



# Optimization of bio-chemical degumming of Ramie fiber for improved strength & luster

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## ABSTRACT

Textile industries are currently not showing much interest in Ramie fibers due to the difficulties associated with their post-harvest downstream processing. The degumming chemicals are often detrimental to the environment upon discharged. Chemical degumming alone results in fibril-released coarse and brittle fibers. This problem has been addressed by combining partial chemical treatment with microbial degumming of the fibers for 72 h at 37 °C using a novel microbial formulation with *Bacillus thuringiensis* MCC2138 and *Bacillus subtilis* ABDR01. The extracellular microbial enzyme-based degumming without the release of fibrils produced a durable, soft, and lustrous fiber with higher tensile strength while utilizing fewer chemicals, thereby leading to lower discharge toxicity. The improved texture and strength compared to complete chemical treatment are attributed to even degumming of the fiber ensuring proper spinnability. Through this approach, Ramie is expected to gain visibility in the global textile market, thereby leading to Ramie cultivators' economic benefits.

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## 1. Introduction

Ramie (*Boehmeria nivea*), which is considered as the oldest fiber crop, is of great interest because of its high economic value [1–3]. This bast fiber possesses high tenacity and durability, excellent luster, and is perfect for fabric production after adequate degumming. Bast fibers include hemp, ramie, flax, jute, kenaf, mesta, urena, banana, and roselle. The emerging global issue related to safer environment-friendly products has shifted the limelight on the use of natural fiber instead of their synthetic counterparts [4]. The quality of the fiber is dependent on growth conditions, degumming, and finishing of the fiber. The conventional process of degumming of natural fiber is energy-intensive and uses many chemicals, which yields high Chemical oxygen demand (COD) in post-degumming effluent [5]. There is ample scope for bio-finishing these natural fibers to make them an essential player in the global textile market.

Ramie plant is easy to grow and can be harvested every 45 days from the second year of plantation up to 16 years. The chemical composition of Ramie is 68.6–76.2 % cellulose, 0.6–0.7 % lignin, 13.1–16.7 % hemicellulose, 1.9 % pectin and 0.3 % wax [6]. The rich cellulose content makes Ramie fiber one of the strongest natural fibers. Despite having several important properties like antimicrobial activity, good absorbency, high durability, the minimum requirement of favorable growth conditions, and pesticides to sustain growth, Ramie has a smaller share in the global natural fiber market to that of cotton and jute [7]. This fact is primarily due to the unfavorable environmental impact of the fiber's downstream processing, which requires the usage of a substantial amount of chemicals and energy. Ramie has, therefore, limited acceptance for textile use. The fiber gum content needs to be reduced through degumming before its application in textile [3,8–10]. The traditional degumming process requires treatment with large amounts of sodium hydroxide (NaOH) and other hazardous chemicals. This process causes serious environmental pollution [11] and necessitates replacement by an environment-friendly degumming method [3]. Different groups have been working on the degumming process of Ramie through the oxidation process [12,13], using Fenton reagent [14], anthraquinone [5] and hydrogen

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peroxide (H<sub>2</sub>O<sub>2</sub>) [15,16]. However, these processes are generating high COD in the degumming effluent [5]. Though microbial enzymes have been used in various industrial applications [17–19], it is only recently that enzymes have become an integral part of textile processing, since they entail great benefits for both environmental impact and quality of the product. Bio-polishing, the process of treating raw materials with biological enzymes for increasing the lustre and strength of the final product, is one of the major thrust areas in this decade [20,21].

Bio-polishing has the edge over chemical polishing in being biodegradable and environment friendly. On the one hand, there is a little chemical residue that would otherwise add to secondary pollution while, on the other hand, the fabric surface becomes smoother and more lustrous. Textile industries search for such novel microbial enzymes that can be effective in a broad pH and temperature range and have short incubation periods and good finishing properties towards fabrics. Enzymes like cellulase, pectinase, xylanase, and amylase are essential in the textile industry. These enzymes playing a significant role in natural fiber finishing. Laboratory-scale cellulase studies have been undertaken to understand their role in ensuring better natural fibers' strength and durability. While prolonged uncontrolled treatment with cellulase makes the natural fibers brittle, this enzyme's controlled application makes the fiber soft and lustrous due to the singeing effect [22]. Pectinase is considered the key enzyme for the removal of pectin substances from the fibers. High pectinase activity does not mean the maximum removal of pectin and may not be sufficient for efficient degumming due to pectin's complex components [20]. An appropriate enzyme system is required for removing gum components from the fibers. Besides, xylanase also contributes to the degumming process. In the textile industry amylases are mainly used in de-sizing, as it removes starch-based size for improved and uniform wet processing without damaging the fabric [23].

