fibre was air left to dry, chopped, and examined for physicochemical and mechanical characteristics.

2.3. Chemical treatment of banana fiber

Raw banana fibres were submerged in a 5N NaOH solution and different concentrations of 5N HCl for an overnight alkalization and acidification treatment to minimize fibre stiffness. After cleaning the fibres in distilled water until they achieved a neutral pH, they were dried in a 60 °C oven for 12 h (Rajamanickam et al., 2021).

2.4. Analysis of physical properties banana fiber after treatment

The following are the physical attributes that were quantified: length, diameter (Rajamanickam et al., 2021), density, linear density (Rodríguez et al., 2022), and moisture absorption. A polarized microscope (Lieca brand) with a magnification of 100 and a computer interface was used to

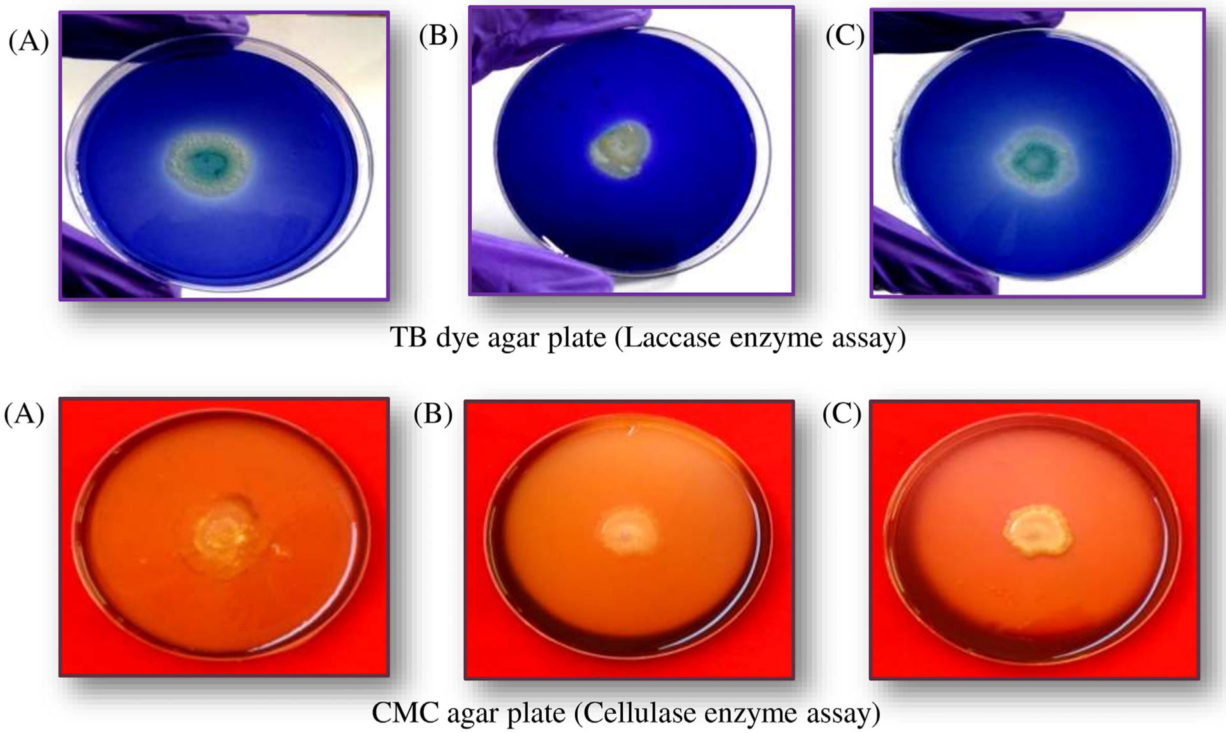

Figure 1. Lignocellulolytic enzyme activity on primary screening (A) *Bacillus aryabhatti* PPSUHB1; (B) *Bacillus subtilis* PPSUHB2; (C) *Bacillus licheniformis* PPSUHB3.

measure the surface morphology and diameter. The average diameter of ten randomly picked fibres was determined microscopically at five distinct places.

2.5. Density (TAPPI, 1980)

The density of the fibre is determined using standard techniques. Before the density test, the fibre specimen was treated for 24 h at 65 % relative humidity and 25 °C. In a certified glass tube 15 (10ml measuring cylinder), 2g of fibre sample was immersed in toluene, and the amount of toluene expelled was proportional to the fibre in the solution (Equation:1) (Leheny et al., 2021).

$$\text{Density} = \text{mass} / \text{volume} \tag{1}$$

2.6. Linear density (ASTM D 1577)

The linear density is calculated according to the ASTM standard. The density of fibre was measured in deniers (Denier is the linear mass density of fibers per 9000 m of the fiber) under typical atmospheric circumstances. The fibre samples were cut and weighed in grammes using a standard length (L) template (5–10 cm). The formula is used to compute the denier (D) of the fibre sample as per Equation:2 (Adamu 2021).

$$D = (9000 \times W) / (L \times N) \tag{2}$$

where, N is the no. of fibers in the sample.

2.7. Moisture regains (%) or Hygroscopicity

It's the quantity of water in a sample given as a % of the dry mass of the specimen. The fibre sample (g) was treated for 24 h at 272 °C before being weighed (L). The treated fibre sample was dried in an oven at 105 °C for 4 h before being weighed (w). The formula was used to compute the % of moisture recovery as per Equation:3 (Soraisham et al., 2021).

$$\text{Moisture regains } (\%) = L - W \times 100/L \tag{3}$$

where, L = Initial weight (g), W= Final weight (g).

2.8. Tensile properties

Untreated and treated banana fibres were tested for tensile strength using the ASTMD 3822–01 typical test technique for tensile characteristics of single textile fibres. The test was carried out in a Zwick tensile tester with a 1kN load cell and a crosshead speed of 5 mm/min. Each sample had roughly 15 fibres tested at 10mm gauge length. Each fiber's fineness was measured via vibrational analysis. The force elongation curve of a single fibre was measured repeatedly. Young's modulus describe the ability of a (0.05–0.5 percent elongation) and strength were calculated based on this. With fibres secured between vulcanite fasteners and 6 bar of pressure, 25 trials at 15 mm/min were done (Brodowsky and Hennig 2022).

