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Thermomechanical Properties of Greige Cotton Fabric Subjected to Chemical and Enzymatic Bioprocessing for Textile Applications.

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Abstract

The study aims to evaluate the cotton fabric on thermal and physical properties as to analyze greige fabric for further biochemical treatments. It also aims for listing thermal and mechanical properties which can further benefit for processing the raw greige fabric for further technical and nontechnical textile treatments. It proves the influence of chemical and enzymatic treatments on the weight loss, tensile strength, thermal stability, and physical properties of cotton fabric. Chemical treatments shifted the degradation profile into three distinct stages, while enzymatic solutions specifically targeted non-cellulosic impurities in the 190°C–295°C range, resulting in a cleaner, more thermally stable cellulosic structure. By analyzing the transition from greige to treated state, the study aims to set up a baseline for further bioprocess treatments. After the process conditions are performed, GRA is used that helped to find a point where process variables can be accounted. Grey Relational Analysis (GRA) helps to improve simple one-variable to a multi-objective decision-making framework. This is essential for textile analysis because improving one property (like tensile strength) often inadvertently degrades another (like elongation or toughness).

Fabric Definition

The grey fabric can be defined as the most basic type of textile material and have most fundamental plain weave (simply 1 wrap:1 weft). The fabric to become greige goes through different chemical, mechanical pre procedures that are ginning, spinning, weaving with chemical procedures like desizing, scouring, bleaching and mercerization [1]. These procedures more or else are used for cleaning the material, removing unnecessary substances and bringing the grace of the material for further usage in various other clothing's and versatile materials or can be used for technical usages. The mentioned chemical stages are important for achieving the final appearance of the material and further processing also depend on these stages. These stages enhance the fabric's moisture retention, better and homogenous appearance and shows better flexibility with upcoming stages of processing.

The Greige with GSM approximately 38 looks like attached [Figure 1]

The fabric which comes to finishing stage after weaving where the quality control is often simple and finishing additives are applied solely based on the end use [2]. As simplified and

broad knowledge of fabric and its associated properties is useful for its applications in further technical and clothing usages [3]. Starting from showing which type of fibers are used, man-made or natural and then how weave is processed after spinning.



Figure1-Greige fabric picture

Thermal characterization of greige fabric (untreated)

TGA/DTG is done for greige fabric for figuring out various properties as mentioned below.

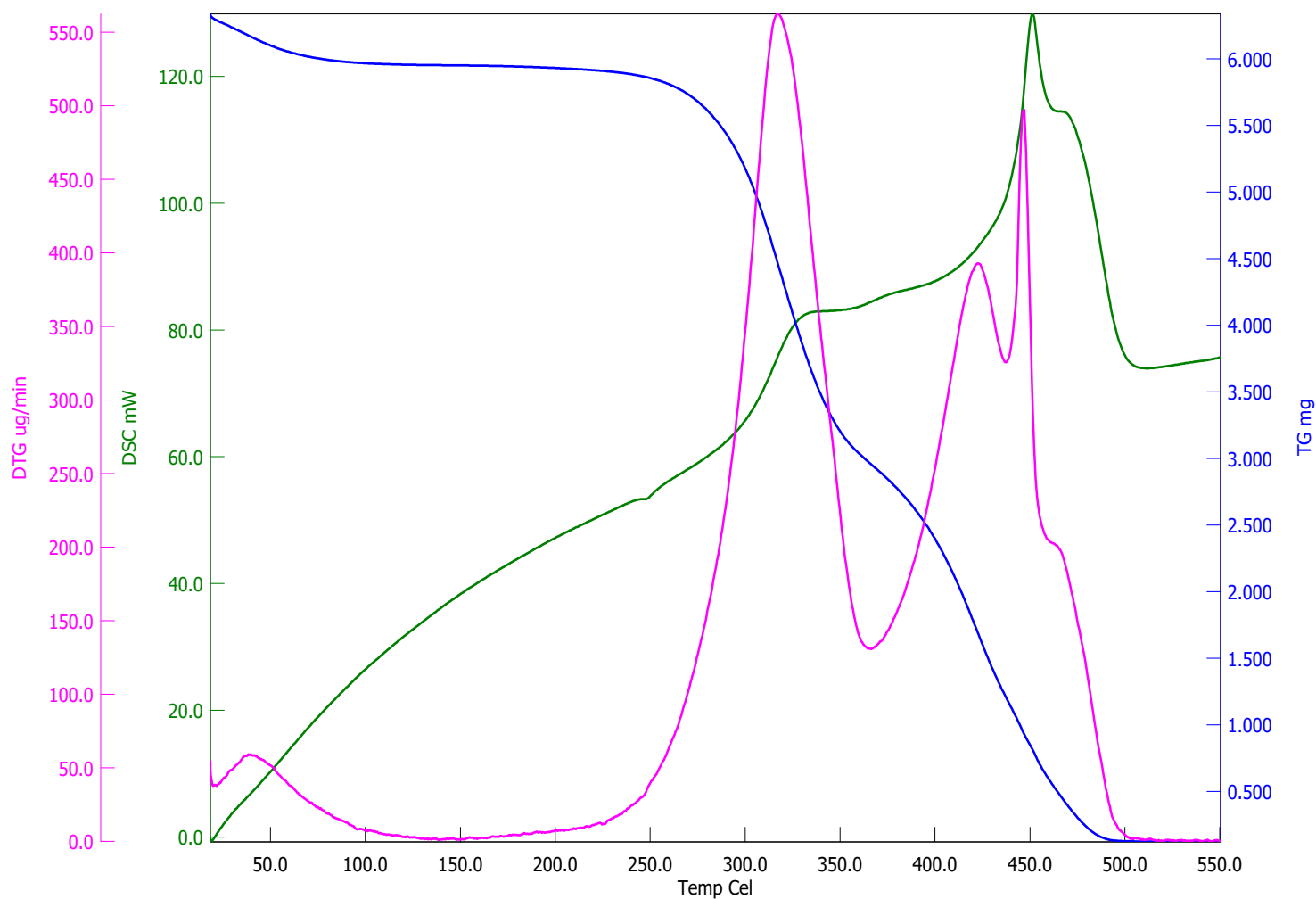
The analysis of the fabric sample (Initial Weight: 6.34 mg) reveals four distinct stages of weight loss during heating from 20°C to 550°C in air. The initial stage involves the evaporation of absorbed moisture, followed by the degradation of non-cellulosic components, such as waxes and pectins, introduced during earlier scouring processes[4].