The relevance of this work in the backdrop of material science research is evident from the fact that despite several unique features of Ramie fiber such as, less stringent growth conditions, continuous production for 16 years from second year of plantation, harvesting every 45 days, antimicrobial properties with high tensile strength of the fiber, to name a few, the usage of the fiber is still limited in the textile industry. This is primarily due to the non-eco-friendly post-harvest downstream processing of the fiber, which is mandatory for textile applications. Research interests in Ramie fibers are growing steadily owing to their potential about sustainability and eco-friendly applications [24]. Ongoing research strives to improve the texture and quality of the finished product through enzymatic degumming to be commercialized [3,25,26]. Multiple bacterial strains were tested to assess Ramie gum removal/gum utilization efficiency [3,24,25,27]. Previous studies by the group reported *Bacillus thuringiensis* MCC2138 to efficiently degum Ramie fiber within 72 h of incubation [3]. Elongation

percentage of the fiber treated with MCC2138 was 1.78 % ± 0.82. The soft, lustrous, and smooth structure was due to even gum removal by the extracellular enzyme, as shown through Atomic Force Microscopy (AFM). The fully chemically treated fiber had fibrils released, which gave it the matt finish and coarse texture. Another study revealed the extracellular enzyme-producing ability of *Bacillus subtilis* ABDR01 [25]. Elongation percentage of the fiber treated with ABDR01 was 1.44 % ± 0.27. Yet another study reported Ramie gum utilizing ability of 10 different isolates for their growth, hence capable of degumming of Ramie fiber [27]. In continuation with these, the current study attempts to assess the impact of microbial extracellular enzymes combinations' secreted by bacterial consortium (developed by mixing previously reported microbes) on the degumming process of partially chemically degummed Ramie fiber (variety R-1411 Hazarika) to achieve smooth, lustrous, and more durable fibers for fabric generation.

## 2. Materials and methods

### 2.1. Consortium development for extracellular enzyme production

Two well-characterized bacterial strains of genus *Bacillus* namely *Bacillus subtilis* ABDR01 [25] from aerosol of Department of Microbiology, Tripura University, India (23°45' N, 91°15'E) and *Bacillus thuringiensis* MCC2138 [3] isolated from the coastal marine water of Mandarmani, Midnapur, West Bengal, India (21°37.012'N, 87°29.881'E) [28] were used for consortium development in 1:1 ratio. Consortium performance was analyzed for their extracellular enzyme-producing ability (pectinase, cellulase, xylanase, and amylase) under suspended and immobilized conditions [25]. The consortium performance was compared with single isolates for each enzyme to understand the interaction between the consortium's bacteria. To assess extracellular enzyme production, 100 µL of culture supernatant was added to 100 µL of 1% freshly prepared substrate and incubated for 1 h at 40 °C. To the above mixture, 400 µL of dinitrosalicylic acid reagent (20 mL of 2 M NaOH, 1 g of dinitrosalicylic acid, and 30 g potassium sodium tartrate added to 100 mL distilled water) was added and heated in a water bath at 100 °C for 15 min. The total volume was made up to 5 mL with distilled water, and absorbance at 540 nm was taken. The substrate for pectinase, cellulase, xylanase, and amylase were pectin (HiMedia GRM396), cellulose (HiMedia MB248), xylan (from Beechwood HiMedia MB141) and starch (HiMedia GRM3029). The isolates, as well as the consortium, were checked for biofilm formation using standard method [29].

### 2.2. Optimization of fiber degumming

The process of degumming utilizes a large quantity of water, chemical, and energy while releasing large volumes of non-eco-friendly effluent. These components and parameters are crucial for

**Table 1**

The extracellular enzyme activity delineated by the isolates and the consortium in suspended and immobilized state showing difference among the two.

Isolate	Extracellular Enzyme Activity in U/mg							
	Pectinase		Xylanase		Cellulase		Amylase	
	Suspended	Immobilization	Suspended	Immobilization	Suspended	Immobilization	Suspended	Immobilization
<b>MCC2138</b>	11.10 ± 3.93	11.12 ± 4.24	3.78 ± 0.68	4.54 ± 0.76	6.23 ± 2.14	8.36 ± 2.89	5.92 ± 0.39	7.64 ± 1.60
p-values	0.99		7.33* 10 <sup>-3</sup>		0.03		3.67* 10 <sup>-4</sup>	
<b>ABDR01</b>	11.72 ± 3.76	13.11 ± 3.69	7.57 ± 1.84	6.85 ± 1.58	10.75 ± 6.22	12.51 ± 5.14	9.66 ± 0.90	11.48 ± 2.67
p-values	0.32		0.27		0.40		0.02	
<b>Consortium</b>	14.04 ± 5.03	14.27 ± 2.79	7.89 ± 2.17	8.51 ± 2.27	11.60 ± 3.96	12.52 ± 3.65	13.34 ± 2.64	14.36 ± 1.92
p-values	0.88		0.45		0.51		0.23	