2.9. The chemical composition of treated and untreated banana fibre was determined

In a tared crucible, one gramme of BP was put following heated to 105 °C until reached its consistent weight. The variance among dry weight and initial weight of BP is presented as Moisture content (Dill and Kraepelin 1986). To calculate ash content, 1 g of BP was heated for 5 h at 550 °C in a tared crucible for remaining the residual ash content. A successive fractionation of lignocellulosic was analyzed via minor alteration in the technique of Datta and co-workers (Datta 1981), and the lignocellulose content was measured. 1 g of BP was transferred in 100 mL of distilled water and heated for 2 h at 100 °C. After that, the sample was dried at 90 °C until a consistent weight. The misfortune loss was calculated as a water-solvent component. The dried material was dissolved in 100 ml of 0.5 M H_2SO_4 and dried, and weight alteration is denoted as

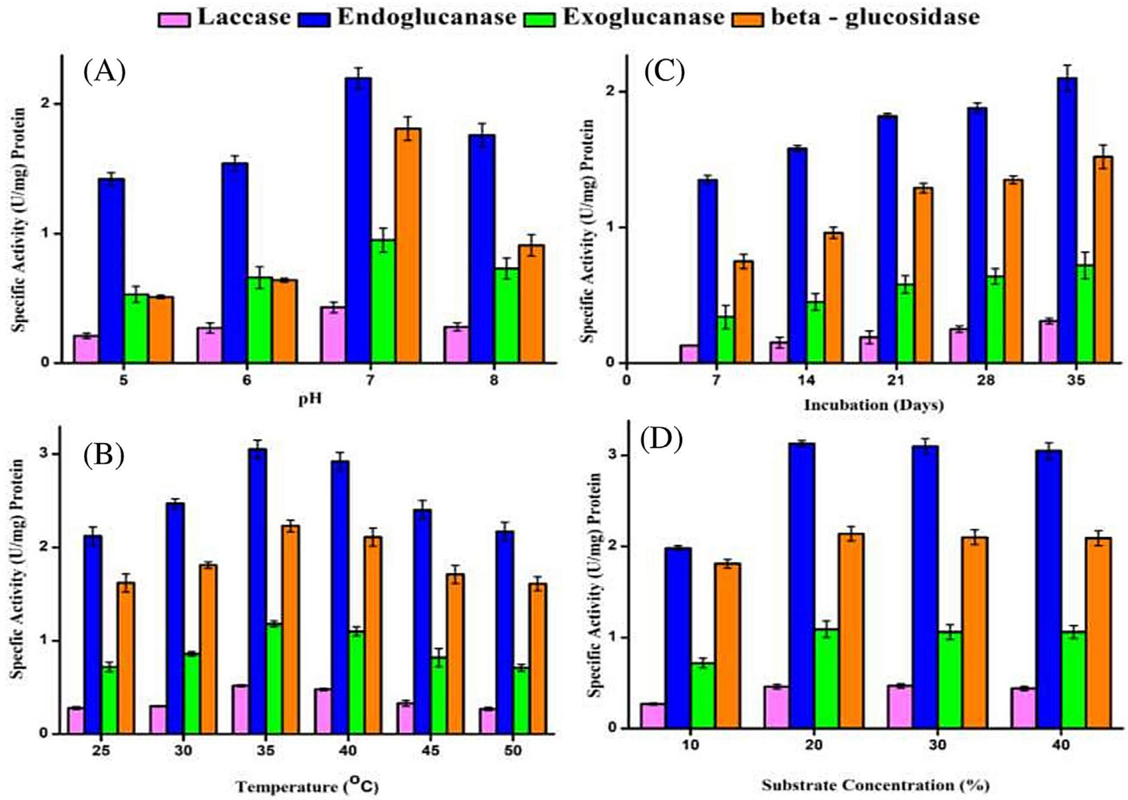

Figure 2. Production pattern of lignocellulolytic enzyme by *Bacillus aryabhatti* PPSUHB1 at (A) different pH, (B) Temperature, (C) Incubation period and (D) Substrate concentration.

hemicellulose. The 72 % H_2SO_4 (10 mL) was added to the above-rebuild-up for cellulose and lignin assessment for 1 h incubation at 30 °C for 200 rpm. (OH Lowry et al., 1951).

2.10. The mechanical characteristics of treated and untreated banana fibre were compared

Individual fibres were tested using a Universal Testing Machine with a volume of 10 kg, a gauge length of 50 mm, and a cross-headhead velocity of 10 mm/min. Ten distinct fibres were assessed for each treatment, and the weight of ten fibres was recorded. Each fibre's peak load and peak elongation were measured. Zwick used conventional ASTM (ASTMD 3822-01) methodologies to evaluate mechanical characteristics such breaking tenacity (g/tex) and young's modulus (kgf/mm). As a control, untreated raw fibre was used.

2.11. Fiber morphology

The morphological categorization Micrographs of untreated and bacterial-treated fibre surfaces were produced using a Scanning Electron Microscope (SEM) coupled with a Princeton Gamma Tech (PGT) IMIX digital imaging system and a Prism Intrinsic germanium (IG) detector (SVNIT). A gold putter coater was used to create conductivity in all samples. A resolution of 4 nm was used for all samples. A voltage of 15–20 kV was used to monitor 0.1 0.005 g of fibre that had been sputtered coated with gold-palladium and placed on conductive adhesive tape (George et al., 2014).

Fourier transform infrared spectroscopy (FTIR) was applied to detect functional groups and their interactions between treated and untreated Banana fibre. Small fibre sections of moulded Biocomposite material were used as samples (approximate thickness of 0.5 mm). The studies were carried out in a SHIMADZU IRAffinity-1S spectrometer (SVNIT). Data was gathered in the 4000–500 cm-1 range (Rodríguez et al., 2022).

