

Araştırma Makalesi / Research Article

MORPHOLOGICAL AND MECHANICAL CHARACTERIZATION OF ERI SILK FIBERS CULTIVATED IN ETHIOPIA

Getnet Belay TESEMA^{1*} 

Axel DRIELING²

Alemayehu Assefa BELETE¹ 

Bantamlak Birie KASSIE¹ 

Anmen ADMAS¹ 

¹Ethiopian Institute of Textile and Fashion Technology, Faculty of Textile, Bahir Dar University, Bahir Dar, Ethiopia

²Faserinstitut Bremen e.V., Bremen, Germany

Gönderilme Tarihi / Received: 17.09.2025

Kabul Tarihi / Accepted: 26.06.2026

ABSTRACT: Eri silk (*Samia ricini*) is increasingly recognized as a sustainable and ethical non-reelable silk with strong potential for advanced textiles, biomedical, and composite applications. However, scientific understanding of the structural and mechanical behavior of Ethiopia-grown Eri silk remains limited. This study presents the first comprehensive morphological and mechanical characterization of three Eri silk varieties: Chinese White, Borduar White, and Kokrajhar Brick-Red (Indian origin) cultivated under different Ethiopian agroecological conditions (Bahir Dar, Arba Minch, and Awash-Melkasa). Scanning electron microscopy (SEM) revealed significant varietal differences in longitudinal and cross-sectional morphology. Prior to degumming, all fibers exhibited characteristic granular sericin coatings; however, the Chinese White variety displayed the smoothest and most homogeneous surface, indicating uniform sericin encapsulation of the fibroin core. Borduar White showed fine, discrete sericin agglomerates, whereas Kokrajhar Brick-Red exhibited larger and more irregular sericin accumulations. Cross-sectional analysis further demonstrated distinct structural organization, with triangular and moderately packed sections dominating Chinese White fibers, mixed bent geometries in Borduar White, and compact oblong morphologies in Kokrajhar Brick-Red. Mechanical characterization demonstrated significant effects of both silk variety and rearing zone on fineness, tenacity, elongation, and Young's modulus ($p < 0.0001$). Fiber fineness ranged from 2.4–4.0 denier and tenacity from 2.5–3.5 g/den. Chinese White consistently produced finer fibers with superior tenacity and modulus, whereas Kokrajhar Brick-Red generated coarser fibers with lower mechanical performance. These findings establish critical structure-property relationships for Ethiopia-grown Eri silk and provide a scientific foundation for varietal selection, ecological optimization, and the development of high-value sustainable silk biomaterials.

Keywords: Eri silk, Fiber fineness, Mechanical properties, Variety- environment interaction, Sustainable textiles

ETİYOPYA'DA YETİŞTİRİLEN ERI İPEK LİFLERİNİN MORFOLOJİK VE MEKANİK KARAKTERİZASYONU

ÖZ: Eri ipeği (*Samia ricini*), gelişmiş tekstil, biyomedikal ve kompozit uygulamaları için güçlü potansiyele sahip, sürdürülebilir ve etik, iplik haline getirilemeyen bir ipek olarak giderek daha fazla kabul görmektedir. Bununla birlikte, Etiyopya'da yetiştirilen Eri ipeğinin yapısal ve mekanik davranışına ilişkin bilimsel anlayış sınırlı kalmaktadır. Bu çalışma, farklı Etiyopya tarımsal ekolojik koşullarında (Bahir Dar, Arba Minch ve Awash-Melkasa) yetiştirilen üç Eri ipeği çeşidinin (Çin Beyazı, Borduar Beyazı ve Kokrajhar Tuğla Kırmızısı (Hint kökenli)) ilk kapsamlı morfolojik ve mekanik karakterizasyonunu sunmaktadır. Tarama elektron mikroskobu (SEM), uzunlamasına ve enine kesit morfolojisinde önemli farklılıkları ortaya koymuştur. Zamk giderme işleminden önce, tüm lifler karakteristik granüler serisin kaplamaları sergilemiştir; ancak Çin Beyazı çeşidi, fibroin çekirdeğinin homojen serisin kapsüllenmesini gösteren en pürüzsüz ve en homojen yüzeyi sergilemiştir. Borduar Beyazı ince, ayrık serisin kümeleri gösterirken, Kokrajhar Tuğla Kırmızısı daha büyük ve daha düzensiz serisin birikimleri sergilemiştir. Kesit analizi ayrıca, Çin Beyazı liflerinde üçgen ve orta derecede paketlenmiş bölümlerin, Borduar Beyazı'nda karışık bükülmüş geometrilerin ve Kokrajhar Tuğla Kırmızısı'nda kompakt uzunlamasına morfolojilerin baskın olduğu farklı yapısal organizasyonu ortaya koymuştur. Mekanik karakterizasyon, ipek çeşidinin ve yetiştirme bölgesinin incelik, dayanıklılık, uzama ve Young modülü üzerinde önemli etkileri olduğunu göstermiştir ($p < 0.0001$). Lif inceliği 2,4-4,0 denye ve dayanıklılık 2,5-3,5 g/denye arasında değişti. Çin Beyazı sürekli olarak üstün dayanıklılığa ve modüle sahip daha ince lifler üretirken, Kokrajhar Tuğla Kırmızısı daha düşük mekanik performansa sahip daha kaba lifler üretmiştir. Bu bulgular, Etiyopya'da yetiştirilen Eri ipeği için kritik yapı-özellik ilişkilerini ortaya koymakta ve çeşit seçimi, ekolojik optimizasyon ve yüksek değerli sürdürülebilir ipek biyomalzemelerinin geliştirilmesi için bilimsel bir temel sağlamaktadır.

Anahtar Kelimeler: Eri ipeği, Elyaf inceliği, Mekanik özellikler, Çeşit-çevre etkileşimi, Sürdürülebilir tekstiller

*Sorumlu Yazarlar/Corresponding Authors: getnet.belay@uni-bremen.de

DOI: <https://doi.org/10.7216/teksmuh.1786052>

www.tekstilmuhendis.org.tr

1. INTRODUCTION

Eri silk (*Samia ricini*), widely known as “ahimsa” or peace silk, is increasingly valued for its ethical harvesting process, distinctive staple fiber structure, and expanding potential in textiles, composites, and biomedical applications [1]. Unlike mulberry silk, which must be reeled from continuous filaments, Eri silk is naturally spun from open-ended cocoons, allowing the moth to emerge without damage making it inherently aligned with cruelty-free silk production [2]. This ethical distinction, combined with its thermal comfort, moisture-management properties, and biodegradability, positions Eri silk as a promising material in the growing sustainable fiber economy.

Fiber morphology and mechanical properties in Eri silk are strongly shaped by both genetic factors (variety/ecorace) and rearing conditions, including host plant, temperature, and humidity [3]. Although environmental drivers are known to influence denier, strength, and sericin deposition, research remains limited in linking microstructural variation directly to mechanical performance across genetically distinct Eri varieties.

Recent advances in SEM and mechanical evaluations of both mulberry and non-mulberry silks support the approaches used in this study. For example, comparative structural mechanical analysis across silkworm species demonstrates how β -sheet content, molecular orientation and crystallinity relate tightly to extensibility and toughness [4]. Regenerated silk films from Eri, Muga, and Tasar silks produced via formic acid self-assembly show distinct morphological and mechanical behaviors under SEM and dynamic mechanical analysis, underscoring how silk processing influences structure [5]. In biomedical contexts, Eri silk-based scaffolds embedded with silver nanoparticles exhibit well-defined nanostructures under SEM and maintain excellent mechanical stability, reinforcing Eri silk’s potential for functional applications [6, 7]. Physical characterization of novel Eri silk strains also reveals variations in fiber diameter, crystallinity, and tensile properties that align with morphological differences visible in electron micrographs [8]. These studies collectively validate that SEM and tensile testing are effective methods for correlating microstructure with mechanical performance across different silk types.

Given the rising importance of ethically produced and sustainability aligned natural fibers, this study aims to advance the scientific understanding of Eri silk cultivated outside its traditional Asian context. While Eri silk research has largely focused on production systems in India and Southeast Asia, the fiber’s performance under Ethiopian ecological conditions remains undocumented. To address this gap, the present work investigates the structural and mechanical characteristics of three Eri silk varieties: Chinese White, Borduar White (India), and Kokrajhar Brick-Red (India) reared across multiple Ethiopian cultivation zones.

Recent studies show that climate variability is emerging as a major factor affecting global silk production systems, influencing both host plant physiology and silkworm development. Rising temperatures, erratic rainfall, and humidity fluctuations decrease

mulberry leaf yield, disrupt voltinism, and increase disease susceptibility in sericulture regions [9]. Research further highlights that heat stress induces molecular responses such as heat-shock proteins, oxidative stress pathways, and compromised cocoon formation, underscoring the need for climate-resilient silkworm genotypes [10].

Although most climate-focused sericulture research centers on *Bombyx mori*, parallel risks apply to non-mulberry silks, including Eri (*Samia ricini*), given similar environmental sensitivity during larval and cocoon stages. Kaushik et al. [11] emphasize the urgency of adopting climate-adaptive production models, including strain selection, improved agronomic practices, and rearing systems tailored to fluctuating climate patterns. In this context, examining Eri silk performance within Ethiopian agro-ecological conditions becomes not only scientifically relevant but also strategically important for establishing a climate-resilient peace-silk value chain.

Recent studies, such as research on mulberry (*Bombyx mori*) peace silk in Turkey [2], highlight global interest in ethical sericulture and the importance of raising consumer awareness about cruelty-free silk production. While mulberry peace silk requires a modified rearing and harvesting approach, Eri silk achieves this ethical standard naturally through its non-reelable cocoon structure.

Eri silk fibers are obtained as staple fibers, characterized by variability in geometry and packing traits strongly influenced by both genetic factors (variety/ecorace) and environmental conditions (host plant, temperature, humidity) [1, 12]. Understanding these genotype–environment interactions is key to optimizing fiber quality for apparel, home textiles, and bio-derived composites.