the degumming of Ramie. Hence optimization of the process of degumming is essential to cut down on excess input while maintaining the fiber quality. The freshly decorticated Ramie fiber was washed in water in 1: 8 fiber: liquor (F: Lq) ratio for different periods (0, 1, 2, 3, 4, 5, 6, 12, 18, 24, 30, 36, 42, 48, 54, 60, 66, 72 h) to assess the difference in fiber weight before and after washing accounting from the weight loss due to gum removal. Keeping the optimum time of washing constant, the F: Lq ratio was changed (1: 6, 1: 7, 1: 8, 1: 10), and the suspension was heated at 121 °C for 45 min. The gum loss at each ratio was assessed by accounting for the weight loss. Using the optimum F: Lq ratio, Ramie fiber suspension in water was heated at 121 °C for different periods (15, 20, 30, 40, and 45 min) to assess the impact of heating duration on the gum removal. The gum was extracted [11] from the treated liquor, and the COD [30] of the liquor was also assessed. Considering the above-optimized parameters, the chemical composition of the degumming solution (DS) was varied. Percentage NaOH was varied from 1 to 6% along with 1% sodium tripolyphosphate and 0.02 % Tween 80 in each case. The difference in weight of the pre and post-treated dry fiber was measured to assess the gum loss. The COD was also assessed for DS pre and post treatment to understand the contribution of Ramie gum on the COD and the effluent on the environmental health. The fiber treated under optimum conditions per the above experiments was further subjected to biological treatment with the consortium at different fiber: culture (F: C) ratio (1:4, 1:5, 1:6, 1:7, 1:8, 1:9 and 1:10) for 72 h at 37 °C. Selecting the optimum F: C ratio, incubation time (48, 54, 60, 63, 66, 69, 72, 75, 78, 84, 90, 96 h) with the culture at 37 °C was varied to ensure sufficient degumming with maintained fiber strength.

### 2.3. Fiber quality assessment upon bio-treatment

Ramie fibers were partially chemically degummed in 1: 10 F: Lq ratio with 2% NaOH, 1% Sodium tripolyphosphate, and 0.02 % Tween 80 at 121 °C for 45 min, followed by repeated washing in water and finally neutralization in 1% acetic acid. The partial chemical degumming was followed by incubation of fiber with the consortium in the F: C ratio of 1:8 at 37 °C for 72 h. After incubation, the fibers were washed thoroughly in tap water and dried. The weight of the dried fiber was assessed before and after treatment to check the extent of degumming. After each step, gum extraction was carried out from the processed fiber to evaluate the residual gum content. The single fiber breaking tenacity was measured in tensile strength tester [H10KS] HOUNSFIELD with the help of software QMAT 5.47 at the Indian Institute of Technology (IIT), Kharagpur, West Bengal, India. The tensile test was carried out on samples with 2.7 cm gauge length. For each type of fiber treatment, 20 tests were performed with stress range (MPa) 100, load cell of 100 N, extension range 10, test speed 10. Force at break (N) and breaking elongation (%) were measured. The data on tensile strength measurement was used for calculating the Weibull's

modulus [31]. The fiber structure was analyzed using Scanning Electron Microscopy (SEM) (Model: ZEISS EVO-MA 10) with EDX analysis and AFM (Bruker Dimension Icon and Bruker Innova). The design stress ( $\sigma_{des}$ ) with 99 % confidence has been calculated to find the amount of stress at which no fracture of the fiber would be observed.

The fiber was opened, processed for making Yarn by blending with wool, silk, viscous, cotton, and were tested for weaving in a loom at the Weavers Service Station, Kolkata, India, with the developed yarn used in the Warp while cotton (2 plies) used in Weft. The developed yarn (thread) was visualized under SEM (Model: ZEISS EVO-MA 10) and compared with that of cotton thread.

### 2.4. Statistical analysis

For statistical analysis of the biofilm formation, enzyme production, and fiber quality testing with pure isolates and consortium, single-factor ANOVA was used. For consortium-based fiber processing, Weibull's modulus was calculated using Microsoft Excel 2007.