Stage 1: Moisture Desorption (20°C – 100°C). The sample lost approximately 5.7% of its weight (from 6336.78 µg to 5972.78 µg). This represents the evaporation of physically adsorbed water and light volatile substances within the raw fabric fibers. This first loss is the evaporation of physically absorbed moisture and volatile matter. A 6% moisture regain is typical for cotton-based fibers (standard regain for cotton is 8.5%).

Stage 2: Degradation of Impurities (190°C – 295°C). A significant weight loss of approximately 9.3% occurred in this range (from 5936.06 µg to 5346.33 µg). In grey fabric, this stage corresponds to the thermal decomposition of non-cellulosic components such as hemicellulose, pectins, and waxes as done in [Graph1]

Stage 3: Cellulose Decomposition (295°C – 400°C). This is the major degradation phase, with a weight loss of roughly 45.8%. The high DTG (Rate of Weight Loss) indicates the rapid breakdown of the α -cellulose polymer chain, which is the primary structural component of the fabric. This is the most significant degradation phase, corresponding to the thermal-oxidative decomposition of cellulose, the primary part of grey fabric. During this phase, the polymer chains break down into levoglucosan and other volatile products.

Stage 4: Char Oxidation & Residue (400°C – 550°C) The remaining carbonaceous char undergoes combustion in the presence of air, leaving a final residue (ash) of approximately 1.9% (120.9 µg) as shown in [graph1]. In an air atmosphere, the carbonaceous char formed during Stage 2 undergoes combustion. This is shown by a secondary weight loss and a strong exothermic peak in the DSC curve at approximately 451.56°C.



Graph 1- TGA /DTA of greige fabric

Sample conditions for TGA/DTA

The sample is 6.340 in weight. The fabric is specified as 40 GSM (grams per square meter), writing down a lightweight, relatively porous material which likely allows for rapid oxygen diffusion and quick thermal response during the STA run. The reference material used is alumina (6.6mg) used in alumina pan. The analysis is conducted in Air (Nitrogen is turned off). This writes down an oxidative environment rather than an inert one. The temperature is ramped from 20°C to 550°C at a heating rate of 10°C/min.

Thermal properties (TGA/DSC)

In the initial phase of TGA (which begins at 30 degrees), a small percentage of weight loss. For greige fabric, this represents the evaporation of absorbed physical moisture. Since the test is performed in Air, the TGA curve would represent the oxidative decomposition of the fabric. For a grey fabric (which is mostly cellulose), a significant weight loss stage between 250°C and 400°C, corresponding to the breakdown of cellulose chains. The program stops at 550°C. In an air atmosphere, most organic components of the fabric had undergone combustion by this temperature, leaving behind only inorganic fillers or residual ash. The starting temperature of 20°C allows for the detection of initial weight loss (usually before 100°C) which characterizes the moisture regain of the 38 GSM fabric. Next is the phase transitions which would capture endothermic peaks for dehydration and exothermic peaks for the oxidation/char-burning phases as the temperature approaches the 550°C limit.

The low residual weight (1.91%) confirms that the grey fabric is predominantly organic (likely 100% cotton). The residue stands for inorganic fillers, salts, or agents (like starch) used during the weaving of the grey fabric. The fabric is thermally stable up to approximately 278°C, after which rapid degradation occurs. This temperature defines the safe processing or usage limit for the material in an oxidative environment. The presence of a significant exothermic peak at 451.56°C indicates the high energy release associated with the combustion of denim site, which is relevant for various applications.

The DTG curve shows the rate of weight loss, helping to name the exact temperature of maximum degradation: A small peak (rate of 10.8 µg/min) confirms the maximum rate of moisture evaporation. The rate increases significantly to 269.7 µg/min as hemicellulose and pectins degrade. The highest rate of weight loss (239.1 µg/min) occurs in this region, identifying the point of most rapid cellulose chain breakdown.

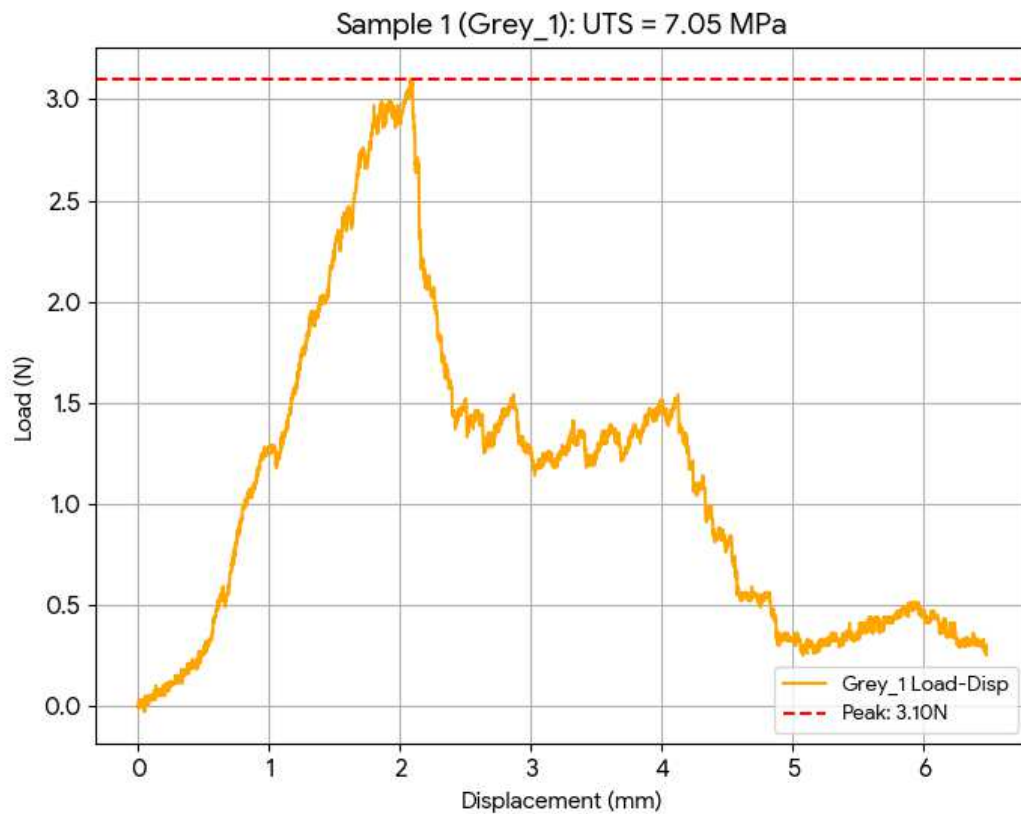
The DSC curve measures the heat flow (in µW), indicating whether reactions are endothermic (absorbing heat) or exothermic (releasing heat). In the range of 20°C – 100°C, the heat flow increases (from -169.1 µW toward positive values), indicating an endothermic process as energy is consumed to evaporate water. Since the test is conducted in air, the cellulose degradation starting after 295°C is accompanied by oxidation. The DSC values show a continuous rise (from 24,335 µW at 92°C to 87,396 µW at 397°C), reflecting the significant energy released during the combustion of the cellulose fibers and char in the presence of oxygen.