3. Result and discussions

3.1. Enrichment, isolation, screening, and characterization of potential bacteria

Out of 15 bacterial isolates, 3 potential isolates were identified on the LB agar plate followed by the BP-containing medium enrichment technique. On Carboxyl methyl cellulose agar (CMC) & toluidine blue (TB) Dye agar, all isolates showed cellulase & laccase activity, when compared to other isolates, *Bacillus aryabhattai* had the highest zone of clearance using Congo red dye & TB dye on all three screening plates (Figure 1 A-C), which demonstrated greatest lignocellulolytic enzyme activity.

3.2. Production optimization of lignocellulolytic enzyme for the treatment of banana fibre

3.2.1. pH and Temperature optimization

The optimal synthesis of lignocellulolytic activity was seen at neutral pH 7 at 35 °C at a constant temperature. This suggests that neutral pH was optimal for enzyme synthesis, but pH above or below 7 significantly reduced enzyme production (Figures 2, 3 and 4). It might happen because the metabolic pathway of bacteria is too much sensitive to pH, especially enzymes which significantly change their structure and function under variable ionic pH. For temperature optimization, initially, pH 7 was set as the standard criteria. At 35 °C, *Bacillus aryabhattai* showed highest production of 0.52 U/mg laccase, 3.05 U/mg endoglucanase, 1.18 U/mg exoglucanase, and 2.23 U/mg β-glucosidase; *Bacillus licheniformis* showed production of 0.31 U/mg laccase, 2.39 U/mg endoglucanase, 1.32 U/mg exoglucanase, and 2.19 U/mg β-glucosidase and *Bacillus Subtilis* showed production of 0.31 U/mg laccase, 2.17 U/mg endoglucanase, 0.82 U/mg exoglucanase, and 1.51 U/mg β-glucosidase. However, above 50 °C, production rapidly decreased. Temperature fluctuations have a significant influence on enzyme synthesis (Figures 2, 3 and 4). Because atoms

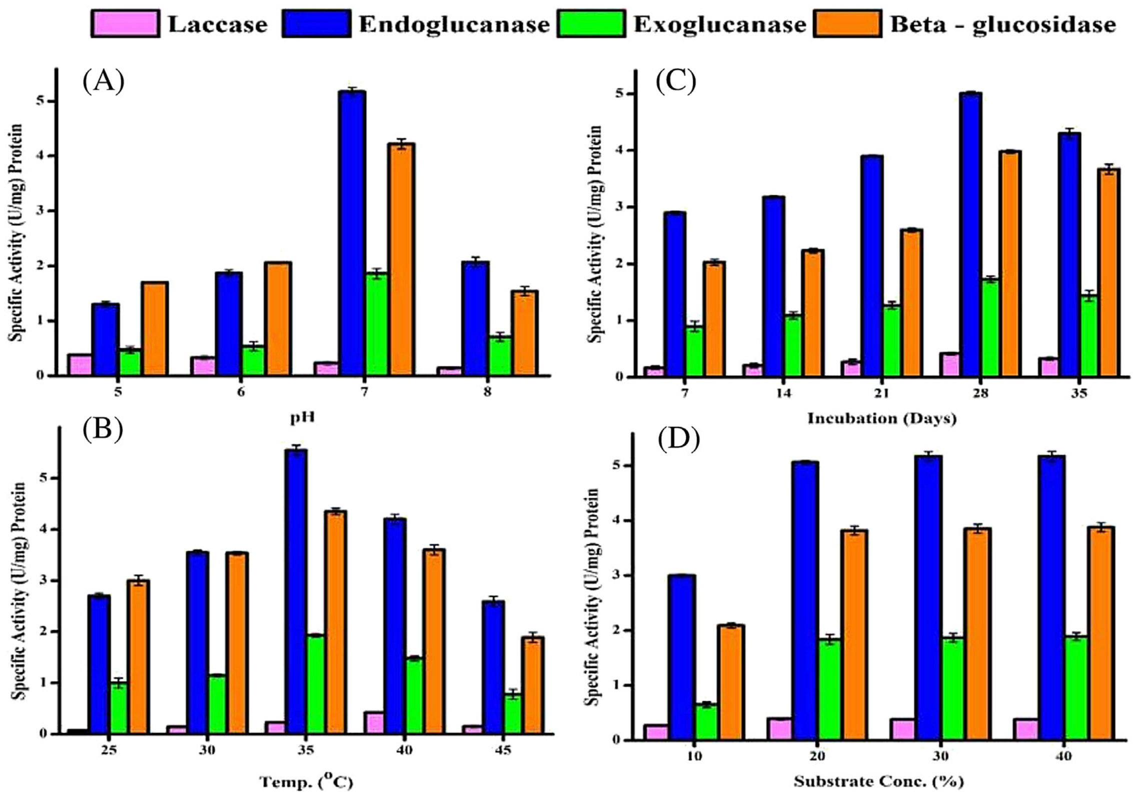

Figure 3. Production pattern of lignocellulolytic enzyme by *Bacillus subtilis* PPSUHB2 at (A) different pH, (B) Temperature, (C) Incubation period and (D) Substrate concentration.

travel more slowly at lower temperatures, all metabolic action comes to a standstill. As the temperature rises, atoms travel faster and enzymes accelerate metabolism. However, at a certain threshold, enzymes begin to denature, with harmful consequences. Furthermore, compare to (Waghmare et al., 2014), who discovered that lignocellulolytic enzyme production by *Klebsiella sp.* Showed highest lignocellulolytic enzyme production in sorghum at pH 8 and temperature 50 °C. He et al. (He et al., 2014) also discovered that *Armillaria tabescens* synthesized maximum laccase enzyme *at* 45 °C temperature.