Across silks, environmental drivers such as temperature and relative humidity modulate larval physiology and cocoon formation, with downstream effects on fiber linear density and uniformity; for Eri, favorable rearing bands around $28 \pm 3^\circ\text{C}$ and $\sim 70\%$ RH have been reported to support survival and robust cocooning [13]. Microstructural investigations further show that cross-sectional geometry and filament packing correlate with mechanics: compact or triangular sections and smoother, more uniform surfaces tend to associate with higher strength/stiffness, whereas irregular/bent sections and loose packing track with lower tenacity [14, 15]. Recent Eri-focused work indicates that, unlike *B. mori*, Eri silk can maintain mechanical robustness across a range of spinning/reeling speeds pointing to intrinsic molecular/structural resilience that may buffer environmental variation during fiber formation [1]

Despite these advances, systematic studies that couple SEM-based morphology (longitudinal and cross-sectional) with mechanical metrics (fineness/denier, tenacity, elongation at break, Young’s modulus) across multiple Eri varieties and rearing locations remain limited. Addressing this gap, the present work evaluates three Eri varieties reared in three ecological zones. By integrating SEM observations with tensile testing, we quantify how microstructural differences (shape, packing density, surface features) translate into fineness and mechanical performance, thereby clarifying variety

environment effects and informing selection and processing strategies for sustainable, value-added Eri silk applications [1, 12].

2. MATERIALS AND METHODS

2.1. Feeding Material Preparation

The host plant, castor (*Ricinus communis L.*), which serves as the sole food source for Eri silkworms, was cultivated using both seed sowing and vegetative propagation through stem cuttings [10]. For example, in the Ethiopian Institute of Textile and Fashion Technology (EiTEX), Selam Campus, Bahir Dar University the cultivation was undertaken at the Mulberry and Eri Silk Research Farm (Figure 1). In a similar way Bere Sericulture Production PLC, Arba Minch and Awash-Mekasa Agricultural Research Center produce their castor plant on their own farms. All the three ecological zones follow similar Eri silk production procedure, namely: Rearing, cocoon production and degumming.

2.2. Rearing, Cocoon Production & Degumming

Disease-free eggs and cocoons were obtained from the grainage center and reared under controlled indoor conditions. The emerged moths were allowed to mate, after which the eggs were collected.

2.2.1. Rearing and Cocoon Production

After collection, the castor leaves were washed in water and preserved in the leaf preservation chamber covering with wet gunny cloth sack all around. The castor leaves were provided without petiole in tray rearing. 4 feedings were given per day at regular intervals during the young age rearing. In late age worms, 5 feeding per day were given (Figure 2). In the night time sufficient leaves were provided to meet the requirement of leaf

consumption throughout the night. In this research work a feeding schedule were prepared and followed strictly till the end of the Eri silk rearing.

Sufficient tender (glossy) and fresh leaves were provided to young age larvae. Maximum care was taken not to expose young age worms to extreme heat or cold. Semi-matured leaves were provided for late age worms which consist of fourth and fifth instars. These stages consumed more amounts of leaves than the young age worms. In the Ethiopian Institute of Textile and Fashion Technology (EiTEX), Bahir Dar University, and other two rearing places similar procedures were used to produce Eir silk fiber which is detailed below:

Following hatching, the larvae were transferred onto rearing trays supplied with fresh host plant leaves. To ensure optimum larval growth and development, the rearing room was maintained at a temperature of 24–26 °C with a relative humidity of 75–80% (Figure 3).

Disease-free layings (DFLs) were sourced from a grainage unit and reared indoors under controlled conditions. After emergence, moths were paired and allowed to mate; eggs were collected and incubated until hatching. Neonate larvae were gently transferred to trays containing fresh castor leaves. Rearing was conducted at 24–26 °C and 75–80% relative humidity (RH), conditions shown to optimize larval development and cocoon quality in Eri and related silkworm species [11, 12]. The larval stage lasted approximately 30–35 days, after which caterpillars were moved to mountages (Chandrikas). Spinning was completed in 2–3 days, yielding white, spindle-shaped cocoons (Figure 4) with no peduncle, resulting in discontinuous filaments characteristic of Eri silk [13].



Figure 1. a) Mulberry (front) and Castor (back) plants cultivated in the Selam campus research farm, Ethiopian Institute of Textile and Fashion Technology (EiTEX), Bahir Dar University **b)** Magnified image of Castor plant

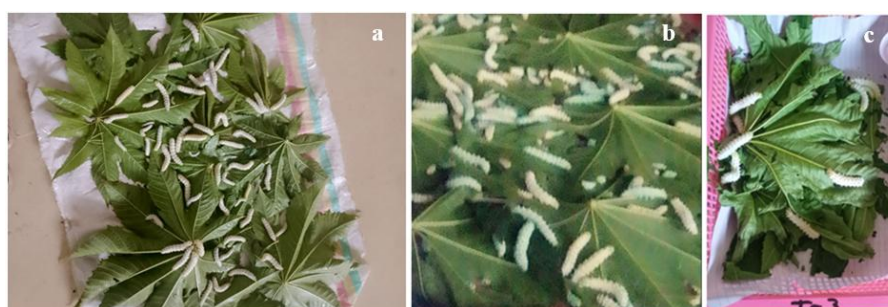


Figure 2. Larvae in the three ecoraces rearing room: a) Borduar White **b)** Kokrajhar, Brick-red **c)** Chinese origin



Figure 3. Sample mature caterpillars: **a, b)** in Ethiopian Institute of Textile and Fashion Technology, Bahir Dar University (EiTEX-BDU) rearing room **c)** Bere Sericulture Production PLC, Arba Minch (BSP-PLC-AM) **d)** Awash-Melkasa Agricultural Research Centre (AMARC)



Figure 4. Sample Cocoons: **a)** produced in EiTEX-BDU **b)** produced in Awash-Melkasa Agricultural Research **c)** produced in Bere Sericulture PLC, Arba Minch, rearing rooms

2.2.2. Degumming

Degumming is a treatment process used to remove sericin, the natural water-soluble gum secreted by silkworms, from raw silk fibers. This process converts rigid, yellowish “hard silk” into soft, lustrous, and highly absorbent “soft silk,” making it suitable for dyeing, printing, and subsequent textile manufacturing processes [16].

Prior to degumming, the cocoons were cleaned to remove floss and residual pupal matter, thoroughly washed, and air-dried. In the present study, degumming of Eri silk cocoons was carried out following a procedure similar to that reported by Debasis Chattopadhyay et al. [17]. The process was conducted using 10% sodium carbonate (Na_2CO_3) and 10% neutral soap solutions under boiling conditions for 1h to ensure uniform degumming of all silk varieties investigated in the study.

To enhance the efficiency of sericin removal, the degumming bath was renewed once after 15 min of treatment. After degumming, the silk fibers were cooled and rinsed three times with distilled water to eliminate residual alkali and dissolved sericin.

Degummed Eri silk samples prepared using the above procedure were collected from three production sites in Ethiopia, representing active sericulture hubs engaged in research, commercial rearing, and technology transfer activities. The three

Eri silk varieties investigated in this study were Chinese origin (white), Kokrajhar (brick-red/brown; Indian origin), and Borduar White (Indian origin) (Figure 5).

The two varieties Borduar White (Figure 5.a), Kokrajhar Brick-red (Figure 5.b) are brought from India and the third one (white variety), (Figure 5.c) from China and cultivated in the three places of Ethiopia. These locations represent some of the agro-ecologies of the country assumed suitable for silkworm.

From each location, 25 cocoons per variety were sampled, giving a total of 225 fiber samples ($3 \text{ varieties} \times 3 \text{ locations} \times 25 \text{ samples}$).

Rationale for Site Selection: the selected sites play key roles in Ethiopia’s sericulture development:

1. *EiTEX, Bahir Dar University - Research and capacity-building center, actively cultivating Eri silk and transferring sustainable rearing technologies to communities.*
2. *Bere Sericulture Production PLC, Arba Minch - Commercial producer engaged in large-scale Eri silk rearing and community-level technology scaling.*
3. *Awash-Melkasa Agricultural Research Center - A national sericulture research center working on wide-area dissemination of Eri production technologies.*

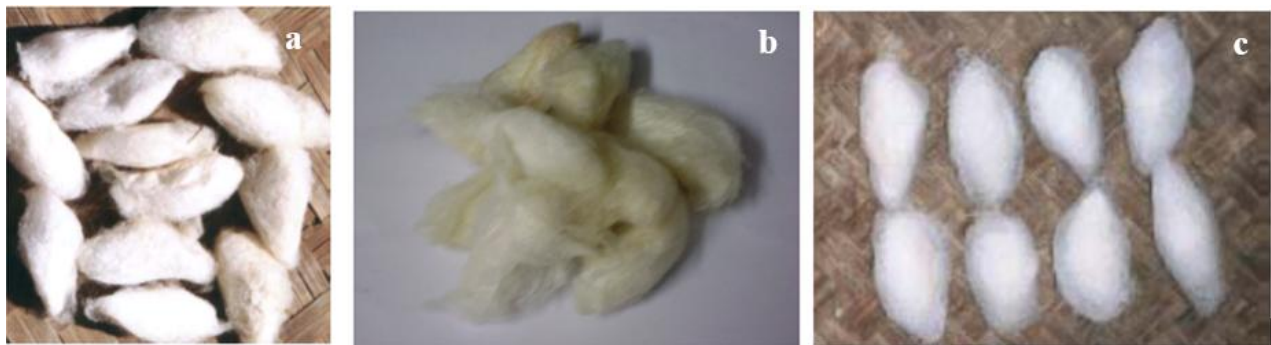


Figure 5. The Eri cocoons types **a)** Borduar white **b)** Kokrajhar Brick-red **c)** Chinese white, reared in the three ecoraces

Table 2. Geographical location of Eri silk reared zones

Sample site	Latitude	Longitude	Altitude (m a.s.l.)
EiTEX-BDU, Bahir Dar University, Bahir Dar	11°36'N	37°23'E	1,799 m
Bere Sericulture PLC, Arba Minch	6°02'N	37°33'E	1,200 m
Awash-Mekasa Agricultural Research Center	8°24'N	39°21'E	1,550 m

2.3. Experimental Methods

2.3.1. Fiber Preparation and Characterization

All fiber properties (except SEM evaluation) of the samples collected from the three places were conducted at the EiTEX Fiber Research Laboratory, Bahir Dar University.