Tensile properties

Tensile strength refers to the amount of stress that the material can withstand before breaking. In the tensile test, the initial linear portion represents elastic deformation (where the material would return to its original shape), followed by plastic deformation (permanent change), reaching the Ultimate Tensile Strength, and finally fracture[5].

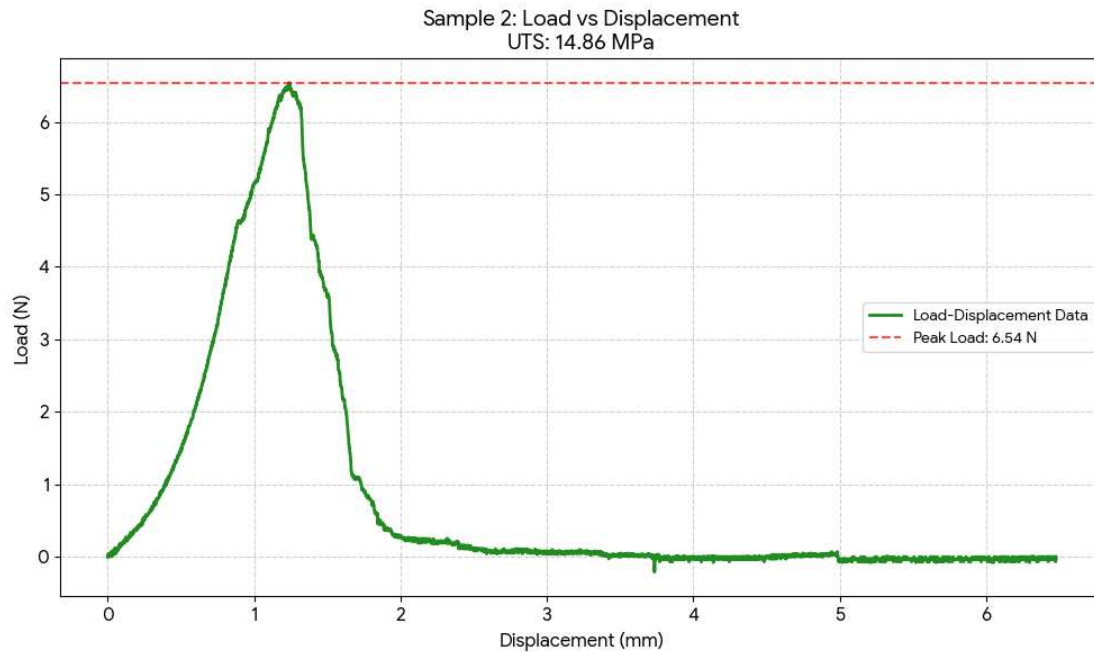
The tensile strength (breaking force) and elongation are calculated from the displacement and load data provided by the UTM (Universal Testing Machine) for the grey fabric[6]. The width between the grips in the UTM is taken as 2mm.

Three samples are taken for UTM testing. For the sample 1, [Graph2] showed the load and displacement.