3.2.2. Incubation period # substrate concentration optimization

Entire lignocellulolytic production began 7 days after inoculation and subsequently amplified up to 35 days. At 35 days, isolate *Bacillus aryabhattai* produced the highest 0.31 U/mg laccase, 2.1 U/mg endoglucanase, 0.72 U/mg exoglucanase, and 1.52 U/mg β-glucosidase. compair to *Bacillus licheniformis* produced the 0.41 U/mg laccase, 2.1 U/mg endoglucanase, 1.21 U/mg exoglucanase, and 2.32 U/mg β-glucosidase and *Bacillus Subtilis* produced the 0.37 U/mg laccase, 2.57 U/mg endoglucanase, 1.07 U/mg exoglucanase, and 1.7 U/mg β-glucosidase (Figures 2, 3 and 4). The bacterial growth will be halted during the last phase of the growth curve due to limited nutritional availability which hampers the metabolic enzymes and normal functioning of bacterial physiology. Acharya and Chaudhary (2012) discovered that cellulase enzyme production was highest during incubation period of 28 days, afterward the production was ceased by *B. licheniformis*.

Enzyme kinetics show that raising the concentration of substrate limits enzyme synthesis to some extent, although it decreases at high concentrations. *B.aryabhattai* has a maximal output of 0.46 U/mg laccase, 3.13 U/mg endoglucanase, 1.09 U/mg exoglucanase, and 2.14 U/mg β-glucosidase, *Bacillus licheniformis* has a output of 0.47 U/mg laccase, 2.2 U/mg endoglucanase, 1.39 U/mg exoglucanase, and 2.39 U/mg β-glucosidase and *Bacillus Subtilis* has a output of 0.51 U/mg laccase, 2.99 U/mg endoglucanase, 1.44 U/mg exoglucanase, and 2.03 U/mg β-glucosidase at a substrate concentration of 20% (Immanuel et al., 2006) discovered that *Cellulomonas* and *Bacillus* bacteria strain produced minimal amounts of endoglucanase enzyme at 0.5 percent of the substrates, gradually increasing to 2 percent of the substrate.

3.3. Chemical treatment on banana fibre

The banana fibres processed with the concentrations of 5N NaOH and 5N HCl, were compared to the untreated fibre. The removal of non-cellulosic elements in the fibres is represented by the fraction of weight loss of the fibres. When compared to other treatments, banana fibre treated with 5N HCl (Table-1) exhibited the largest weight loss (25%) and 5N NaOH (Table-1) showed 2^{nd} the maximum weight loss (15%), suggesting that banana fibre had superior softening qualities (Howe et al., 2019). As the alkali content grew, the mass of the banana fibre decreased (Tholkappiyan 2016). Furthermore, banana pseudostem fibre treated with 5 N HCl showed the greatest removal of lignin and hemicellulose. When cellulose fibres are alkalized and bleached, the crystalline part of the cellulose becomes amorphous, hydrophobic components such as lignin, pectin, wax, and sticky substances are removed, and the fibres become specific, smooth and soft due to the cellulose portion (Temesgen and Sahu 2014). In comparison with Temesgen and Sahu (2014) data, BP fibre treated with bacteria showed great smoothness and softing quality which is further confirmed through SEM & FTIR data.

3.4. Physical properties of banana fiber

For the manufacture of low weight composites, fibre density is an important characteristic to consider for industrial uses (Figure 5). The elimination of low density regions such as lignin and hemicelluloses, as well as the higher density area of cellulose content, results in an increase in density (Vardhini et al., 2016). Raw banana fibre had a density of 0.96

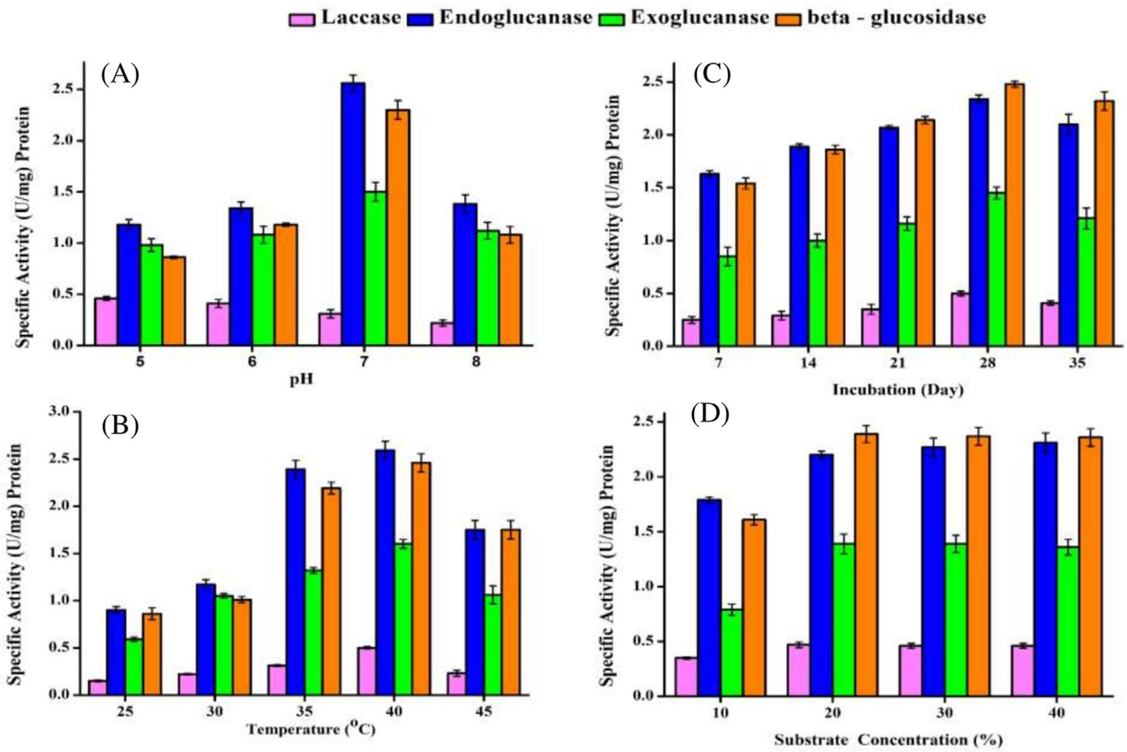

Figure 4. Production pattern of lignocellulolytic enzyme by *Bacillus licheniformis* PPSUHB3 at (A) different pH, (B) Temperature, (C) Incubation period and (D) Substrate concentration.