## 3. Results and discussion

Bacteria survive better in an environment as consortium than pure isolate [32] (during synergistic interaction), resulting in better performance through production of desired enzyme combination [28]. In this study, two well-characterized bacterial strains, viz. *Bacillus thuringiensis* MCC2138 (GenBank Acc No FJ377720) from the marine coastal water of Mandarmani, Midnapur, West Bengal, India and *Bacillus subtilis* ABDR01 (GenBank Acc No MK301273) isolated from the aerosol of the Department of Microbiology, Tripura University, West Tripura, India, were combined in 1:1 ratio to develop a consortium. While *Bacillus thuringiensis* MCC2138 was reported earlier to be gram-positive diplo bacilli producing protease, amylase, DNase, oxidase, catalase, pectinase, cellulase, and xylanase [28], the newly isolated *Bacillus subtilis* ABDR01 was found to be gram-positive bacilli, which produced oxidase, catalase, amylase, lipase, protease, pectinase, xylanase and cellulase while lacked production of DNase. Pectinase, xylanase, amylase, and cellulase were quantified for each isolate (Table 1). The bacterial isolates used in the formulation have a strong biofilm-forming ability (ABDR01: 9.026 optical density at 620 nm; MCC2138: 0.953 optical density at 620 nm), as per Martin's definition [29]. This observation opens up the opportunity of setting up biofilm reactor for continuous enzymes production. The enzyme production by the isolates was also checked under the immobilized condition (Table 1). This consortium ( $4.1 \times 10^9$  colony-forming unit/mL) produced extracellular pectinase, xylanase, cellulase, and amylase (Table 1) under suspended and immobilized conditions in batch mode operation at 37 °C. The consortium's enzyme production was more than the

**Table 2**

Quality assessment of the fiber. Weibull's modulus parameters with respect to strength of the treated fibre.

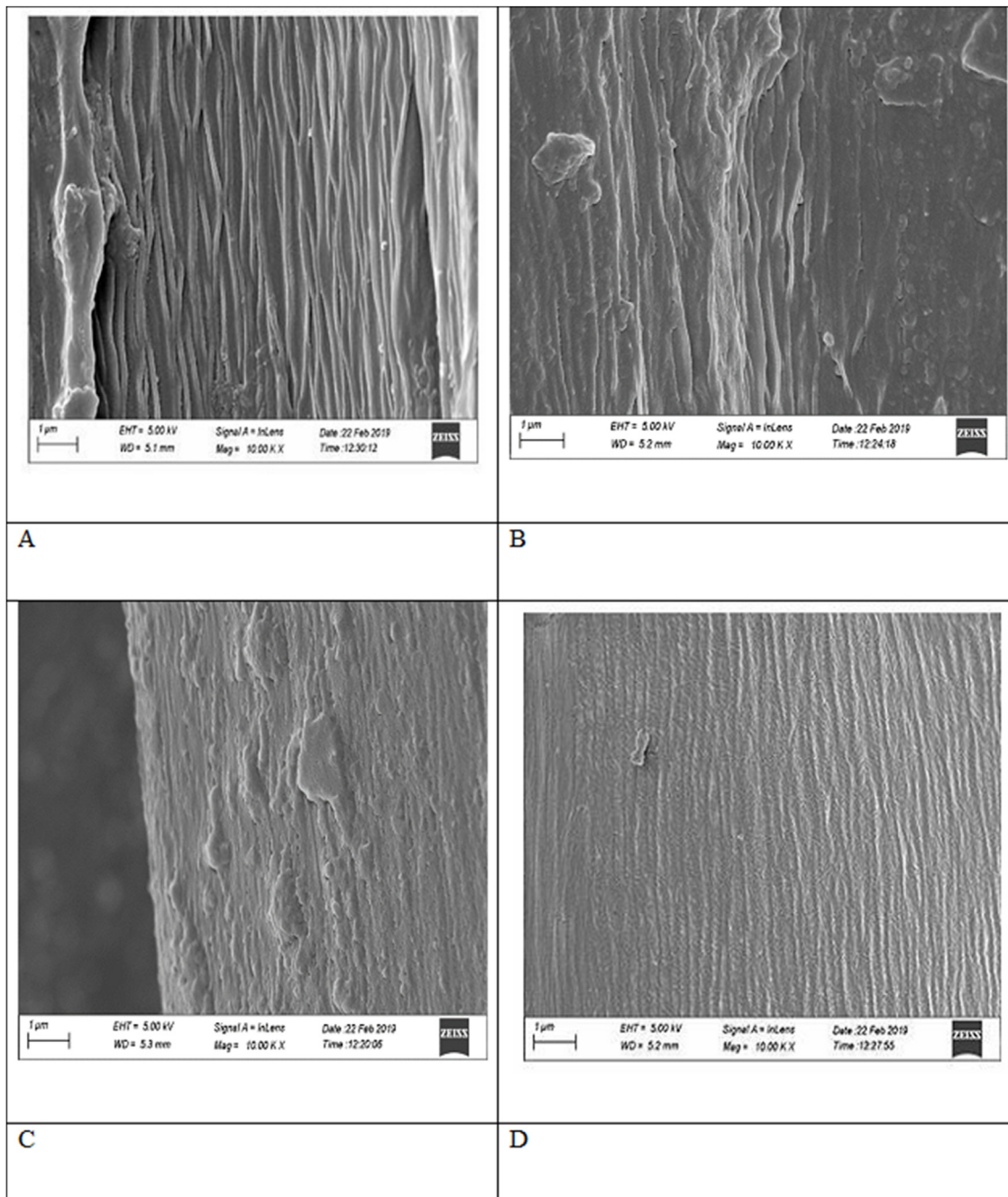
	Raw Ramie Fiber	Fully chemically treated (FCT)	Partially chemical treated (PCT)	72 hs enzyme treatment after PCT
<b>m</b>	1.6975	1.7074	2.4278	2.803
<b><math>\sigma_0</math></b>	798.9975	391.2356	793.46931	859.7909
<b><math>\sigma_{des}</math></b>	53.16512	26.445	119.3286	166.59
<b>R<sup>2</sup></b>	87%	93.8 %	86.9 %	96.4 %
<b>E</b>	2.09 %	2.36 %	2.33 %	2.32 %