Analytical Objective: This study aimed to elucidate the combined effects of genetic variety and rearing environment on the performance of Eri silk fibers, by integrating structural characterization (SEM) with mechanical property analysis.

2.3.1.1. Mechanical Properties

Tensile testing followed ASTM D3822/D3822M-14 (2020) using an Instron tensile tester (Model 3340; USA), fitted with fiber grips and a 5 N load cell. Tests were performed at 20 mm/min extension rate and 20 mm gauge length, after conditioning fibers at 21 ± 1 °C and $65 \pm 2\%$ RH for 24 h. Tenacity (g/den), Elongation at break (%), and Young's modulus (GPa) were recorded, providing comprehensive mechanical profiling [18].

2.3.1.2. Morphology Analysis

The filament cross-section and the longitudinal shape of the studied varieties of silk were observed under a SEM. For this study, silk filaments were pulled through soft cork to ensure proper alignment and mechanical support prior to sectioning. Thin sections were then prepared and mounted on specimen holders for SEM observation. Before analysis, the samples were sputter-coated with a thin gold layer of approximately 3-5 nm thickness to enhance surface conductivity and suppress charging effects, thereby improving image resolution and contrast during SEM imaging. Fiber surface and cross-sectional morphology were examined using a Thermo Scientific Quattro S Field-Emission Scanning Electron Microscope at 20 kV as indicated by

instrument settings displayed on the micrograph. SEM facilitated visualization of fibril alignment, porosity, and cross-sectional shape [14, 15].

The cross-sectional and longitudinal morphologies of Eri silk filaments from three randomly selected representative varieties collected from three geographical regions were examined using SEM. The present study primarily focuses on evaluating the influence of varietal differences on the morphological characteristics of Eri silk fibers. A subsequent and complementary study will investigate the effects of geographical location on the morphological properties of Eri silk in greater detail, with particular emphasis on the influence of environmental and cultivation conditions on fiber structure and surface characteristics.

2.3.1.3. Fineness Measurement

Linear density (denier) was measured gravimetrically per ASTM D1577: $D = (\text{weight in grams} \times 9000) / \text{length in meters}$. Samples were measured using Vibroskop 500 (Model: Lenzing Instruments GmbH & Co. KG A-4851 Gampern, Austria; partner Texttechno Herbert Stein GmbH & Co. KG D-41066 Mönchengladbach, Germany) an instrument for the automatic determination of the titer (dtex, den) of single fibers. By an advanced and patented approach of the vibration method (Vibroskop method) it assures best accuracy and reliability and it eliminates any influence of the operator.

2.3.2. Data Analysis Using Design Expert 13 Software

The experimental data were analyzed using a randomized full factorial design in Design-Expert Version 13. Two categorical factors, namely silk variety and production place, each at three levels, were considered. A two-factor interaction (2FI) model was employed to evaluate the main and interaction effects on fineness,

tenacity, elongation at break, and Young's modulus. The data of all studied varieties processed using design expert 13 software is presented in Annex 1.

3. RESULTS AND DISCUSSION

3.1. Surface Morphology of Eri Silk Fiber Varieties

Generally, before the degumming process, the surface of the silk fibers exhibited filaments enveloped by an outer layer of sericin, which was predominantly intact [1]. Occasionally, thin cracks or locally abraded regions could be observed on the sericin layer surrounding the fibers [19].

SEM analysis of the longitudinal morphology of Eri silk filaments prior to degumming revealed distinct variations in sericin coverage and granulation patterns among the studied varieties (Figure 6). All samples exhibited a characteristic uneven and granular texture attributable to the presence of sericin; however, the degree of surface smoothness and the size of sericin agglomerates varied significantly. The white China origin (Figure 6.a) variety displayed the smoothest surface morphology, with minimal granulation, indicating a uniformly distributed and continuous sericin layer encapsulating the fibroin core. In contrast, Borduar white variety (Figure 6.b) exhibited discrete, fine sericin agglomerates distributed along the filament surface, suggesting partial aggregation of the sericin during secretion or post-secretion solidification.

The observation of fine sericin agglomerates distributed along the filament surface indicates a partial aggregation of sericin either during secretion or subsequent solidification of the silk filament. This phenomenon reflects the complex biochemical and physicochemical processes governing sericin - fibroin interactions during spinning in *Samia ricini*.

Silk secretion involves the simultaneous extrusion of fibroin and sericin through the spinneret, where fibroin forms the semi-crystalline core and sericin acts as an amorphous coating. As the silk dope travels through the gland, it experiences shear stress, pH

reduction, and ionic exchange, which together induce conformational transitions from random coil to β -sheet structures [20, 21].

Sericin agglomeration on raw Eri filaments reflects the convergence of several molecular and process-level mechanisms. Intrinsic sericin features including sequence-dependent hydrophobicity, molecular-weight distribution, and phase-transition behavior promote localized clustering under shear and dehydration [22]. Spinneret rheology and extrusion dynamics further modulate sericin flow and deposition patterns [23], while metal-ion/pH shifts drive coil - globule transitions that favor agglomerate nucleation [24]. Ambient drying conditions during cocoon spinning (temperature-humidity regime) influence the rate of sericin solidification and coalescence [25]. Additionally, host-plant diet and genotype-mediated gland physiology alter sericin concentration and viscosity, producing distinct surface topographies across varieties [10]. The smoothest surface morphology, with minimal granulation observed in Chinese white (Figure 6.a) relative to Borduar White (Figure 6.b) and Kokrajhar Brick-Red (Figure 6.c) therefore likely arise from genotype-specific sericin chemistry interacting with subtle environmental or feeding-history factors, even when environmental effects were not explicitly controlled due to random sampling across rearing zones.

Sericin is a glycoprotein complex composed primarily of serine, aspartic acid, and glycine, whose molecular behavior is highly sensitive to its amino acid composition and molecular weight distribution [26, 27]. Varieties exhibiting higher ratios of acidic amino acids (aspartic and glutamic acid) often display stronger intermolecular hydrogen bonding and electrostatic interactions during secretion, leading to denser and more extensive aggregation on the fiber surface [28, 29].

The appearance of Sericin on the undegummed and degummed Borduar white and Kokrajhar Brick-red varieties was also observed by Bindhu et al. [30].

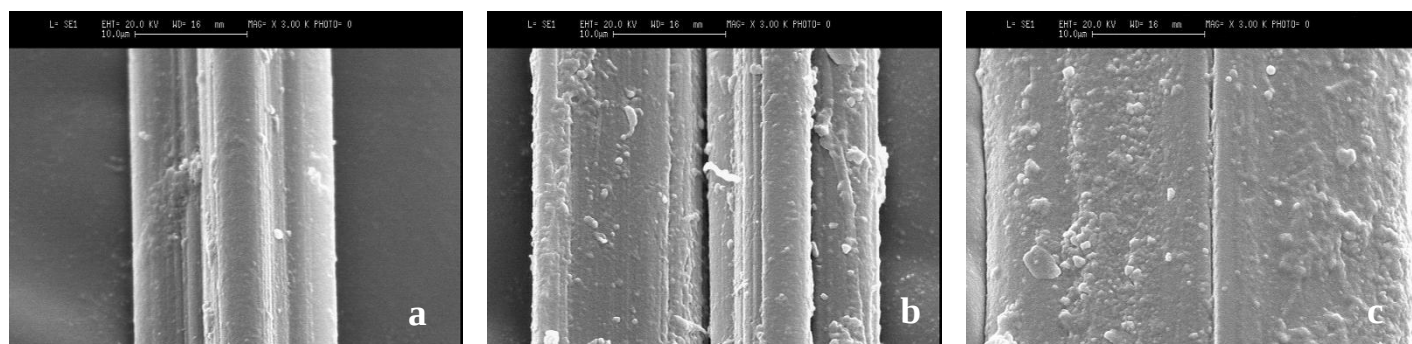


Figure 6. SEM Longitudinal view for the Eri silk varieties: **a)** Chines white variety: sericin uniformly covers the surface **b)** Borduar white variety: sericin forms very small agglomerates **c)** Kokrajhar Brick-red variety: sericin forms agglomerates which are larger than that of Borduar white

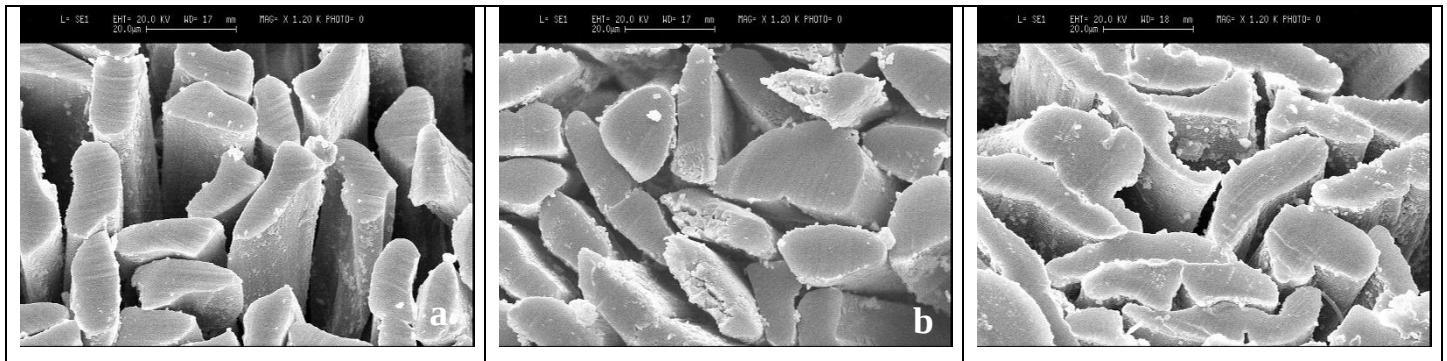


Figure 7. SEM Cross-sectional view for: a) Chinese white variety b) Borduar white variety c) Kokrajhar Brick-red variety

The cross-sectional views of the three Eri silk varieties obtained using a SEM are presented in Figures 7. It can be observed that, in this respect, Chinese white variety (Figure 7.a), Borduar white variety (Figure 7.b), and Kokrajhar Brick-red (Figure 7.c) silks exhibit notable different cross-sectional morphology and packing density. Chinese origin white variety showed predominantly triangular, flat, and smooth sections with moderate inter-fiber spacing while Borduar white variety exhibited a mix of triangular and bent cross-sections with relatively loose packing. Kokrajhar Brick-red variety was characterized mainly by oblong, flat, smooth sections, minimal bending, and closely packed fibers. Overall, triangular cross-sections were most prevalent in Chinese origin and Borduar white varieties while oblong cross-sections dominated in Kokrajhar Brick-red, indicating distinct varietal differences in structural morphology.