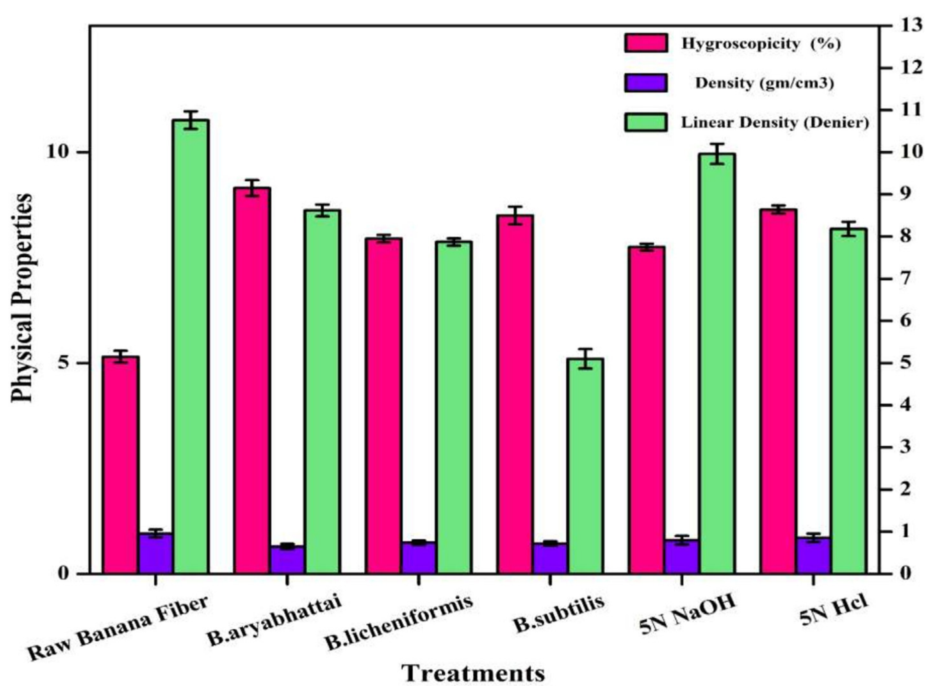

Figure 5. Physical properties of banana fiber.

g/cm^3, while softened banana fibre had densities of (*Bacillus aryabhattai*) 0.89 g/cm^3, (*Bacillus Subtilis)* 0.75 g/cm^3, and (*Bacillus licheniformis)* 0.82 g/cm^3, outstanding material for low weight composites. The lower density fibre, on the other hand, is best suited to textile applications (Sivaranjana and Arumugaprabu 2021). The linear density indicates the fiber's fineness. Softened and raw banana fibre had linear densities ranging from 10.76 to 5.1 Denier. In concern with data, it is found that *B. Subtilis* treatment was more effective compare to others which give lowest denier to the banana fiber. This result is more suitable to wards to application of banana fiber in textile industries. Cotton with a denier range of 3–8, linen with a denier range of 1.7–17.8, and hemp with a denier range of 3.2–20 were all closer to their maximum value (Ronald Aseer, Sankaranarayanasamy et al., 2013). When compared to raw banana fibre, the density and linear density of soft banana fibre decreased.

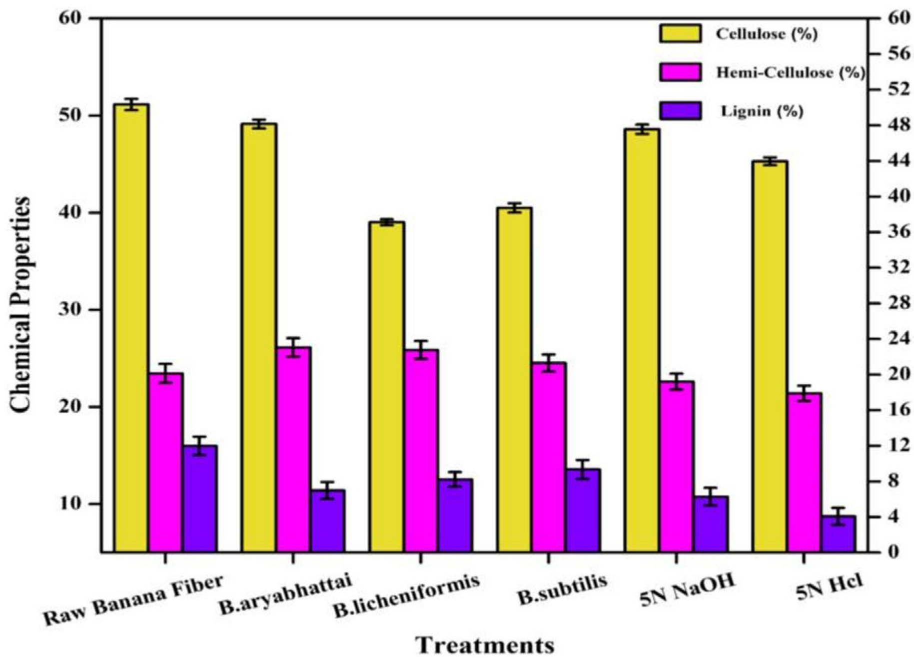

Figure 6. Chemical properties of banana fiber.