Graph 2- Sample 1 loadvs displacement plot

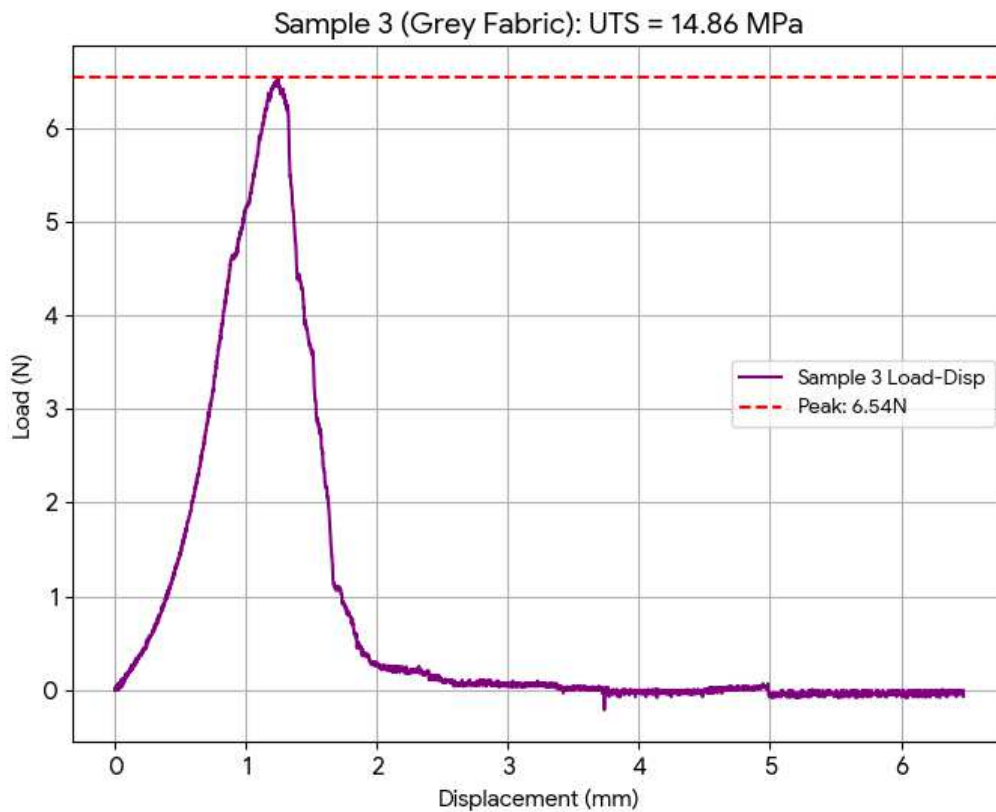
Sample 1 has 3.10 N as peak load. the strength is 7.05 MPa, displacement at peak load is 2.08 mm and maximum displacement seen is 6. 47mm.Forsample 2, The [Graph 3] illustrates the relationship between the applied force (Load) and the extension of the material (Displacement).



Graph 3 - Sample 2 Tensile Test Graph

Sample 1 has 6.54 N as peak load. the strength is 14.86 MPa and maximum displacement seen is 6.47mm. The curve shows a clear elastic region followed by plastic deformation, reaching its maximum strength before the load begins to drop as the sample approaches fracture. For sample 3, Based on the data Sample 3 has 6.54 N as peak load. The strength is 14.86 MPa, displacement at peak load is 1.24 mm and maximum displacement seen is 6.47mm. The average of all is given in [Table 1]

The Load vs. Displacement curve for Sample 3 is as per the data shown in [Graph 4].



Graph 4-Sample 3 displacement vs load

Sample ID	Peak Load (N)	Ultimate Tensile Strength (MPa)	Max Displacement (mm)
Sample 1	3.1	7.05	6.47
Sample 2	4.88	11.09	6.47
Sample 3	6.54	14.86	6.47
Average	4.84	11	6.47

Table 1-Peak load, strength and displacement of 3 samples taken for UTM

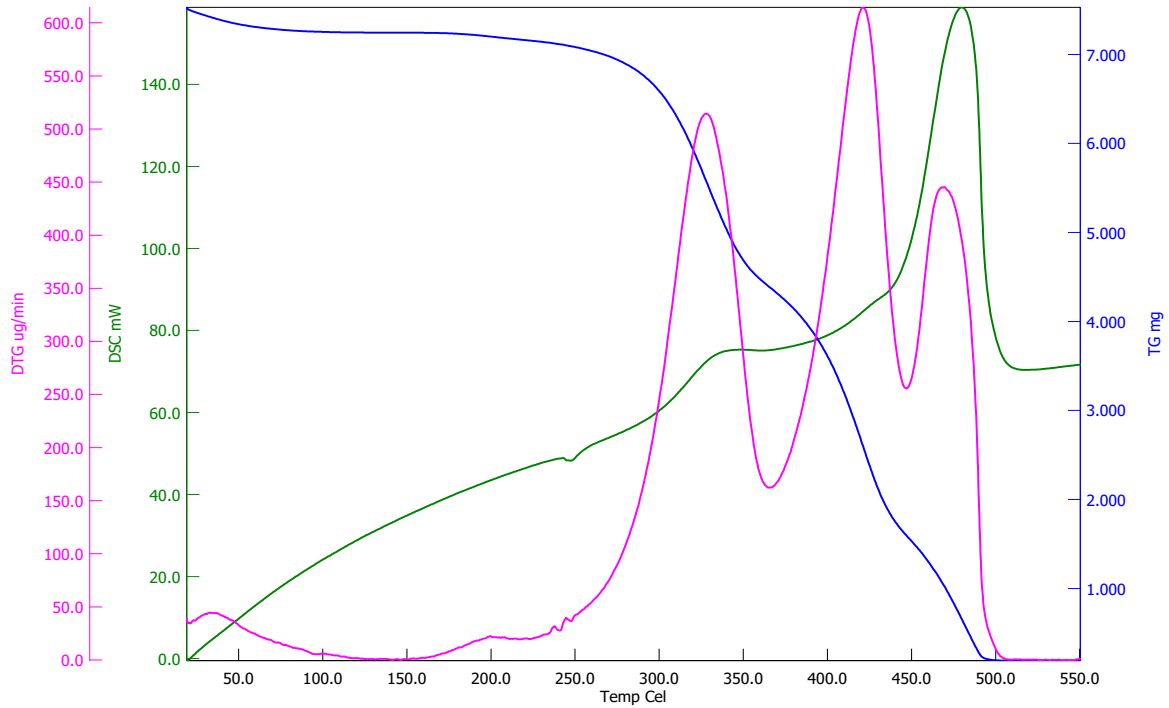
The average tensile strength across all three samples is 11 MPa. Sample 3 exhibited the highest strength 14.86 MPa, while Sample 1 is the weakest 7.05 MPa. All three samples showed an identical maximum displacement of approximately 6.47mm. However, the samples reached their peak loads at different stages. Sample 1 required more displacement to reach its (lower) peak, whereas Sample 3 reached a much higher peak load earlier. The fabric shows a ductile profile with a clear post-peak softening region. The final representative Tensile Strength for this material batch is 11MPa with standard deviation of 3.91 MPa. The wide range suggests that fabric has slubs and defects.