Sen, K. and Babu, K.M. also [31] showed the SEM cross-section of Indian Eri silk variety. They revealed that Eri variety has a triangular cross-section while tasar and muga, from the non-mulberry silk varieties, exhibit an elongated rectangular or a wedge-shape cross section and a large cross-sectional area.

3.2 Fineness of Eri Silk Fiber Varieties

Linear density (denier - Weight in grams $\times$ 9000 / Length in meters) of Eri silk fiber, was measured according to the ASTM D1577. Varieties and places have substantial impact on single fiber fineness (denier). In AMARC and EITEX-BDU zones

single fiber fineness is finer than BSP-PLC-AM zone (Figure 8). The difference is significant at 5 % level of confidence (Table 2).

The analysis of variance (ANOVA) showed that both variety (A) and place of rearing (B) exerted a statistically significant effect on the fineness of Eri silk fibers ($p < 0.0001$). The F-values for variety (9131.05) and place (10015.44) were extremely high, indicating that the differences in fiber fineness across varieties and places (ecoraces) are highly significant and not due to random variation.

Even under controlled indoor rearing designed to minimize temperature and humidity effects, the interaction between variety and place (AB) was significant ($F = 264.67$, $p < 0.0001$). This indicates that fineness variation arises not only from genetic differences among varieties but also from location-specific factors that persist despite environmental standardization. Such factors may include variation in host-plant nutritional profiles, larval handling practices, or subtle micro-environmental differences inherent to each facility. Comparable findings have been reported, showing that fine-scale management or dietary differences can influence cocoon morphology and fiber diameter even when macro-environmental conditions are held constant [32]. Taken together with evidence of strain-specific physiological responses [33], these results suggest that genotype $\times$ rearing-context interactions, rather than climate alone, play a central role in determining Eri silk fineness. Variety and geographical region (G. Region) 3D plots of fineness (g/den) for the studied varieties is presented in Figure 8.

Table 3. ANOVA: Fineness (denier) evaluation between variety (A) and place (B)

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	57.13	8	7.14	4918.96	< 0.0001	significant
A-Variety	26.51	2	13.26	9131.05	< 0.0001	
B-Place	29.08	2	14.54	10015.44	< 0.0001	
AB	1.54	4	0.3843	264.67	< 0.0001	
Pure Error	0.3136	216	0.0015			
Cor Total	57.45	224				

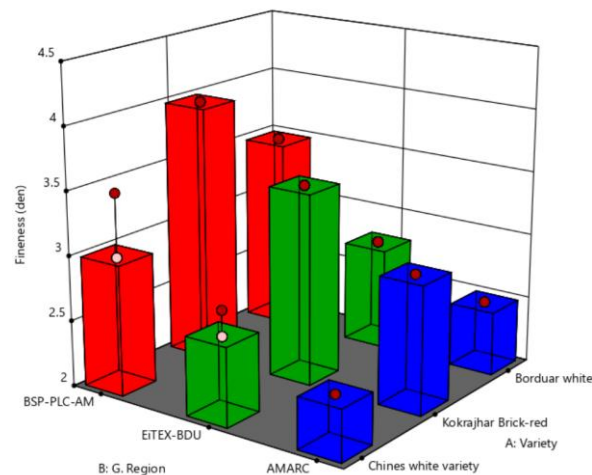


Figure 8. Variety and geographical region (G. Region) 3D plots for fineness

Table 3. ANOVA: Tenacity (g/den) evaluation between variety (A) and place (B)

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	17.24	8	2.16	1939.75	< 0.0001	significant
A-Variety	9.14	2	4.57	4111	< 0.0001	
B-Place	8	2	4	3601	< 0.0001	
AB	0.1044	4	0.0261	23.5	< 0.0001	
Pure Error	0.24	216	0.0011			
Cor Total	17.48	224				

3.3. Tenacity of Eri Silk Fiber Varieties

The ANOVA results (Table 3) reveal that both variety and rearing place exerted a highly significant influence on the tenacity of Eri silk fibers ($p < 0.0001$).

3.3.1. Effect of Variety (A)

The factor 'Variety' accounted for a large proportion of variability in fiber tenacity (Sum of Squares = 9.14, $F = 4111.00$). This indicates that genetic differences between Eri strains strongly influence molecular packing and crystallinity, which govern breaking strength. Finer denier fibers generally exhibited higher tenacity values, consistent with the principle that thinner filaments often have fewer defects per cross-sectional area, better molecular alignment, and more effective stress distribution.

3.3.2. Main Effect of Place (B)

The rearing location exerted a highly significant effect on tensile properties (Sum of Squares = 8.00, $F = 3601.00$), indicating that fiber performance varied consistently across production sites. Although temperature and relative humidity were maintained within controlled ranges to minimize environmental variability, complete uniformity among rearing locations is difficult to achieve in biological systems. Minor differences in microenvironmental and management-related conditions may still influence silkworm physiology and silk biosynthesis.

In the present study, location-related variation may have arisen from subtle differences in castor leaf nutritional composition, freshness of feed, feeding interval, larval handling practices, stocking density, ventilation efficiency, light exposure, or sanitation conditions. Even small variations in these factors can affect larval metabolism, cocoon formation, fibroin synthesis, and sericin deposition. Consequently, differences in filament packing density, molecular orientation, crystallinity, and the sericin-fibroin ratio may develop, ultimately influencing tensile strength, elongation, and Young's modulus [34, 35].

Furthermore, the silk gland is highly sensitive to physiological stress and environmental fluctuations during spinning and filament solidification. Previous studies have shown that even under partially controlled rearing environments, silkworms may exhibit measurable differences in mechanical fiber properties due to site-specific biological responses and metabolic adaptation [36]. Therefore, the highly significant location effect observed in the ANOVA suggests that rearing site remains an important contributory factor affecting Eri silk fiber quality, despite the implementation of controlled environmental conditions.

3.3.3. Interaction Effect (AB)

The interaction between strain and cultivation place ($F = 23.50$, $p < 0.0001$) was statistically significant, although smaller in magnitude compared with the individual main effects. This indicates that the response of each strain to different rearing

environments was not consistent. In other words, the relative performance ranking of strains changed depending on the ecological conditions of the rearing site. A strain that produced higher tenacity fibers in one location possibly due to more favorable host-plant nutrition, microclimate stability, or stress tolerance might show reduced performance in another environment. This confirms that genetic potential alone does not

determine mechanical properties; instead, phenotypic expression is strongly shaped by the surrounding cultivation ecology.

Pure Error: The very low pure error value (0.0011) indicates high measurement repeatability and minimal experimental noise, confirming the reliability of the mechanical test results.

Variety and geographical region (G. Region) 3D plots of tenacity (g/tex) for the studied varieties is presented in Figure 9.

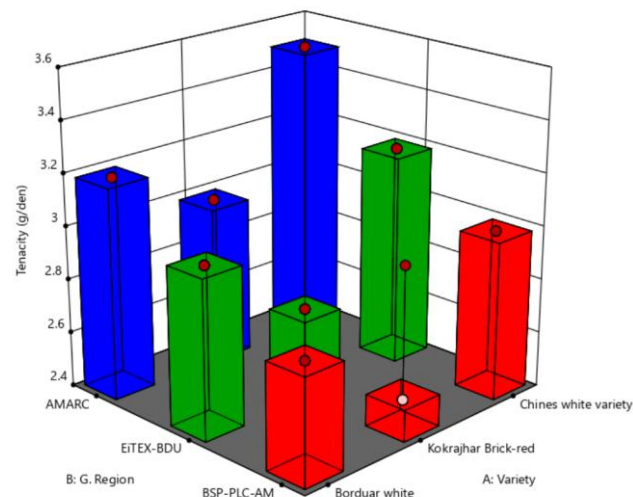


Figure 9. Variety and geographical region (G. Region) 3D plots for tenacity

3.4. Elongation at Break (%) of Eri Silk Fiber Varieties

The ANOVA results (Table 4) revealed that the factorial model for elongation at break (%) was highly significant ($F = 678.96$, $p < 0.0001$), indicating that variety, geographical region, and their interaction collectively influenced the elongation behavior of the studied Eri silk fibers. The pure error mean square (0.0600) was relatively small compared with the treatment mean squares, demonstrating high measurement repeatability and low experimental noise, thereby confirming the reliability of the mechanical testing procedure.

3.4.1. Interaction Effect (AB)

The interaction between variety and geographical region was statistically significant ($F = 38.74$, $p < 0.0001$), although its magnitude was considerably smaller than those of the main effects. The interaction plot (Figure 10) shows that the lines corresponding to the three geographical regions (B1, B2, and B3) exhibit similar trends and do not intersect, indicating a weak but statistically detectable interaction. The relative ranking of the varieties remained unchanged across the production regions, with Chinese White consistently exhibiting the highest elongation values, Kokrajhar Brick-Red the lowest, and Borduar White intermediate behavior.