Because cellulose molecules are capable of forming hydrogen bonds, they may swiftly absorb water. Based on the chemical components of banana pseudo stem fibres, the % of moisture content of treated and raw fibre ranged from 5.15 % to 9.15%. According to the moisture regains of the treated banana fibre in this study, hemp and kenaf had similar values of 8%–12% and 9% to 10.05 %, respectively. In comparison to the other two treatments, the fibre treated with *Bacillus aryabhattai* regains the maximum % of moisture content (9.15%). Because of their more hydrophilic nature, fibres with a higher moisture retentive capacity are more appropriate for textile applications.

3.5. Chemical properties of banana fiber

Cellulose has an impact on the most important factor in determining the fiber's quality. The main structural component that provides plant cell walls their strength and stability is cellulose. Cellulase enzyme is generated by cellulolytic microorganisms and may breakdown cellulose materials. It is thought to be more important in the modification of low-grade roughage.

In solid state fermentations, bacteria constitute the most significant category of microorganisms who produced lignocellulolytic enzymes. *Bacillus aryabhattai, Bacillus licheniformis,* and *Bacillus Subtilis* were evaluated for plant fibre cell wall disintegrating enzymes in this research (Rehman et al., 2014). The quantity of cellulose in a fibre that determines its suitability for various purposes. Raw banana fibre and softened banana fibre had cellulose concentration ranging from 39.2 to 51.15%. Its value was comparable to that of jute (64.4%) and flax (64.3%), but it was lesser than that of cotton (82.7%). As a result, it might be a good replacement for flax and jute fibres (Figure 6). According to various research on fibre composition and morphology, cellulose content and micro fibril angle affect the mechanical properties of cellulosic fibres (Biswas et al., 2011).

Hemicellulose serves as a plaster between two cells of plants. Treated and raw banana fibre had hemicellulose concentration ranging from 23.45 to 26.13%, which was greater than jute (12%) and cotton (6%). The fibres get tougher and stiffer as the lignin level rises. Lignin offers overall strength to plant tissue and individual fibres. Softened banana fibre and raw banana fibre had lignin levels ranging from 11.40 to 15.98%. Tenacity reduced when the lignin level dropped below 0.78 % (Preethi 2011). The fibre treated with *Bacillus aryabhattai* had the lowest lignin level in the percent study (11.4%). The % of cellulose and lignin content of banana fibre treated with *Bacillus aryabhattai, Bacillus licheniformis,* and *Bacillus Subtilis* was lower than that of the alkaline (5N of NaOH) treated fibre, whereas the % of hemicellulose content was higher in the fibres treated with *Bacillus aryabhattai, Bacillus licheniformis,* and *Bacillus Subtilis*. As a result, variations in lignin and cellulose content, which were drivers of fibre quality, may be useful in categorizing fibre for certain applications. The reduction in lignin and hemicellulose may lead to better exposure of cellulose which has high level of surface contact to absorb the moisture (Vardhini et al., 2016).

3.6. Mechanical properties of banana fibers

Mechanical properties including initial modulus (YM), ultimate tensile strength (UTS), and percentage elongation are analyzed to achieve better quality of fibre. The enhanced tenacity and tensile strength of *Bacillus aryabhattai* treated fibre was discovered to be approximately 5.77 (g/den), *Bacillus licheniformis* 6.33 (g/den), and *Bacillus Subtilis* 5.71 (g/den) compared to raw fibre. The enhancement in the tensile strength of untreated fibre compares to that of acidic/alkaline and Bacterial treated fibres vary in between 2.84 and 7.16 Mpa. The decrease in fibre is linked to an increase in tensile strength.

As indicated in Figure 6, the loss of hemicelluloses in the fibres is promoted by chemical and microbiological treatments, resulting in increased diameter. The cellulose % of the fibres increases after chemical treatment with 5N NaOH, 5N HCl, and bacterial treatment, resulting in high tensile strength. The diameter, length, and test speed of a fibre define its tensile strength or tenacity. The loss of lignin content will cause microfibrils to compress, lowering the tensile strength of softened banana fibre and increasing tenacity (Vigneswaran and Jayapriya 2010). The data indicated that the maximum lignin loss was observed during the 5N HCl treatment (8.73% lignin) followed by *B.aryabhattai* (11.4% lignin), *Bacillus licheniformis* (12.54% lignin), *Bacillus Subtilis* (13.56% lignin). The Young's modulus of treated banana fibre was lower than that of raw banana fibre. Increasing the elongation of treated banana fibres, on the other hand, shows that the treated procedure did not degrade the banana

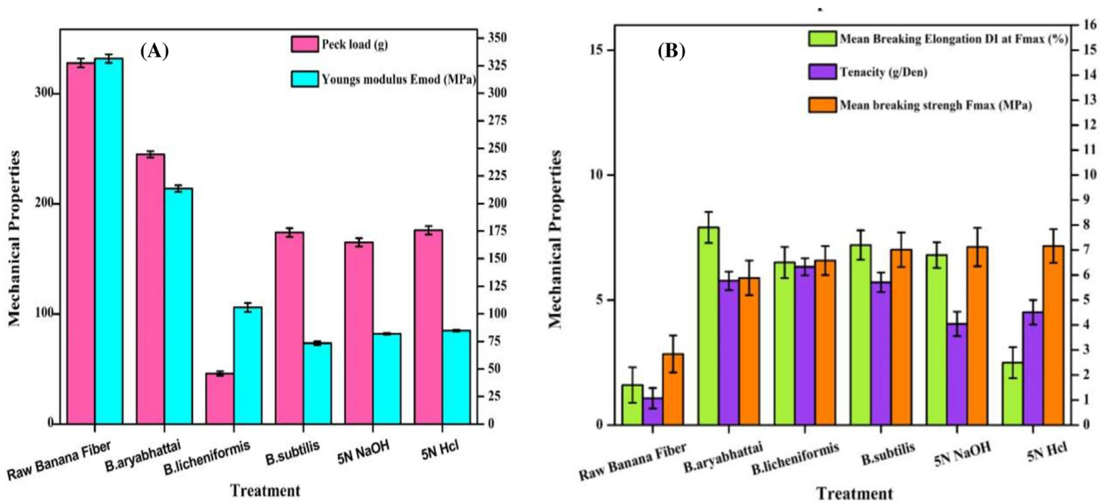

Figure 7. Mechanical properties of banana fiber (A) Peak load (g), and Youngs modulus Emod(MPa)), and (B) Mean breaking elongation DI at Fmax (%), Tenacity (g/den) and mean breaking strength Fmax (MPa)).