Chemically treatment

The fabric is treated with PERC 5ml in 100 ml for polishing [7], 1g/L NaoH for scouring and 1% sulphuric acid for desizing as generally done at industry level. After the treatment, the chemically treated fabric is analyzed to determine its thermal stability. Initial weight of sample is 7.53 mg, using alumina as a reference. At the onset of heating (approx. 19.2°C), the sample weight is recorded at 7527.85 µg. The treatment affects the degradation profile, ensuring the fabric is stabilized for high-temperature industrial processing. There is a slight, shallow dip at the start, due to the evaporation of adsorbed moisture. The fabric remains stable until roughly 280°C. At this point, the curve drops sharply, indicating the primary decomposition of the fabric polymers (likely cellulose if it's cotton, or synthetic blends). There is a rapid mass loss at 300°C – 480°C. The mass falls from 7 mg to near 0 mg. This suggests that the chemical treatment and the base fabric are almost entirely volatilizing or turning into gaseous products. By 500°C, the mass is effectively zero. For a "fire-retardant" treatment, you would usually expect a higher residual char (a flat line at the end that isn't zero) as shown in [Graph 5]. The fact that it hits zero suggests the treatment might be more focused on thermal stability or processing rather than high-char flame retardancy.

The pink line is the derivative of the TG curve. Peaks here indicate the maximum rate of weight loss at peak 1 (325°C) which Represents the first major breakdown stage (decarboxylation or dehydration of the treated fibers), peak 2 (420°C): This is the most intense peak, representing the most aggressive thermal degradation of the polymer backbone and peak 3 (475°C): This final peak usually corresponds to the oxidation or "glowing" combustion of the remaining carbonaceous residue.

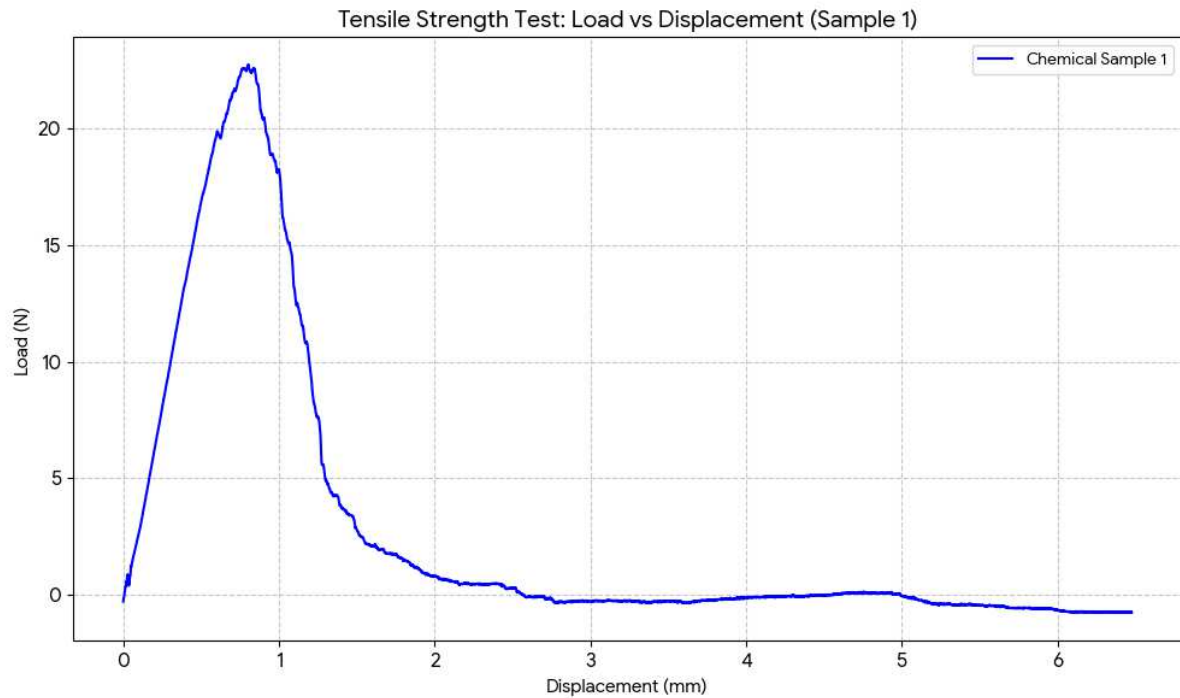
The DSC Curve (Green) shows the Energy Flow. The green line shows the heat flow (mW). Because the slope is generally upward, this indicates a predominantly exothermic process (releasing heat) as the temperature increases. The steady rise suggests the fabric is undergoing oxidative degradation. There is major exothermic peak (480°C) which aligns perfectly with the final DTG peak and the final drop in mass. This is the burn-off point where the fabric residue is completely oxidized. The treatment appears to shift the degradation into three distinct stages. The chemically treated fabric is analyzed to determine its thermal stability.