\*m: Weibull's modulus.

\* $\sigma_0$ : scaling parameter.

\* $\sigma_{des}$ : design stress with 99 % confidence.

\*R<sup>2</sup>: goodness of fit in %. E : breaking elongation

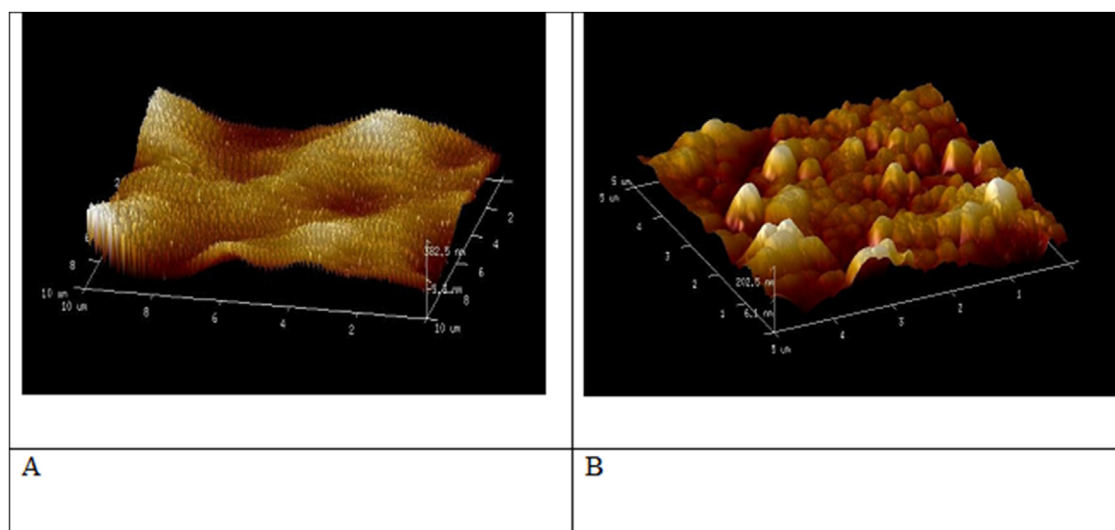


**Fig. 1.** Field Emission Scanning Electron micrographs (Sigma 300, Carl Zeiss with a gold coating of 7 nm with Quorum Q150 TES) of Ramie fiber without treatment (A), Ramie fiber with PCT followed by degumming with extracellular enzymes produced by isolate MCC2138 (B), produced by isolate ABDR01 (C) and produced by the consortium (D). Images reflect that the enzymes produced by the consortium and not the isolates alone to be appropriate for adequate fiber degumming.

individual isolates in most of the cases (except for cellulase under immobilized condition). In case of MCC2138, the extracellular production of xylanase (p-Value  $7.33 \times 10^{-3}$ ), cellulase (p-Value 0.03), and amylase (p-Value  $3.67 \times 10^{-4}$ ) were significantly increased under the immobilized condition. Similarly, in the case of ABDR01, amylase production was significantly (p-Value 0.02) increased upon immobilization. The enzyme production by the consortium under suspended and immobilized conditions was similar. As stated in the literature, this finding again reconfirms that immobilization either enhances or maintains system performance [32]. Also, it protects the microbes from external perturbations. Hence for continuous production of the desired enzyme mixture, a biofilm reactor could be used. Microbes in a

biofilm are less susceptible to environmental stress [32,33] requiring one-time inoculation of the microbial culture with a sustained performance for a prolonged period.