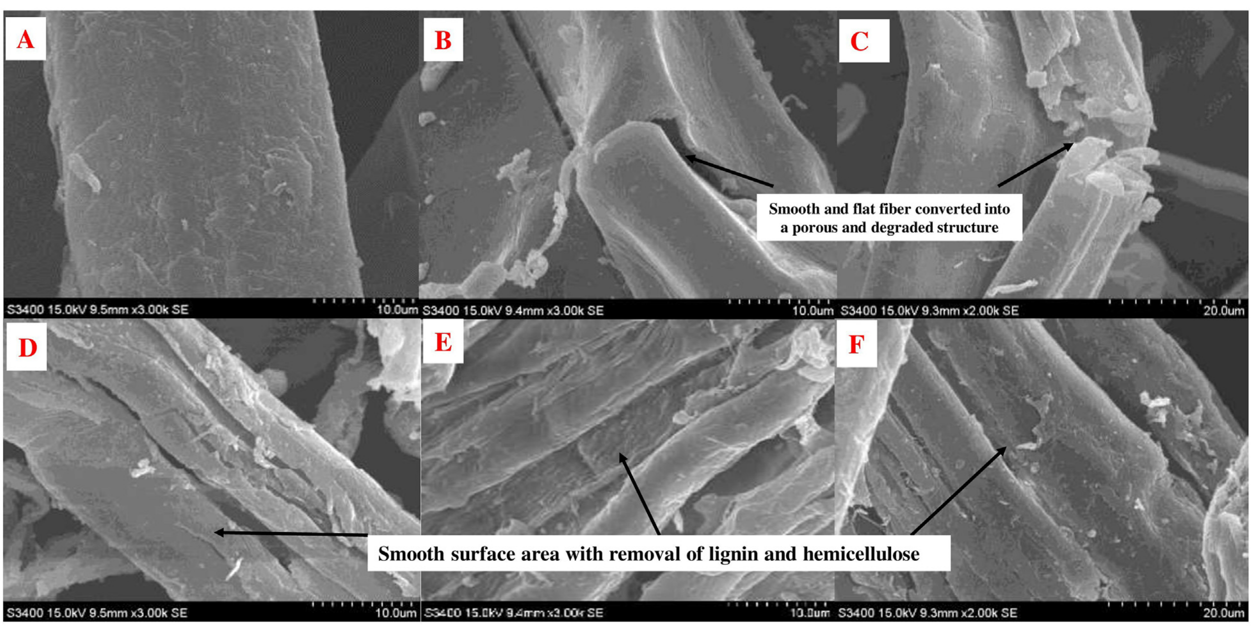

Figure 8. SEM analysis of banana fiber after different treatments (A) Control, (B) 5N NaOH, (C) 5N HCL, (D) *Bacillus aryabhatti* PPSUHB1, (E) *Bacillus subtilis* PPSUHB2 and (F) *Bacillus licheniformis* PPSUHB3.

fiber's quality. Banana pseudostem fibre is a possible material due to its high tensile strength, modulus of elasticity, and stiffness. This improvement improves the fiber's spinability and increases the wearability of the yarn.

The mechanical characteristics of the treated fibres, such as peak load (g), Young's modulus (kgf/mm), peak elongation (%), and tenacity (g/tex) were investigated, and the findings are provided in Figure 7. The peak load (g) in treated fibres was lower than in untreated fibres. Among the various treatments, microbial treated fibre had the highest peak elongation (8.2 %). The microbial treatment (7 days) had the highest tenacity (g/tex), followed by 72 h. The young's modulus was greater in the microbial treatment (7 days), while it was lower in the other treatments (control) (Balakrishnan et al., 2021). The findings are consistent with a recent study, which found that microbial treated (*Bacillus aryabhattai)* banana fibre had a tenacity of 5.77 (g/den), (*Bacillus licheniformis)* banana fibre had a tenacity of 6.33 (g/den), (*Bacillus Subtilis)* banana fibre had a tenacity of 5.71 (g/den).

3.7. Fiber morphology

SEM was used to examine the microstructure of BP before and after bacterial treatment. Figure 8 (A) depicts SEM pictures of raw Banana fiber at various magnifications in which various treatments resulted in various surface morphologies similar to the results of (Brodowsky et al., 2020). A longitudinal slice reveals parallel-oriented unit cells with tube-like structures made of lignin, hemicellulose, and cellulose. This structure is very rigid and difficult to break (Pereira et al., 2014). The data showed that when 5N NaOH & 5N HCl treated were given to fibre, the smooth and flat BP fiber converted into a porous and degraded exterior structure which may lead to degradation of cellulose as well (Figure 8 (B, C)). The complete BP structure was burst after a lignocellulose fiber deteriorated. In comparison to fibres treated with bacteria, It exhibited a smooth surface area with removal of lignin and hemicellulose (Figure 8 (D,E,F)) which has high polymerization an aqueous environment, generating polydopamine molecules which has similar results as