This pattern suggests that environmental conditions primarily altered the magnitude of elongation rather than modifying the intrinsic extensibility characteristics of individual varieties. In practical terms, the varieties responded similarly to changes in cultivation environment, indicating that the genetic influence on elongation remained relatively stable across regions. The statistically significant interaction may therefore reflect quantitative differences in environmental responsiveness rather than qualitative changes in varietal performance.

3.4.2. Main Effect of Geographical Region (B)

Geographical region exerted the strongest influence on elongation at break ($F = 1844.96$, $p < 0.0001$), accounting for approximately 65.3% of the total variation in the response. This contribution was substantially greater than that of variety, indicating that environmental conditions associated with different production regions played a dominant role in determining fiber extensibility.

Regional variations in temperature, relative humidity, altitude, host-plant quality, soil characteristics, and rearing management practices can influence silkworm physiology and fibroin biosynthesis. Such environmental factors affect the formation and distribution of crystalline and amorphous domains within silk fibers, thereby modifying molecular mobility and elongation behavior. Increased moisture availability and improved host-plant

nutrition, for example, may promote a greater proportion of amorphous regions, leading to enhanced extensibility.

The present findings therefore suggest that optimizing environmental and cultivation conditions may be more effective in improving elongation performance than relying solely on varietal selection.

3.4.3 Main Effect of Variety (A)

Variety also significantly affected elongation at break ($F = 793.41$, $p < 0.0001$), contributing approximately 28.1% of the total variation. Based on the mean elongation values obtained in this study, the varieties may be ranked as follows:

- Chinese White ... highest elongation at break;
- Borduar White ... moderate elongation at break;
- Kokrajhar Brick-Red ... lowest elongation at break.

These differences indicate inherent genetic variations in the extensibility characteristics of Eri silk fibers. Such variations may arise from differences in fibroin molecular structure, filament morphology, molecular orientation, and the balance between crystalline and amorphous regions within the fiber.

Although the varietal effect was statistically significant, its influence was notably smaller than that of geographical region, implying that environmental conditions exert a stronger control over elongation behavior than genetic background under the conditions investigated.

The present results are generally consistent with previous investigations on Eri silk elongation behavior. Marlin P. Maldia et al. [37] reported no statistically significant differences in elongation (15–26%) among six newly developed Eri silk strains relative to wild *Samia cynthia ricini*, despite measurable

differences in other filament characteristics. Their findings suggest that elongation is often less sensitive to genetic variation than other mechanical properties such as tenacity and modulus.

A mechanistic explanation was provided by Kushal Sen and Murugesh Babu K [38], who demonstrated strong negative correlations between elongation and both crystallinity and crystallite orientation function. Increased molecular order was shown to enhance tenacity and initial modulus while simultaneously reducing extensibility. Consequently, moderate differences in molecular organization among Eri silk varieties may lead to only limited variations in elongation behavior.

Similarly, Jianmei Xu et al. [39] reported that extension speed significantly affects breaking tenacity but exerts no measurable influence on breaking elongation, highlighting the inherent stability of elongation as a mechanical parameter.

The findings of the present study extend previous knowledge by demonstrating that environmental conditions associated with geographical region may exert a stronger influence on elongation behavior than genetic differences among the studied varieties. Variations in climate, altitude, humidity, host-plant nutrition, and rearing practices can modify silkworm metabolism and fibroin synthesis, thereby affecting the molecular architecture and extensibility of the resulting fibers. Although varietal characteristics significantly contributed to elongation performance, the weak interaction pattern indicates that regional factors primarily shifted elongation levels without altering the relative ranking of the varieties.

Overall, the results indicate that elongation at break in Eri silk fibers is governed by both genetic and environmental factors, with environmental conditions exerting the dominant influence under the experimental conditions considered in this study.

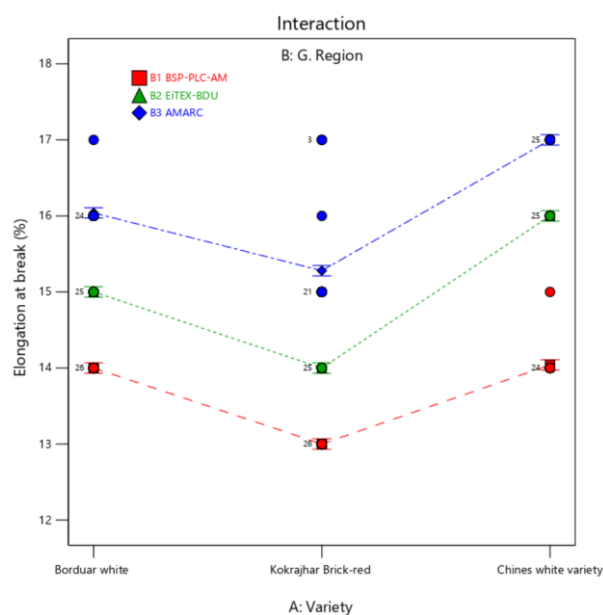


Figure 10. Interaction view: Elongation variation across varieties and rearing regions

Table 4. ANOVA: Elongation (%) evaluation between variety (A) and place (B)

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	325.90	8	40.74	678.96	< 0.0001 significant
A-Variety	95.21	2	47.60	793.41	< 0.0001
B-G. Region	221.40	2	110.70	1844.96	< 0.0001
AB	9.30	4	2.32	38.74	< 0.0001
Pure Error	12.96	216	0.0600		
Cor Total	338.86	224			

3.5. Young's Modulus of Eri Silk Fiber Varieties

The Young's modulus (g/den) of the Eri silk samples showed highly significant differences attributable to both variety and rearing place ($p < 0.0001$), with the interaction between the two factors (AB) also statistically significant. ANOVA results (Table 5) demonstrated that genetic factors accounted for the greatest proportion of variation (Sum of Squares = 2103.79), followed by rearing place (821.79). This pattern aligns closely with the trends observed for fineness and tenacity, confirming that the stiffness of Eri silk fibers is fundamentally a hereditary property, yet still responsive to external influences.

Although all experimental sites employed indoor rearing with controlled temperature and relative humidity to minimize environmental bias, variations in Young's modulus remained significant. This indicates that even under standardized conditions, microenvironmental differences including subtle differences in feeding quality (castor leaf maturity, nutrient status), microclimatic variation within rearing rooms, and strain-

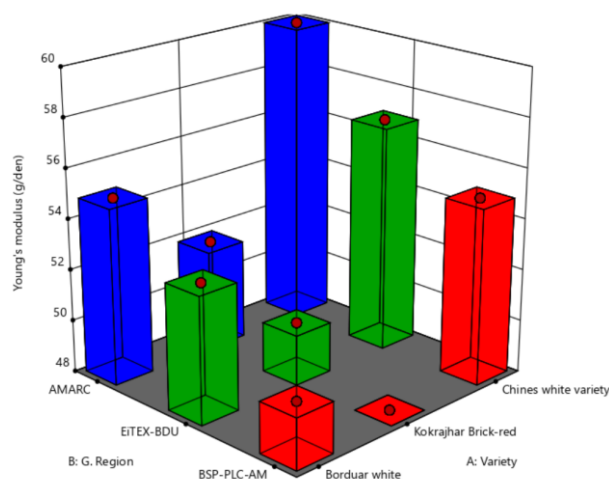
specific physiological responses - can influence fibroin assembly during spinning. Young's modulus is strongly associated with the proportion and alignment of β -sheet crystalline domains in the fibroin matrix. These crystalline regions confer rigidity and are determined not only by genetic programming of the silk gland but also by fine-scale biochemical and mechanical stimuli experienced during extrusion.

The significant interaction effect further suggests that different varieties do not respond uniformly to the same controlled environments. Some strains may optimize crystallinity more efficiently when reared under particular feeding or handling conditions, while others may show reduced capacity for molecular orientation during spinning. This supports the concept that genotype-environment coupling remains influential even when major climatic parameters are standardized.

Variety and geographical region (G. Region) 3D plots of Yong's modulus (g/den) for the studied varieties is presented in Figure 11.

Table 6. ANOVA: Young's modulus (g/den) evaluation (Between variety (A) and place (B))

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	2936.48	8	367.06	82588.5	< 0.0001 significant
A-Variety	2103.79	2	1051.89	2.37E+05	< 0.0001
B-Place	821.79	2	410.89	92451	< 0.0001
AB	10.91	4	2.73	613.5	< 0.0001
Pure Error	0.96	216	0.0044		
Cor Total	2937.44	224			

**Figure 11.** Variety and geographical region (G. Region) 3D plots for Young's modulus

4. CONCLUSION

This study presents the first comprehensive scientific evaluation of Eri silk cultivated in Ethiopia, generating benchmark data on fiber morphology, fineness, tensile strength, elongation, and Young's modulus for three genetically distinct strains. By rearing silkworms indoors under controlled temperature and humidity across different ecological locations, the research effectively distinguishes inherent genetic contributions from localized environmental influences. The combined use of SEM microstructural analysis and mechanical properties study provides a robust structure property interpretation, demonstrating how variations in fibroin and sericin distribution, filament cross-sectional geometry, and microfibrillar packing govern the performance of Eri silk under load.

The results reveal that, even under standardized rearing conditions, genetic diversity and subtle environmental micro-variations significantly shape mechanical outcomes, particularly fineness, tenacity, and modulus. These insights strengthen the scientific basis for strategic improvement in Eri silk production. Selective breeding programs, genotype-environment matching, and optimized rearing protocols hold strong potential to enhance fiber uniformity, stiffness, and strength. Such advances would not only improve textile processing performance but also expand the applicability of Ethiopian Eri silk in high-value markets including technical textiles, composites, medical biomaterials, and environmentally aligned product development.

Overall, this study provides a foundational reference for future research on African Eri silk, supporting the development of region-specific breeding strategies and contributing to sustainable value-chain growth in a rapidly emerging silk-producing economy.