Optimization experiments revealed 6-h dipping in water at 1:8 F: Lq ratio to be best for gum removal through washing from the freshly decorticated fiber. Literature suggests that decorticated Ramie fiber contains 22–30% [34] gum, of which around 20% needs to be removed for spinning [1]. This experiment revealed the crude Ramie fiber to contain 23.87 g of gum per 100 g of fiber. The gum was reduced to 20.78 g/100 g after washing. Further analysis of partial chemical degumming revealed 1:8 F: Lq ratio, 45 min of heating at 121 °C with 3% NaOH, 1% sodium tripolyphosphate, and 0.02 % Tween 80 to yield maximum degumming. Since our



**Fig. 2.** Atomic Force Microscopy (Bruker Dimension Icon and Bruker Innova) images of (A) Fully chemically treated Ramie fiber with released fibrils represented as spikes (B) image of biochemically treated fiber (partial chemical followed by enzymatic treatment) showing evenly distributed gum on the fiber.

approach involves microbial finishing of the fiber [3], hence some gum needs to be left after chemical treatment for enzymatic degumming, which improves texture, luster, and strength of finished fibers. Thus for further experiments, the partial chemical degumming was carried out at 121 °C for 45 min with DS composition as 2% NaOH, 1% sodium tripolyphosphate, and 0.02 % Tween 80. The residual gum after partial chemical treatment (PCT) was 6.42 g/100 g.

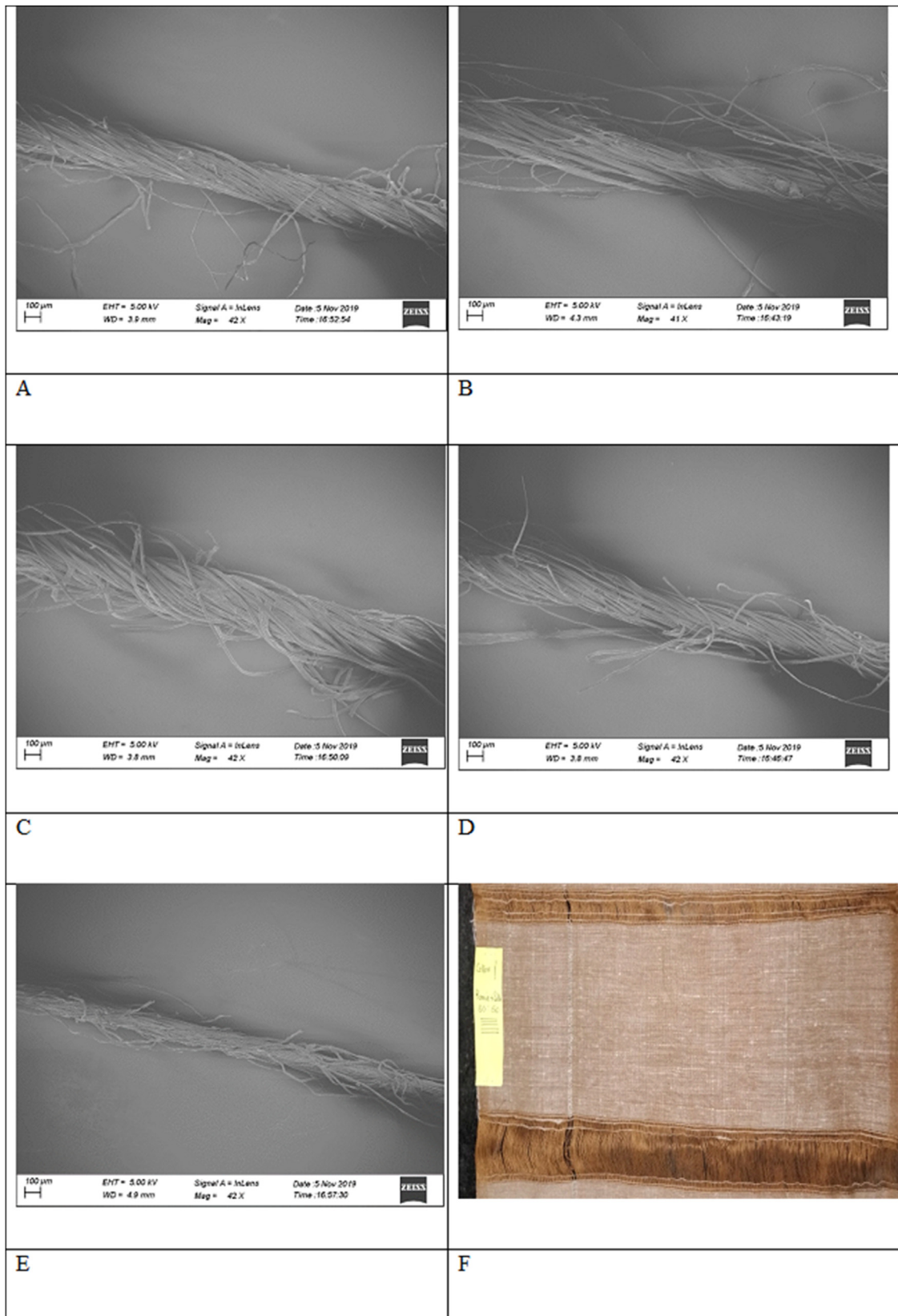
The COD analysis of the pre-treated and post-treated DS showed a value of 297.62 and 5152.46 mg/L (with 1% NaOH containing DS), 329.10 and 6690.03 mg/L (with 2% NaOH containing DS), 385.33 and 8696.88 mg/L (with 3% NaOH containing DS), 422.06 and 8331.80 mg/L (with 4% NaOH containing DS), 476.79 and 6660.79 mg/L (with 5% NaOH containing DS) while 533.76 and 6185.50 mg/L (with 6% NaOH containing DS) respectively. The result shows pre-treated DS with 1% and 2% NaOH to be close to the discharge level {250 mg/L as per the Environmental Protection Agency (EPA), India}. However, post-treatment the COD increases drastically, which could be due to the gum removed or the interaction between the chemicals in the DS and the removed gum. In order to understand the same, COD of the gum solution extracted at 1:6 F: Lq ratio upon heating at 121 °C for 15 (3422.98 mg/L), 20 (3575.91 mg/L), 30 (4920.81 mg/L), 40 (6238.73 mg/L) and 45 min (6544.59 mg/L) was assessed. The data indicates the gum to be the primary reason for enhancing the COD in the degumming effluent. Hence, proper washing of the freshly decorticated fiber is an important step in the fiber's downstream processing, which results in substantial gum removal before the use of any DS-based treatment. The conventional degumming process yields 28,000 mg/L of COD of wastewater, while the oxidation degumming process containing anthraquinone reduced it to 18,000 mg/L with residual gum of 8.23 gm/100 g [5]. The current study revealed the developed process to generate the wastewater with COD of 6690.03 mg/L while containing 6.42 g/100 g gum. Hence the current process is more efficient as well as eco-friendly compared to other available in the literature. The chemically treated fibers were then subjected to microbial degumming. The extent of gum removal was similar at 1:8 to 1:10 F: C ratio. However, the lustre, texture, and strength being maintained, 1:8 F: C ratio was considered for subsequent study. The optimum degumming was observed upon 72 h of incubation at 37 °C with 1:8 F: C ratio resulting in 3.96 g/100 g residual gum. Freshly decorticated washed fibers were also directly subjected to