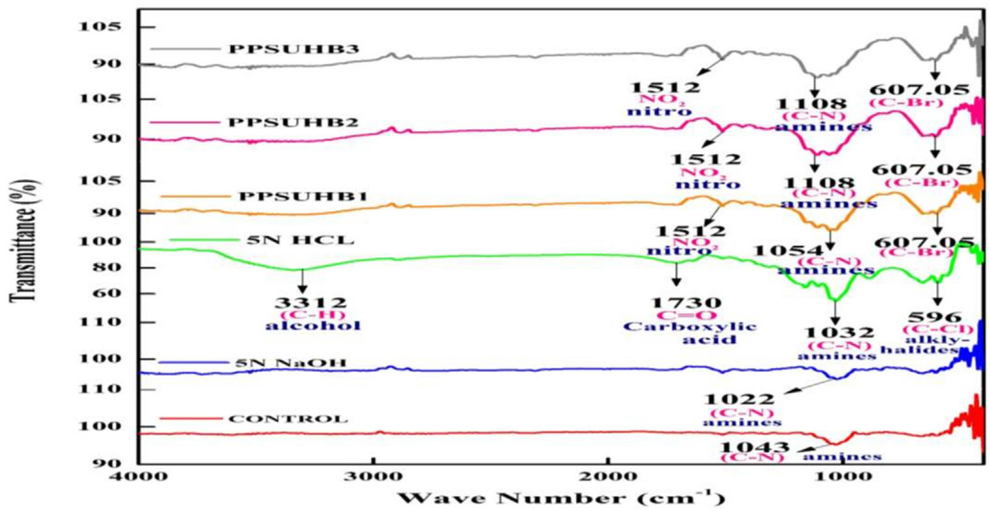

Figure 9. FTIR analysis of banana fiber after different treatments (A) Control, (B) 5N NaOH, (C) 5N HCL, (D) *Bacillus aryabhatti* PPSUHB1, (E) *Bacillus subtilis* PPSUHB2 and (F) *Bacillus licheniformis* PPSUHB3.

per (Brodowsky et al., 2020). The rigid banana fibre was converted into flaky layer surface shape having cellulose exposure which has significant application in textile industry due to the higher lignocellulolytic enzyme activity by bacteria.

3.8. FTIR analysis of intermolecular interactions

The FTIR spectra of deteriorated and undamaged banana fibres. The existence of –OH stretching vibrations in a broad absorption band in the 3000–3500 cm^{-1}range is connected with the organic elements of pseudostem (lignin, hemicellulose, and cellulose) (Pereira et al., 2014). Furthermore, in Figure 9 aliphatic –CH group stretching indicates the existence of cellulose and hemicellulose at peaks of around 2888 cm^{-1} (Das et al., 2018). C=O and C–O stretching of the acetyl group at 607 cm^{-1}and 1108 cm^{-1} bands, respectively, were used to investigate hemicellulose breakdown.

Carbonyl (C=O) group stretching in asymmetric and symmetric with aromatic ring structure arises at 1730 cm^{-1} was used to examine aromatic lignin characteristics. At 3312 cm^{-1}, the absorption bands are –NH symmetric, suggesting hemicellulose and cellulose breakdown. At the 1029 cm^{-1}band, the cellulose plane deformation is linked to the –OH stretching group (Das et al., 2017). The C–O–C group extending symmetrically and the C–H group of alkenes, respectively, exhibit distinctive peaks at 1156 cm^{-1} and 898 cm^{-1} in cellulosic materials-glyosidic linkages. The C–O–C stretch ether vibration showed cellulose (Pappas et al., 2002), and C–O–C group asymmetric stretching at 1156 cm^{-1} recognized mixed cellulose and hemicellulose (Johar et al., 2012). The successful modification happening in the fibre molecular structure as a result of physical and chemical treatments is shown by FTIR. Peaks in FTIR spectra are ascribed to molecular contributions, allowing for the interpretation of probable interactions as well as the determination of the crystallinity index (Monteiro et al., 2014). This data indicated that bacterial treated fibre has low lignin and hemicellulose content which enhance their physical and mechanical properties.

4. Conclusion

Natural fiber–reinforced composites are more sustainable in terms of raw materials than other composite. Because of their high specific characteristics, they are desirable, especially when large damping is required. Because the interphase between fibre and matrix is subjected to the highest stress, a solid bond between the two is essential for any composite's quality. Banana fibre is presently a waste product of banana manufacturing that is either misused or just partially used. The major purpose of this study was to see if banana stem fibre might be used in the textile and fibre industries as a source of lignocellulosic fibres. The proportion of lignin in untreated Banana fibres (15.98%) was higher in fibres treated with 5N NaOH (10.75%), 5N HCl (8.73%), *Bacillus aryabhattai* (11.4%), *Bacillus licheniformis* (12.54%), and *Bacillus subtilis* (13.56%). Tenacity (g/tex) of microbial treated (*Bacillus licheniformis*) (7 days) fibre was higher, at 6.33, although average peak elongation (%) of (*Bacillus subtilis*) was higher, at 8.2. Compared to raw banana fibre, treated fibres demonstrated gradual improvements in mechanical properties. It was also possible to detect frictional stress following surface breakup using this method. Lignin and hemicellulose may be removed from fibre surfaces using lignocellulolytic bacteria, resulting in more homogeneous fibre surfaces with improved thermal properties. The elimination of these components resulted in an increase in individual bundle exposure from a structural aspect, as observed in the SEM micrographs and FTIR data, which yields desired banana fibre qualities for a wide range of applications in the textile and fibre industries. The research data indicated that the banana pseudostem treated with *Bacillus aryabhattai* showed greater quality of textile fibre in terms of physical, chemical and mechanical properties followed by other bacterial and chemical treatment. It is also observed that chemical treatment showed higher degradation of lignin, hemicellulose and cellulose which is not favor the superior quality of banana pseudostem fibre for textile industry. Banana fibre has huge potential for use as the primary component in the manufacture of sanitary pads, which are now composed of plastic and are significant polluters because to their good absorption and strength qualities. Banana fibre can therefore be a cost-effective and environmentally beneficial substitute for synthetic fibres. Future applications for banana fibre should be investigated, such as plastic-free eco-friendly N95-type masks, PPE kits, carry bags, eco-friendly garments, beds, and carpets, as well as use in art and craft design. Therefore, exploiting banana fibre for various industrial uses offers new paths for academics and business to investigate potential uses in the future.

Declarations

Author contribution statement

Binal Y. Patel: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Hiren K. Patel: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

The data that has been used is confidential.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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