Research Highlights

The results of this study have practical implications for the silk and textile industry. Varieties and rearing environments that yield finer and stronger Eri fibers can be prioritized for high-performance yarns and luxury textiles, where strength, handle, and durability are essential. In contrast, fibers with moderate stiffness and irregular morphology may be directed toward blended textiles or nonwoven applications. By aligning varietal selection with regional ecological strengths, producers can maximize both fiber quality and production efficiency, while contributing to the growing demand for sustainable and ethically sourced silks in global textile markets.

Funding Statement

This study was supported by a competitive grant awarded through the 2024/25 Mega Research Proposal Call of the Research Affairs Directorate, Office of the Vice President for Research and Community Engagement, Bahir Dar University.

Ethical Approval

This research did not involve human participants, clinical trials, or vertebrate animals. The experimental work was conducted in accordance with institutional and national ethical guidelines for research involving invertebrates. The handling and rearing of silkworms (Eri and Mulberry)

followed standard sericulture practices approved by the Ethiopian Institute of Textile and Fashion Technology (EiTEX), Bahir Dar University.

Conflicts of Interest

The authors declare that there is no conflict of interest in the research results or publication.

Acknowledgments

The authors gratefully acknowledge the Ethiopian Institute of Textile and Fashion Technology, Bahir Dar University, for providing access to mulberry and Eri silk plantation facilities essential for this research. The support of technical staff and colleagues during the course of the study is also sincerely appreciated.

REFERENCES

1. Yazawa, K., Tatebayashi, Y. & Kajiura, Z., (2022). Eri silkworm spins mechanically robust silk fibers regardless of reeling speed. *Journal of Experimental Biology*, 225(3), jeb243458. Available at: <https://journals.biologists.com/jeb/article/225/3/jeb243458/274266/Eri-silkworm-spins-mechanically-robust-silk-fibers> [Accessed 21 Aug. 2025].
2. Elvan Ozkavruk Adanir, Berna İleri, Feza Can & Başak Ulasli (2024) An Ethical Approach to Sericulture: Production of Peace Silk in Hatay/Turkey, *TEXTILE*, 22:1, 20-30, DOI: 10.1080/14759756.2022.2036072
3. Devi YS, Anowar H, Sapana Devi W, Debaraj Y, Majumdar S and Raviraj VS. (2025) Assessment of stable strains of eri silkworms (*Samia ricini*) for commercial silk production under the climate of Manipur. *Adv Res*. 26(1): 369-377.
4. Fang, G, Zhang, X, Chen, X, Shao, Z & Vollrath, F (2016), 'Comparative studies on mechanical properties and structural characterization of silks from different silkworms', *Biomacromolecules*, vol. 17, no. 3, pp. 1131-1138.
5. Poluri, KM, Babu, KN & Asokan, R (2021), 'Regenerated non-mulberry silk films produced via formic acid self-assembly: structure-property correlation and mechanical performance', *International Journal of Biological Macromolecules*, vol. 182, pp. 1105-1116.
6. Dam, S, Chakraborty, S & Mandal, BB (2024), 'Nanostructured Eri silk scaffolds embedded with silver nanoparticles for biomedical applications', *Materials Science & Engineering C*.
7. Dam, P., ^a Shaw, S., ^a Mondal R., ^a Chakraborty, J., ^b Bhattacharjee, T., ^c Kumar, I. S., ^d Manna, S., ^e Sadat, A., ^a Suin, S., ^f Sarkar, H., ^b , Ertas. Y. N., ^{*ghi} and Mandal, A. K. ^{*a}, (2024). Multifunctional silver nanoparticle embedded eri silk cocoon scaffolds against burn wounds-associated infection, *RSC Adv.*, , 14, 26723-26737.
8. Babu, K. M., (2020), 'Silk fibers – structure, properties and applications, *Journal of Natural Fibres, Handbook of Natural Fibres*, Pages 385-416. <https://doi.org/10.1016/B978-0-12-818398-4.00013-X>
9. Ashrith, S., Pavithra, M.R., Reddy, H.C., Jekinakatti, B., Kumar, A.M.R. & Suhas, B.V. (2025) 'Climate change and its impact on sericulture: A brief review', *Biochemistry and Biotechnology Research*, 9(8), pp. 23-29.
10. Talukdar, M., Kaushik, A., Saikia, B., Sangma, A. & Dehingia, S. (2025) 'Molecular mechanisms of climate stress tolerance in silkworms', *Journal of Advances in Biology & Biotechnology*, 33(4), pp. 12-21.

11. Kaushik, A., Borah, G., Saikia, S., Kaushiki, B. & Phukan, T. (2025) 'Climate-resilient sericulture: Strategies for sustainable silk production in a changing climate', *Biochemistry and Biotechnology Research*, 9(8), pp. 112–120.
12. Maldia, M.P., Nugraha, R., Pranowo, H.D., Yanto, H. & Handayani, D., (2024). Physical characterization of Indonesian Eri silk fiber derived from new strains. *Egyptian Journal of Chemistry*, 67(6), pp.1–12 (article PDF reports diameter 14–33 μm ; tensile 350–497 MPa; 15–26% elongation). Available at: [PDF] (Accessed 21 Aug 2025). ejchem.journals.ekb.eg
13. Vaidya, S., (2014). Effects of temperature and relative humidity on rearing performances of Eri silkworm (*Philosamia ricini*). *Environment Conservation Journal*, 15(3), pp.189–193. (Reports optimal bands near $28 \pm 3^\circ\text{C}$ and ~70% RH for growth and pupation). journal.envirocnj.in
14. Reddy, N. & Yang, Y., (2010). Structure and properties of wild silk fibers. *Journal of Polymers and the Environment*, 18(1), pp.109–114. (Review linking microstructure to properties in non-mulberry silks, including Eri.) digitalcommons.unl.edu
15. Zhang, L., Yang, G., Johnson, B.N. & Jia, X., (2021). Systematic review of silk scaffolds in musculoskeletal tissue engineering. *ACS Biomaterials Science & Engineering*, 7(2), pp.543–571. (Synthesizes links between silk microstructure and mechanical function; useful context for SEM–mechanics interpretations). *ACS Publications*
16. Oksijen İçeren Farklı Düşük Frekans Plazmalarının Ham İpek Liflerinden Serisin Giderilmesine Etkisinin Karşılaştırılması; Bengi KUTLU (2020); Comparison of Effects of Several Oxygen Containing Low Frequency Plasmas on the Removal of Silk Sericin Layer of Raw Silk Fabrics, *Tekstil ve Mühendis*, 27: 117, 41-47. <https://doi.org/10.7216/1300759920202711705>
17. Debasis Chattopadhyay, Arijit Chakraborty & S. M. Chatterjee (2017) Studies on degumming of eri silk cocoons, *The Journal of The Textile Institute*, 108:8, 1327-1339, DOI:10.1080/00405000.2016.1247617; <http://dx.doi.org/10.1080/00405000.2016.1247617>
18. Kundu, B.^a, Kurland, N. E.^b, Bano, S.^a, Patra, C.^c, Engel, F. B.^c, Yadavalli, V.K.^b, (2014). Silk proteins for biomedical applications: Bioengineering perspectives. *Progress in Polymer Science*, Volume 39, Issue 2, Pages 251-267. <https://doi.org/10.1016/j.progpolymsci.2013.09.002>
19. Malay, A. D.; Sato, R.; Yazawa, K.; Watanabe, H.; Ifuku, N.; Masunaga, H.; Hikima, T.; Guan, J.; Mandal, B. B.; Damrongsakkul, S.; Numata, K. (2016). Relationships between physical properties and sequence in silkworm silks. *Sci. Rep.*, 1–11. <https://doi.org/10.1038/srep27573>
20. Mu, X., Li, Y., Wang, X., et al. (2023). A brief review on the mechanisms and approaches of silk spinning. *Frontiers in Bioengineering and Biotechnology*, 11, 1252499. <https://doi.org/10.3389/fbioe.2023.1252499>
21. Frydrych, M., Chen, B., Bader, D. L., & Parker, K. K. (2019). Artificial spinning of natural silk threads. *PLoS ONE*, 14(10), e0223366. <https://doi.org/10.1371/journal.pone.0223366>
22. Regina Inês Kunz¹, Rose Meire Costa Brancalhão^{2,*}, Lucinéia de Fátima Chasko Ribeiro², Maria Raquel Marçal Natali¹, (2016). Silkworm Sericin: Properties and Biomedical Applications. *Journal: BioMed Research International*. <https://doi.org/10.1155/2016/8175701>
23. Sparkes, J. & Holland, C. (2018) 'The rheological properties of native sericin', *Acta Biomaterialia*, 69, pp. 234–242
24. Schaefer, C. & McLeish, T. C. B. (2021) 'Theoretical rheo-physics of silk: Intermolecular associations reduce the critical specific work for flow-induced crystallisation', *arXiv preprint*, arXiv:2112.01965
25. Hariraj, G. & Somashekar, T.H. (2001) 'Studies on drying of multi-bivoltine cocoons (III): effect of hot air drying temperature on sericin hardening', *The Journal of Silk Science and Technology of Japan*, 10, pp. 81–86. [21]
26. Kunz, B., Laufenberg, G. & Knorr, D. (2016) 'Impact of amino acid composition and molecular weight on sericin functionality', *Food Hydrocolloids*, 61, pp. 110–117.
27. Padamwar, M.N. & Pawar, A.P. (2004) 'Silk sericin and its applications: a review', *Journal of Scientific & Industrial Research*, 63, pp. 323–329.
28. Aramwit, P., Srichana, T. & Siritientong, T. (2012) 'Effects of amino acid composition on sericin aggregation and fiber surface properties', *Journal of Biomedical Materials Research Part B: Applied Biomaterials*, 100B, pp. 2403–2410.
29. Zhang, Y., Wang, X., Li, Q. & Shao, Z. (2013) 'Sericin molecular interactions and fiber morphology', *International Journal of Biological Macromolecules*, 62, pp. 101–108.
30. Brahma, B.B., Kalita, P. & Baruah, M.B. (2025) 'Physical analysis of white and brick red Eri silk fiber', *Fibers and Polymers*, 26, pp. 2327–2340. <https://doi.org/10.1007/s12221-025-00958-5>
31. Kushal Sen,¹ Murugesh Babu K2. Studies on Indian Silk. I. Macrocharacterization and Analysis of Amino Acid Composition. *Journal of Applied Polymer Science*, Vol. 92, 1080–1097 (2004)
32. Offord, L., Martin, F., Gupta, R. & Sharma, K. (2016) 'Influence of diet and habitat micro-management on cocoon and filament properties in domesticated silkworm strains', *Journal of Sericulture Science*, 52(3), pp. 145–152.
33. Wang, Y., Li, Q. & Zhou, X. (2024) 'Strain-specific physiological responses and silk production characteristics in Eri silkworm rearing', *International Journal of Textile Science*, 19(2), pp. 88–99.
34. Kumari, R. & Kumar, S. (2023) 'Environmental and management drivers of cocoon and filament quality in Eri silkworm production', *International Journal of Sericulture and Silk Technology*, 61(2), pp. 88–96.
35. Sari, D., Utami, R., Prasetyo, N. & Darmawan, H. (2024) 'Effects of controlled rearing parameters on biochemical structure and tensile response of silk filaments', *Journal of Biomaterials and Textiles*, 7(1), pp. 55–66.
36. Aramwit, P., Kanokpanont, S. & Srichana, T. (2017) 'Influence of rearing and processing conditions on mechanical and biochemical properties of silk', *Journal of Applied Polymer Science*, 134(12), pp. 1–9.
37. Maldia MP, Darmawan N, Endrawati YC, Suparto IH, Syamani FA, Noor RR. Physical characterization of Indonesian Eri silk fiber derived from novel strains of *Samia cynthia ricini*. *Egypt J Chem*. 2024;67(4):55–63.
38. Sen K, Babu KM. Studies on Indian silk. II. Structure–property correlations. *J Appl Polym Sci*. 2004; 92:1098–1115.
39. Xu J, Zhou Y, Bai L. Analysis of the affecting factors on single-end tenacity and elongation test of raw silk. *Adv Mater Res*. 2011;175–176:570–574.