biological treatment before PCT. They showed 7.44 g/100 g residual gum. This shows that both PCT and biological treatment are effective, but its combination gives the right texture, feel and strength to the fiber.

Partial chemical degumming followed by bio-treatment with microbial enzymes was sufficient for producing proper spinnable fibers. The microbial enzyme suspension produced durable (Table 2), soft and lustrous Ramie fiber when processed for 72 h under the dipped condition at room temperature. The improved texture and strength compared to complete chemical treatment are attributed to even degumming of the fiber (Table 2, Figs. 1 and 2) with about 3.96 % remaining gum. The enzyme combination ensured sufficient degumming to achieve proper spinnability while preventing the release of the fibrils, the latter resulting in the matt (coarse) finish of the fully chemically treated fiber. This is in agreement with the previous work done with pure isolate MCC2138 [3].

According to the current study from fresh decorticated Ramie fiber, the optimized degumming condition is as follows: 1. Washing in water (1: 8 F: Lq ratio) after 6 h of dipping; 2. Partial chemical degumming in 1: 8 F: Lq ratio with 2% NaOH, 1% Sodium tripolyphosphate, and 0.02 % Tween 80 at 121 °C for 45 min, followed by washing in water, neutralizing (pH 7.0) in 1% acetic acid and again washing in water; 3. Biological treatment of PCT fiber in 1:8 F: C ratio at 37 °C for 72 h followed by rinsing in liquid detergent followed by water. The gum content of the finished fiber was 3.96 g/100 g. Available literature revealed residual gum content of 4.17 g/100 g [15], and 7.72–9.88 g/100 g [14] using different degumming methods. That further explains the current process to yield softer and lustrous Ramie fiber.