Graph 5- TGA /DTA of greige fabric

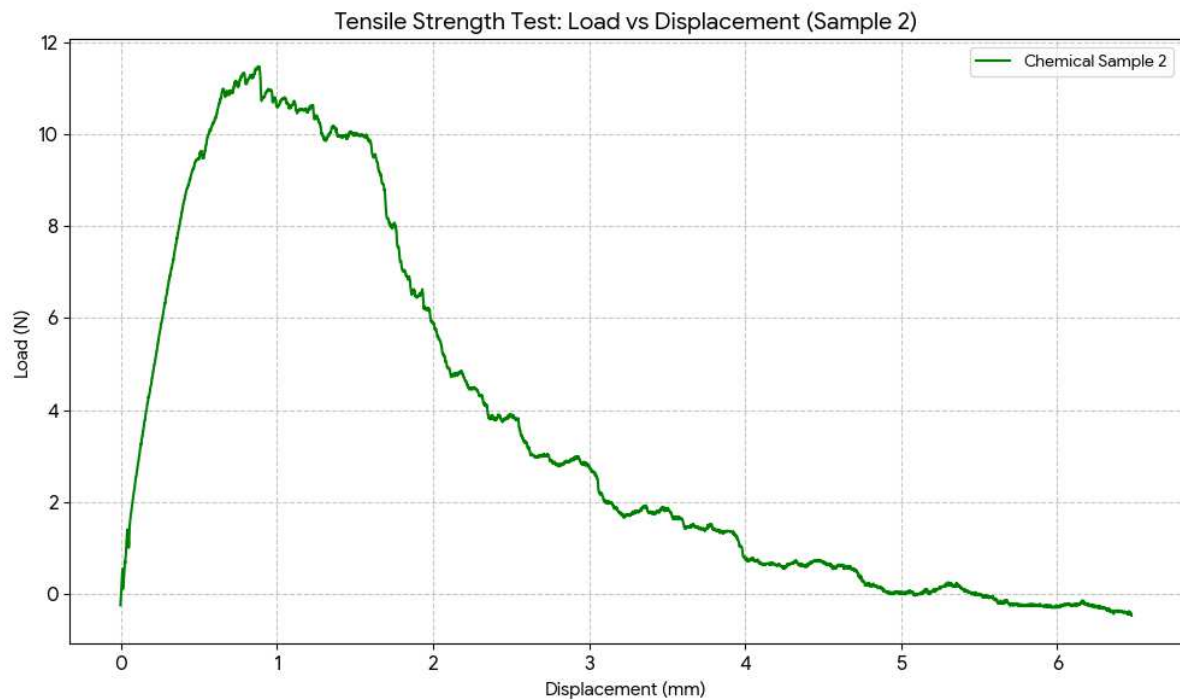
Tensile Strength

Sample1's tensile test recorded as shown in [Graph 6] the fabric response to an axial load over time, measuring displacement and the resulting force. At 0 seconds, the sample had a negligible displacement of -0.001144 mm and a baseline load of -0.27 N. As the test progressed, both displacement and load increased steadily, indicating the material was under tension. The maximum recorded load in the provided data was 19.87 N, occurring at approximately 6.0150 seconds with a displacement of 0.602803 mm. The data shows a consistent increase in load relative to displacement, which is characteristic of the elastic and early plastic deformation regions. Near the end of the recorded data (around 6.0300 seconds), the load began to fluctuate and slightly decrease (dropping from 19.87 N to 19.80 N), which may indicate the sample was starting to experience necking.



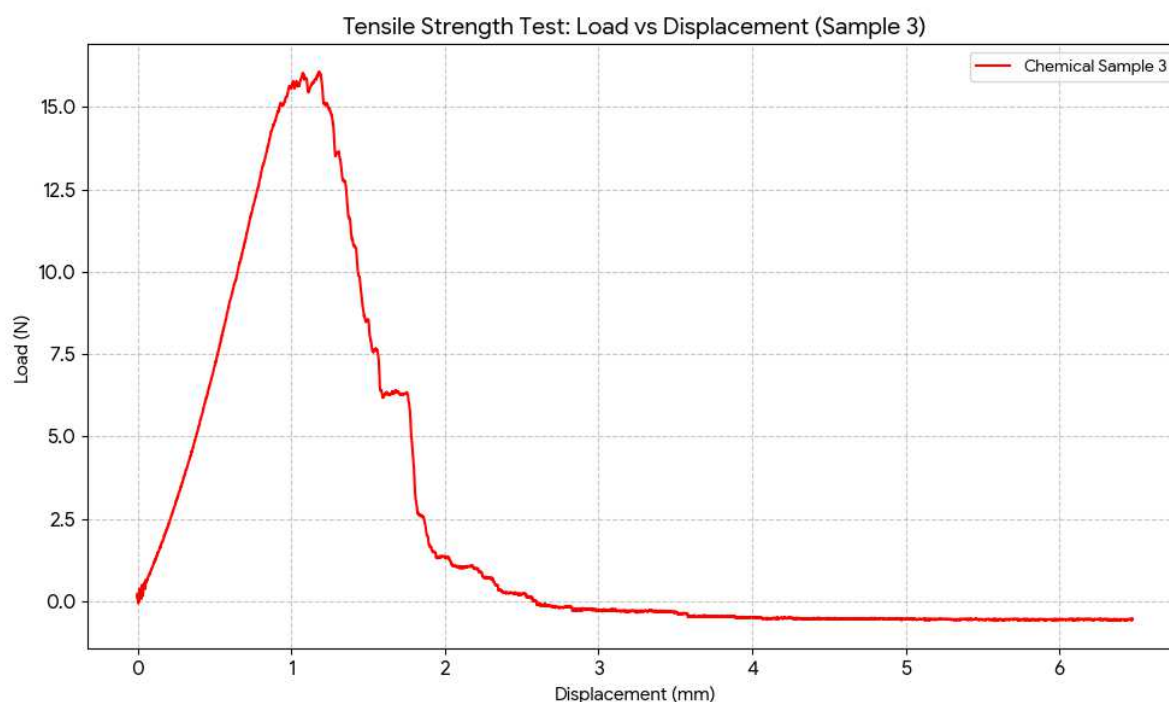
Graph 6-chemical sample 1 tensile strength

Sample 2 exhibits a distinct profile compared to the other samples, characterized by higher ductility (stretch ability). The mechanical behavior of chemicalSample 2 suggests a specific effect from its chemical treatment. With a break strain of 23.15%, this sample is significantly more flexible as shown in [Graph 7]. In a textile context, this usually means the chemical treatment did not overly



Graph 7- Chemical sample 2 tensile strength

Chemical Sample 3 reached its peak load at a higher displacement. The sample shows a steady increase in load up to 16.08 N. Interestingly, the displacement at peak load 1.181 mm, while the peak load itself is lower. After reaching the peak, there is a distinct drop in load, signifying the point of failure or rupture. The [Graph 8] highlights the structural integrity of the sample under tension.