APPENDIX-I

Data of studied varieties produced in the three zones

	Factor 1	Factor 2	Response 1	Response 2	Response 3	Response 4
	A: Variety	B: G. Region	Fineness (den)	Tenacity (g/den)	Elongation at break (%)	Young's modulus (g/den)
1	Borduar white	AMARC	3.5	3.2	16	55
2	Borduar white	EiTEX-BDU	2.8	3	15	53
3	Chinese white variety	BSP-PLC-AM	2.4	3	14	55
4	Borduar white	BSP-PLC-AM	2.5	2.8	14	50
5	Kokrajhar Brick-red	BSP-PLC-AM	3	2.5	13	48
6	Chinese white variety	EiTEX-BDU	2.6	3.2	16	57
7	Borduar white	AMARC	3.5	3.2	16	55
8	Chinese white variety	AMARC	3	3.5	17	60
9	Borduar white	AMARC	3.5	3.2	16	55
10	Borduar white	EiTEX-BDU	2.8	3	15	53
11	Borduar white	AMARC	3.5	3.2	17	55
12	Kokrajhar Brick-red	EiTEX-BDU	3.5	2.7	14	50
13	Kokrajhar Brick-red	EiTEX-BDU	3.5	2.7	14	50
14	Chinese white variety	BSP-PLC-AM	2.4	3	15	55
15	Borduar white	EiTEX-BDU	2.8	3	15	53
16	Borduar white	EiTEX-BDU	2.8	3	15	53
17	Kokrajhar Brick-red	AMARC	4	3	15	52
18	Borduar white	BSP-PLC-AM	2.5	2.8	14	50
19	Chinese white variety	BSP-PLC-AM	2.4	3	14	55
20	Borduar white	AMARC	3.5	3.2	16	55
21	Kokrajhar Brick-red	AMARC	4	3	16	52
22	Borduar white	AMARC	3.5	3.2	16	55
23	Chinese white variety	AMARC	3	3.5	17	60
24	Kokrajhar Brick-red	EiTEX-BDU	3.5	2.7	14	50
25	Kokrajhar Brick-red	BSP-PLC-AM	3	2.5	13	48
26	Kokrajhar Brick-red	AMARC	4	3	15	52
27	Borduar white	EiTEX-BDU	2.8	3	15	53
28	Borduar white	AMARC	3.5	3.2	16	55
29	Chinese white variety	BSP-PLC-AM	2.4	3	14	55
30	Chinese white variety	EiTEX-BDU	2.6	3.2	16	57
31	Kokrajhar Brick-red	EiTEX-BDU	3.5	2.7	14	50
32	Kokrajhar Brick-red	BSP-PLC-AM	3	2.5	13	48
33	Kokrajhar Brick-red	BSP-PLC-AM	3	2.5	13	48
34	Borduar white	BSP-PLC-AM	2.5	2.8	14	50
35	Borduar white	EiTEX-BDU	2.8	3	15	53
36	Borduar white	BSP-PLC-AM	2.5	2.8	14	50
37	Chinese white variety	AMARC	3	3.5	17	60
38	Chinese white variety	AMARC	3	3.5	17	60
39	Borduar white	EiTEX-BDU	2.8	3	15	53
40	Borduar white	BSP-PLC-AM	2.5	2.8	14	50
41	Kokrajhar Brick-red	BSP-PLC-AM	3	2.5	13	48
42	Kokrajhar Brick-red	EiTEX-BDU	3.5	2.7	14	50
43	Kokrajhar Brick-red	AMARC	4	3	17	52
44	Kokrajhar Brick-red	EiTEX-BDU	3.5	2.7	14	50
45	Chinese white variety	AMARC	3	3.5	17	60
46	Borduar white	AMARC	3.5	3.2	16	55
47	Chinese white variety	BSP-PLC-AM	2.4	3	14	55
48	Chinese white variety	AMARC	3	3.5	17	60
49	Kokrajhar Brick-red	EiTEX-BDU	3.5	2.7	14	50
50	Kokrajhar Brick-red	AMARC	4	3	15	52
51	Kokrajhar Brick-red	AMARC	4	3	15	52
52	Chinese white variety	EiTEX-BDU	2.6	3.2	16	57
53	Chinese white variety	EiTEX-BDU	2.6	3.2	16	57
54	Borduar white	BSP-PLC-AM	2.5	2.8	14	50
55	Borduar white	BSP-PLC-AM	2.5	2.8	14	50
56	Borduar white	BSP-PLC-AM	2.5	2.8	14	50

	Factor 1	Factor 2	Response 1	Response 2	Response 3	Response 4
	A: Variety	B: G. Region	Fineness (den)	Tenacity (g/den)	Elongation at break (%)	Young's modulus (g/den)
57	Borduar white	EiTEX-BDU	2.8	3	15	53
58	Kokrajhar Brick-red	BSP-PLC-AM	3	2.5	13	48
59	Chinese white variety	BSP-PLC-AM	2.4	3	14	55
60	Borduar white	BSP-PLC-AM	2.5	2.8	14	50
61	Borduar white	EiTEX-BDU	2.8	3	15	53
62	Borduar white	BSP-PLC-AM	2.5	2.8	14	50
63	Chinese white variety	AMARC	3	3.5	17	60
64	Kokrajhar Brick-red	BSP-PLC-AM	3	2.5	13	48
65	Borduar white	AMARC	3.5	3.2	16	55
66	Kokrajhar Brick-red	AMARC	4	3	15	52
67	Chinese white variety	BSP-PLC-AM	2.4	3	14	55
68	Chinese white variety	BSP-PLC-AM	2.4	3	14	55
69	Kokrajhar Brick-red	BSP-PLC-AM	3	2.5	13	48
70	Chinese white variety	EiTEX-BDU	2.6	3.2	16	57
71	Chinese white variety	BSP-PLC-AM	2.4	3	14	55
72	Kokrajhar Brick-red	BSP-PLC-AM	3	2.5	13	48
73	Chinese white variety	BSP-PLC-AM	2.4	3	14	55
74	Kokrajhar Brick-red	AMARC	4	3	17	52
75	Borduar white	EiTEX-BDU	2.8	3	15	53
76	Chinese white variety	AMARC	3.5	3.5	17	60
77	Chinese white variety	BSP-PLC-AM	2.4	3	14	55
78	Borduar white	EiTEX-BDU	2.8	3	15	53
79	Borduar white	BSP-PLC-AM	2.5	2.8	14	50
80	Borduar white	EiTEX-BDU	2.8	3	15	53
81	Kokrajhar Brick-red	BSP-PLC-AM	3	2.5	13	48
82	Borduar white	AMARC	3.5	3.2	16	55
83	Chinese white variety	AMARC	3	3.5	17	60
84	Kokrajhar Brick-red	AMARC	4	3	15	52
85	Borduar white	EiTEX-BDU	2.8	3	15	53
86	Borduar white	AMARC	3.5	3.2	16	55
87	Kokrajhar Brick-red	BSP-PLC-AM	3	2.5	13	48
88	Kokrajhar Brick-red	AMARC	4	3	15	52
89	Chinese white variety	BSP-PLC-AM	2.4	3	14	55
90	Chinese white variety	BSP-PLC-AM	2.4	3	14	55
91	Kokrajhar Brick-red	AMARC	4	3	15	52
92	Chinese white variety	EiTEX-BDU	2.6	3.2	16	57
93	Kokrajhar Brick-red	EiTEX-BDU	3.5	2.7	14	50
94	Borduar white	AMARC	3.5	3.2	16	55
95	Kokrajhar Brick-red	AMARC	4	3	15	52
96	Borduar white	EiTEX-BDU	2.8	3	15	53
97	Chinese white variety	AMARC	3	3.5	17	60
98	Chinese white variety	EiTEX-BDU	2.6	3.2	16	57
99	Kokrajhar Brick-red	AMARC	4	3	17	52
100	Borduar white	EiTEX-BDU	2.8	3	15	53
101	Kokrajhar Brick-red	AMARC	4	3	15	52
102	Kokrajhar Brick-red	BSP-PLC-AM	3	2.5	13	48
103	Kokrajhar Brick-red	AMARC	4	3	15	52
104	Chinese white variety	EiTEX-BDU	2.6	3.2	16	57
105	Chinese white variety	BSP-PLC-AM	2.4	3	14	55
106	Chinese white variety	EiTEX-BDU	2.6	3.2	16	57
107	Kokrajhar Brick-red	EiTEX-BDU	3.5	2.7	14	50
108	Kokrajhar Brick-red	BSP-PLC-AM	3	2.5	13	48
109	Kokrajhar Brick-red	BSP-PLC-AM	3	2.5	13	48
110	Kokrajhar Brick-red	EiTEX-BDU	3.5	2.7	14	50
111	Borduar white	EiTEX-BDU	2.8	3	15	53
112	Chinese white variety	AMARC	3	3.5	17	60
113	Borduar white	EiTEX-BDU	2.8	3	15	53
114	Borduar white	BSP-PLC-AM	2.5	2.8	14	50