It was observed that fibers treated with the consortium had better-polished finish with higher tensile strength having Weibull's modulus of 166.6. The tensile strength of the individual fibers (20 replicates) calculated by Weibull's Modulus revealed the consortium treated fiber as more durable than that of fully chemically treated ones (Table 2). The biologically treated fiber could withstand the force of 166.59 N (96.4 % Goodness of Fit) without introducing any fracture in the fiber in 99 % of the cases. In comparison, the fully chemically treated fiber could just withstand up to 26.44 N (94 % Goodness of Fit). This difference might be due to the fiber's extensive degumming resulting in the release of fibril and hence decrease in tensile strength in the case of chemical treatment. The breaking elongation (%) for fully chemically treated



**Fig. 3.** SEM images of threads formed with and without blending. A. Threads of Ramie with 50% cotton blending, B. Threads of Ramie with 50% silk blending, C. Threads of Ramie with 50% wool blending, D. Threads of Ramie with 50% viscous blending, E. Cotton thread, F. Fabric woven with the blending of cotton in weft and blended Ramie and silk (50:50) in warp.

fiber (2.36 %), PCT fiber (2.33 %) and PCT followed by biologically treated fiber (2.32 %) were similar (p value: 0.977). The process could produce durable, lustrous fibers that were easily blended with wool, silk, cotton, viscous for production of yarn (Fig. 3a–e), and was successfully woven into the fabric (Fig. 3f). The blended yarns were found to be finely spun. The SEM images reflect that pure cotton thread is more compact than either of the Ramie mixed thread. The images indicate that the spinning process could be achieved but can be further improved to make it similar to cotton thread in fineness. It also shows the quality of yarn that can be easily woven into cloth. These features are clearly reflected in the SEM images.

The theoretical explanation of the degumming process described in this study is detailed below. The gum in Ramie consists of 19–30 g/100 g of non-cellulosic gummy matter, consisting of pectins, waxes, lignin, and hemicellulose which needs to be substantially removed from the cell wall to use the fiber for fabric production. The gum is the cementing material to hold the fibers together to form bundles. Lipid waxes, water-soluble pectins, and hemicellulose are removed first being water-soluble. Its removal is evident during washing (for 6 h at 1:8 fiber: water ratio) of the freshly decorticated fiber resulting in 20.78 g/100 g residual gum. The PCT involves treating these washed fibers in 1:8 ratio with 2% NaOH and 1% sodium tri-polyphosphate and 0.02 % Tween 80. NaOH creates the alkaline condition which dissolves Lignin through removing the calcium pectate in the cementing material. Sodium tripolyphosphate acts as a chelating agent that converts calcium pectate into soluble compound under alkaline condition. Tween is the non-ionic wetting agent, which ensures better interaction of the gum with the degumming solution.

The elevated temperature of 121 °C facilitates the process of gum removal. To avoid persistence of alkalinity leading to uncontrolled fiber damage due to degradative action of oxygen on the cellulose, the fibers after degumming solution treatment are washed with water and then are neutralized with 1% acetic acid to bring the pH down to 7.0. This process was also essential for microbial action after chemical treatment. The extent of residual gum after conventional chemical treatment is 5 g/100 g [35]. In the current case, it is maintained at 6.42 g/100 g. This is to ensure that there is adequate gum for the microbial enzymes to work on the fiber. The microbes, as well as the consortium, produce extracellular pectinase, xylanase, lipase, amylase, and cellulase. All these enzymes work on different gum components to degrade it except for cellulase, which works on the cellulose backbone. However, the incubation time is such that the enzyme causes singeing effect instead of breaking the backbone, making the fiber soft, smooth and lustrous instead of weakening as in case of full chemical treatment as well as 96 h of treatment with microbial enzyme alone as reported elsewhere [3].

#### 4. Conclusion

This work tries to eliminate the shortcoming of the Ramie fiber application in the textile industry by judiciously combining partial chemical treatment with bio-treatment utilizing microbial enzymes. The integrated process results in a finished fiber of superior quality characterized by softer texture, lustrous appearance, and higher tensile strength. The reason behind this improvement has been identified through advanced microscopic techniques. The degumming process's optimization has been verified through spinning and weaving into fabric upon blending with different natural fibers like cotton, wool, silk, and viscous. Ramie fiber's enhanced usage in the textile industry is expected to spawn economic benefits to those undertaking cultivation of Ramie crop for fiber production. Thus this work depicts a process that improves the quality of processed Ramie fibers with better

environmental protection and adds value in economic terms, which is of profound relevance from the perspective of material science and subsequent economic activity.

#### CRediT authorship contribution statement

**Shaon Ray Chaudhuri:** Conceptualization, Funding acquisition, Supervision, Project administration, Writing - review & editing, Formal analysis. **Mandakini Gogoi:** Formal analysis. **Tethi Biswas:** Formal analysis. **Soumya Chatterjee:** Formal analysis. **Chaitali Chanda:** Formal analysis. **Ronald Jamatia:** Formal analysis. **Ajoy Modak:** Formal analysis. **Sunil K. Sett:** Formal analysis. **Indranil Mukherjee:** Writing - review & editing, Supervision.

#### Declaration of Competing Interest

The authors report no declarations of interest.

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#### Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.btre.2020.e00532>.

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