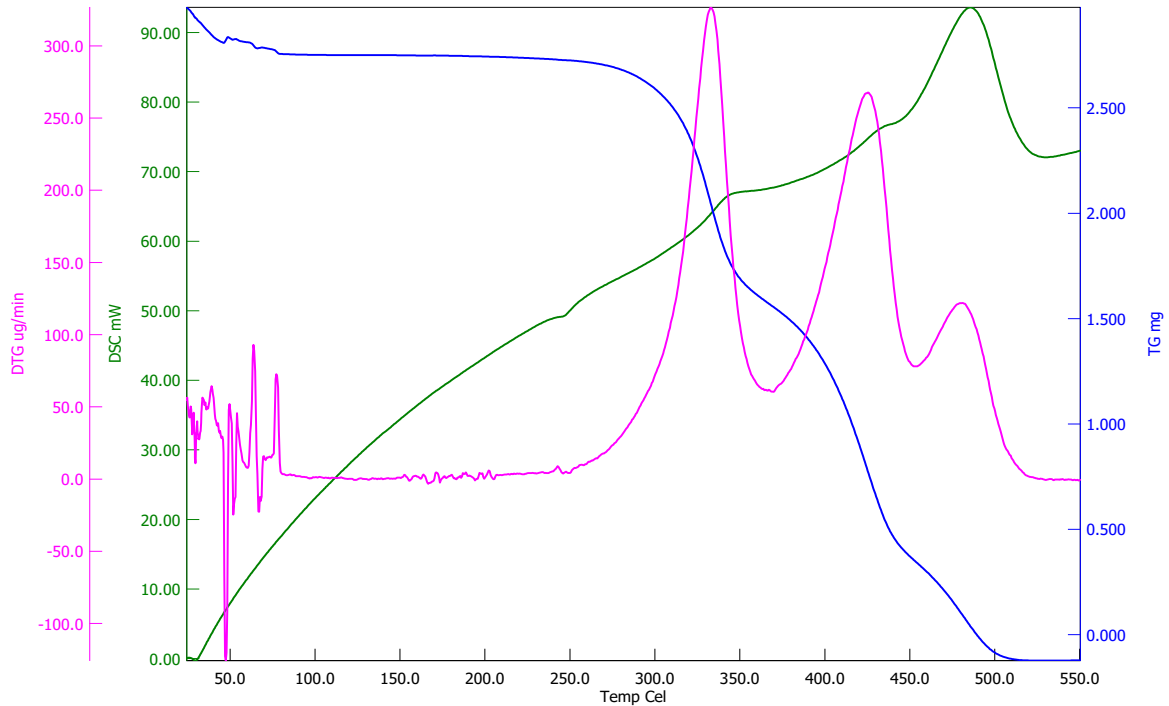
Graph 8- Chemical sample 3 tensile strength

Enzymatic treatment

While greige fabric contains primary impurities and chemically treated fabric focuses on bulk removal, the enzyme treated fabric utilizes a specific 1:1:1 cocktail of cellulase (for surface fuzz removal), Amylase (for starch/size removal), and pectinase (for cuticle degradation) [8]. These kind of biological treatment aims to achieve increased softness, luster, hydrophilicity, and a cleaner fiber surface by not using formulas which are harsh to environmental than the ones that has impact of traditional caustic chemicals[3].

Thermal Characterization

The enzymatically treated sample is analyzed for changes in thermal degradation, which indicates changes in crystallinity and surface composition. Initial weight of sample is 2.98 mg, using alumina as a reference. At the start of the measurement (approx. 24.58°C), the sample weight is recorded at 2976.55 µg as shown in [Graph 9]. As the ramp continued toward 550°C, the sample showed distinct exothermic peaks, reflecting the modified surface area and the removal of amorphous cellulose regions by the cellulase component of the cocktail.



Graph 9-Enzyme treated fabric TG/DTA

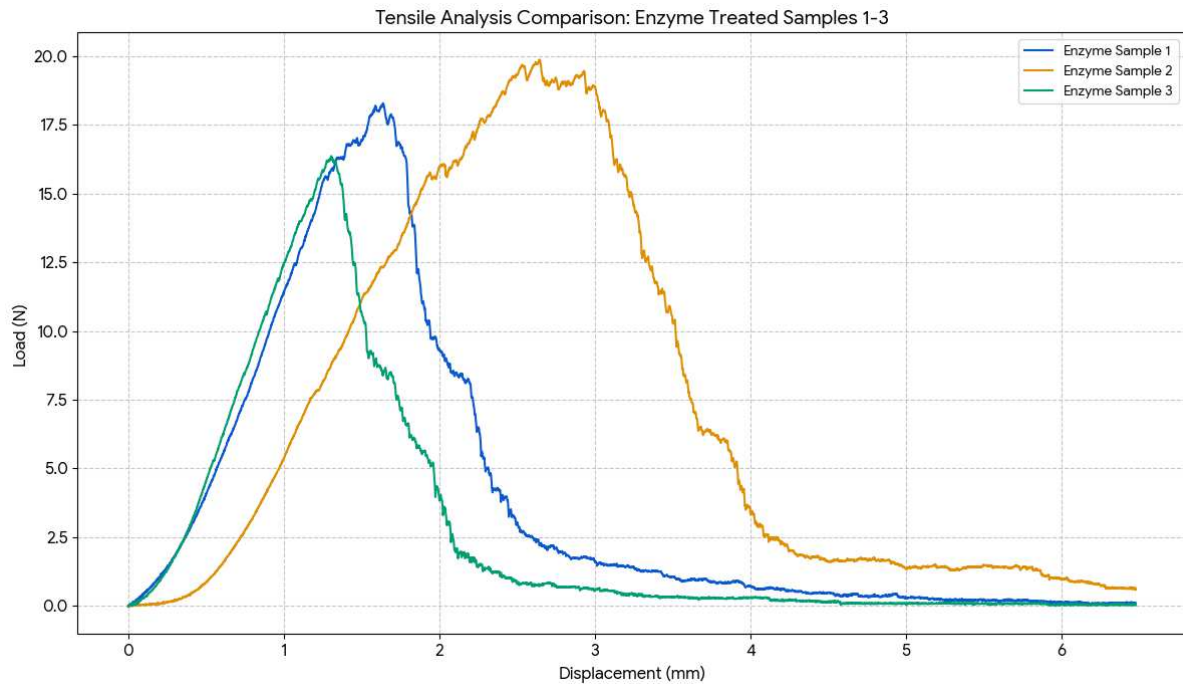
Tensile properties

The enzyme-treated samples show varied mechanical responses, exhibiting the highest strength and significantly more elongation before reaching its peak load compared to the others as shown in [Table 2]