	Factor 1	Factor 2	Response 1	Response 2	Response 3	Response 4
	A: Variety	B: G. Region	Fineness (den)	Tenacity (g/den)	Elongation at break (%)	Young's modulus (g/den)
115	Borduar white	EiTEX-BDU	2.8	3	15	53
116	Kokrajhar Brick-red	EiTEX-BDU	3.5	2.7	14	50
117	Borduar white	AMARC	3.5	3.2	16	55
118	Kokrajhar Brick-red	BSP-PLC-AM	3	2.5	13	48
119	Kokrajhar Brick-red	BSP-PLC-AM	3	2.5	13	48
120	Chinese white variety	EiTEX-BDU	2.6	3.2	16	57
121	Borduar white	AMARC	3.5	3.2	16	55
122	Kokrajhar Brick-red	AMARC	4	3	15	52
123	Borduar white	EiTEX-BDU	2.8	3	15	53
124	Kokrajhar Brick-red	AMARC	4	3	15	52
125	Borduar white	EiTEX-BDU	2.8	3	15	53
126	Kokrajhar Brick-red	BSP-PLC-AM	3	2.5	13	48
127	Kokrajhar Brick-red	EiTEX-BDU	3.5	2.7	14	50
128	Kokrajhar Brick-red	BSP-PLC-AM	3	2.5	13	48
129	Chinese white variety	BSP-PLC-AM	2.4	3	14	55
130	Chinese white variety	BSP-PLC-AM	2.4	3	14	55
131	Borduar white	AMARC	3.5	3.2	16	55
132	Chinese white variety	AMARC	3	3.5	17	60
133	Kokrajhar Brick-red	AMARC	4	3	15	52
134	Chinese white variety	EiTEX-BDU	2.6	3.2	16	57
135	Kokrajhar Brick-red	EiTEX-BDU	3.5	2.7	14	50
136	Chinese white variety	BSP-PLC-AM	2.4	3	14	55
137	Borduar white	BSP-PLC-AM	2.5	2.8	14	50
138	Kokrajhar Brick-red	AMARC	4	3	15	52
139	Kokrajhar Brick-red	AMARC	4	3	15	52
140	Kokrajhar Brick-red	BSP-PLC-AM	3	2.5	13	48
141	Kokrajhar Brick-red	EiTEX-BDU	3.5	2.7	14	50
142	Chinese white variety	EiTEX-BDU	2.6	3.2	16	57
143	Kokrajhar Brick-red	BSP-PLC-AM	3	2.5	13	48
144	Chinese white variety	AMARC	3	3.5	17	60
145	Borduar white	BSP-PLC-AM	2.5	2.8	14	50
146	Chinese white variety	EiTEX-BDU	2.6	3.2	16	57
147	Chinese white variety	AMARC	3	3.5	17	60
148	Borduar white	EiTEX-BDU	2.8	3	15	53
149	Chinese white variety	BSP-PLC-AM	2.4	3	14	55
150	Chinese white variety	EiTEX-BDU	2.6	3.2	16	57
151	Borduar white	EiTEX-BDU	2.8	3	15	53
152	Chinese white variety	AMARC	3	3.5	17	60
153	Borduar white	AMARC	3.5	3.2	16	55
154	Chinese white variety	EiTEX-BDU	2.6	3.2	16	57
155	Borduar white	BSP-PLC-AM	2.5	2.8	14	50
156	Borduar white	AMARC	3.5	3.2	16	55
157	Kokrajhar Brick-red	BSP-PLC-AM	3	3	13	48
158	Kokrajhar Brick-red	EiTEX-BDU	3.5	2.7	14	50
159	Borduar white	EiTEX-BDU	2.8	3	15	53
160	Kokrajhar Brick-red	EiTEX-BDU	3.5	2.7	14	50
161	Chinese white variety	EiTEX-BDU	2.6	3.2	16	57
162	Chinese white variety	AMARC	3	3.5	17	60
163	Borduar white	AMARC	3.5	3.2	16	55
164	Chinese white variety	AMARC	3	3.5	17	60
165	Chinese white variety	AMARC	3	3.5	17	60
166	Borduar white	AMARC	3.5	3.2	16	55
167	Kokrajhar Brick-red	EiTEX-BDU	3.5	2.7	14	50
168	Borduar white	BSP-PLC-AM	2.5	2.8	14	50
169	Chinese white variety	EiTEX-BDU	2.6	3.2	16	57
170	Chinese white variety	AMARC	3	3.5	17	60
171	Kokrajhar Brick-red	EiTEX-BDU	3.5	2.7	14	50
172	Chinese white variety	EiTEX-BDU	2.8	3.2	16	57

	Factor 1	Factor 2	Response 1	Response 2	Response 3	Response 4
	A: Variety	B: G. Region	Fineness (den)	Tenacity (g/den)	Elongation at break (%)	Young's modulus (g/den)
173	Kokrajhar Brick-red	EiTEX-BDU	3.5	2.7	14	50
174	Chinese white variety	BSP-PLC-AM	2.4	3	14	55
175	Borduar white	BSP-PLC-AM	2.5	2.8	14	50
176	Borduar white	BSP-PLC-AM	2.5	2.8	14	50
177	Chinese white variety	BSP-PLC-AM	2.4	3	14	55
178	Chinese white variety	EiTEX-BDU	2.6	3.2	16	57
179	Kokrajhar Brick-red	EiTEX-BDU	3.5	2.7	14	50
180	Borduar white	AMARC	3.5	3.2	16	55
181	Borduar white	EiTEX-BDU	2.8	3	15	53
182	Chinese white variety	AMARC	3	3.5	17	60
183	Kokrajhar Brick-red	BSP-PLC-AM	3	2.5	13	48
184	Borduar white	BSP-PLC-AM	2.5	2.8	14	50
185	Borduar white	BSP-PLC-AM	2.5	2.8	14	50
186	Chinese white variety	BSP-PLC-AM	2.4	3	14	55
187	Borduar white	AMARC	3.5	3.2	16	55
188	Chinese white variety	BSP-PLC-AM	2.4	3	14	55
189	Chinese white variety	BSP-PLC-AM	2.4	3	14	55
190	Borduar white	BSP-PLC-AM	2.5	2.8	14	50
191	Chinese white variety	AMARC	3	3.5	17	60
192	Kokrajhar Brick-red	BSP-PLC-AM	3	2.5	13	48
193	Kokrajhar Brick-red	AMARC	4	3	15	52
194	Borduar white	BSP-PLC-AM	2.5	2.8	14	50
195	Chinese white variety	BSP-PLC-AM	2.4	3	14	55
196	Borduar white	BSP-PLC-AM	2.5	2.8	14	50
197	Chinese white variety	AMARC	3	3.5	17	60
198	Kokrajhar Brick-red	EiTEX-BDU	3.5	2.7	14	50
199	Chinese white variety	EiTEX-BDU	2.8	3.2	16	57
200	Kokrajhar Brick-red	EiTEX-BDU	3.5	2.7	14	50
201	Borduar white	AMARC	3.5	3.2	16	55
202	Borduar white	AMARC	3.5	3.2	16	55
203	Kokrajhar Brick-red	AMARC	4	3	15	52
204	Chinese white variety	AMARC	3	3.5	17	60
205	Chinese white variety	EiTEX-BDU	2.6	3.2	16	57
206	Chinese white variety	AMARC	3	3.5	17	60
207	Kokrajhar Brick-red	EiTEX-BDU	3.5	2.7	14	50
208	Chinese white variety	EiTEX-BDU	2.6	3.2	16	57
209	Kokrajhar Brick-red	EiTEX-BDU	3.5	2.7	14	50
210	Kokrajhar Brick-red	BSP-PLC-AM	3	2.5	13	48
211	Borduar white	AMARC	3.5	3.2	16	55
212	Chinese white variety	EiTEX-BDU	2.6	3.2	16	57
213	Kokrajhar Brick-red	AMARC	4	3	15	52
214	Chinese white variety	AMARC	3	3.5	17	60
215	Chinese white variety	EiTEX-BDU	2.6	3.2	16	57
216	Kokrajhar Brick-red	BSP-PLC-AM	3	2.5	13	48
217	Kokrajhar Brick-red	AMARC	4	3	15	52
218	Kokrajhar Brick-red	EiTEX-BDU	3.5	2.7	14	50
219	Borduar white	BSP-PLC-AM	2.5	2.8	14	50
220	Borduar white	EiTEX-BDU	2.8	3	15	53
221	Chinese white variety	BSP-PLC-AM	2.4	3	14	55
222	Borduar white	BSP-PLC-AM	2.5	2.8	14	50
223	Kokrajhar Brick-red	AMARC	4	3	15	52
224	Borduar white	AMARC	3.5	3.2	16	55
225	Chinese white variety	EiTEX-BDU	2.6	3.2	16	57