Sample Name	Peak Load (N)	Displacement at Peak (mm)	Time to Peak (s)
Enzyme Sample 1	18.29 N	1.6367 mm	16.36 s
Enzyme Sample 2	19.87 N	2.6416 mm	26.42 s
Enzyme Sample 3	16.37 N	1.3052 mm	13.05 s

Table 2-Peak load, strength and displacement of 3 samples taken for UTM

The [Graph 10] shows enzyme Sample 2 is the strongest of the set, reaching a peak load of 19.87 N. It also shows the highest ductility, stretching over 2.6 mm before peak load. Enzyme Sample 3 reached its peak the earliest (at 1.30 mm) and had the lowest peak load (16.37 N), suggesting it may be more brittle or less reinforced than Sample 2. The combined graph below illustrates the Load-Displacement curves for all three samples. The Blue curve (Sample 1) and green curve (Sample 3) follows similar paths initially. The Orange curve (Sample 2) extends much further, demonstrating superior energy absorption or toughness compared to the other two.



GRAPH 10- Enzyme treated fabric sample tensile properties

Now the data from all 3 types of fabric (untreated, treated with chemical and treated with enzymes), by using GRA. Grey relational analysis states that response 1 (X1) will be peak tensile strength (Load in N) which is better if larger. Same is with response 2(X2) which is DTG temperature and response 3 ductility /elongation(X3)[9].

GRA Calculation

The tensile strength is measured in Newtons and DTG peaks in Celsius, we normalize the data to a range of 0 to 1 using the "Higher-the-Better" formula:

$$X(k) = \frac{X - \min}{\max - \min}$$

Table 3 shows the peak load and DTG peak temperature and then equating it[10].

Sample State	Peak Load (X1)	DTG Peak (X2)	Normalized X1	Normalized X2
Untreated (Greige)	12.5 N	320°C	0.000	0.000
Chemical Treated	19.41 N	345°C	1.000	0.833
Enzyme Treated	18.18 N	350°C	0.824	1.000

Table 3-Peak load [X1] and DTG peak [X2]

Grey Relational Coefficient (GRC)

The GRC (Y) is calculated to determine how close the actual normalized results are to the ideal (1.0).

Grey Relational Grade (GRG)

The GRG is the average of the coefficients. It represents the Overall Performance Score of the fabric is shown in [Table 4]

Sample State	GRC (Strength)	GRC (DTG)	Grey Relational Grade (GRG)	Rank
Untreated	0.333	0.333	0.333	3
Chemical	1.000	0.750	0.875	1
Enzyme	0.741	1.000	0.871	1+

Table 4-GRC for 3 types of fabric

The chemical treatment is higher in score but still we gave 1+(plus) rank to enzyme treated seeing the sustainability effects it creates for environment and usages[11]. Although chemical method of treatment scored a little bit high score in raw mechanical metrics, by the Grey Relational Grade, we ranked enzymatic method of treatment as the best overall process (Rank 1+) when accounting for environmental sustainability. This study provides a better material-science baseline specially for textile applications, demonstrating that multi-enzyme cocktail has effectively replaced chemicals without compromising majorly on the structural or thermal integrity of the textile.

Conclusions

The TGA helps to provide a basis for working on fabric (in upcoming further stages as scouring, mercerization, desizing etc) and hereby improving its quality and overall appearance for different usages.

This type of biotreatment focuses on the components degrading in Stage 2 (190°C – 295°C). Enzymes like pectinases and cellulases can selectively remove these impurities (pectins and hemicellulose) that often hinder while dyeing and finishing. A successful biotreatment would result in a less weight loss percentage in the 190°C–295°C range in a post-treatment TGA, indicating a cleaner, more pure cellulosic fabric. This thermogravimetric analysis characterization is crucial for establishing a baseline for the greige fabric's thermal stability and compositional profile, against which the effects of subsequent treatments, such as biopolishing or other finishing processes, can be rigorously evaluated [12].

The chemical processing of cotton textiles is essential for achieving a material that is not only clean but also structurally optimized. The data obtained from TGA and UTM confirms that the chemical treatment significantly alters the morphology and composition of the fabric.

The enzymatic hydrolysis results in a more flexible fabric, as evidenced by the consistent displacement values recorded up to 6.47 mm before failure. The application of a commercial brought enzyme cocktail (Cellulase, Amylase, Pectinase) provides a sustainable alternative for textile refinement. The STA data confirms a modified thermal signature, while UTM results highlight the delicate balance required to maintain structural integrity during bioprocessing. This enzymatically treated fabric is optimized for high-end apparel applications where surface smoothness and eco-friendly processing are prioritized. The GRA reveals that chemical treatment is the good for Strength (highest GRC for load), but Enzyme treatment provides a superior balance when thermal stability (DTG) and flexibility are considered.[13]

While the untreated fabric shows earlier weight loss due to hemicellulose and pectin degradation, the DTG curve for enzyme treated shows likely show a sharper, higher-temperature peak because the bio-scouring (enzyme cocktail) has removed the low-thermal-stability impurities, leaving behind more purified α -cellulose.[14] This GRA assessment confirms that the transition to Bio-enzymatically treated fabric is statistically the most efficient route for high-performance greige fabric processing[7] .

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Declarations

The authors declare no competing interests.

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Authorship contribution

The first author is Somya Tyagi with the corresponding author as Prof. Sanjoy Ghosh, Department of Biosciences and Bioengineering, Indian Institute of Technology Roorkee, Uttarakhand, India. All authors read and approved the final manuscript.

Contributions

The author conceived and developed the idea and concept for this study. The author also carried out the experimental work, collected the scientific material and data, and performed the statistical analysis independently. Furthermore, the author wrote, edited, analyzed, and discussed all sections of the study from start to finish.

Data availability The data that support the findings of this study are available on reasonable request from the principal author.

Code availability Not applicable.

Ethics and Consent to participate declarations Not applicable

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