***Review Article***

**MUGA SILK: A REVIEW ON ITS STRUCTURAL, PHYSICAL, AND BIOMEDICAL SIGNIFICANCE**

**ABSTRACT**

Muga silk, secreted by the semi-domesticated silkworm Antheraea assamensis, is a unique natural fiber indigenous to northeastern India, renowned for its golden luster, exceptional durability, and regional exclusivity. As global demand grows for sustainable and high-performance biomaterials, Muga silk is emerging as a promising alternative to the extensively studied Bombyx mori silk. This review critically examines the structural, physicochemical, and thermal characteristics of Muga silk, with emphasis on its molecular organization, fibroin crystallinity, and surface morphology. Comparative analysis with mulberry, tasar, and eri silks highlights superior thermal stability (>300 °C), mechanical strength (up to 7.5 MPa), and biocompatibility of muga silk, making it suitable for biomedical applications such as scaffolds, wound dressings, and composite biomaterials. Additionally, this review discusses the influence of environmental factors—seasonality, host plant variability, and regional microclimate—on cocoon quality and silk yield. Despite its advantages, Muga silk faces significant challenge including limited geographical adaptability, processing difficulties, and lack of standardized biomaterial fabrication protocols. Future research must focus on molecular-level characterization, host plant management, climate-resilient sericulture, and scalable silk fibroin extraction methods. With interdisciplinary collaboration and targeted innovation, Muga silk can transcend its traditional textile niche and evolve into a globally relevant, sustainable biomaterial for next-generation biomedical and industrial applications.

*Keyword: Muga silk;* Antheraea assamensis*; non-mulberry silk; biomaterials; silk fibroin films; thermal stability; biocompatibility; tissue engineering*

1. **INTRODUCTION**

Silks are high-molecular-weight organic polymers composed of repetitive hydrophobic and hydrophilic peptide sequences, which confer them with a unique blend of mechanical properties (Valluzzi *et al.,* 2002). Among natural fibers, silk stands out as one of nature’s most sophisticated structural materials, exhibiting an extraordinary combination of strength and toughness that remains difficult to replicate synthetically (Rousseau *et al.,* 2004). The biosynthesis of silk proteins begins within the epithelial cells of specialized glands, followed by secretion into the glandular lumen, where they are stored prior to fiber spinning (Altman *et al.,* 2003).

Historically, silk has held a prominent place among natural fibers, being one of the earliest utilized by humans. Its composition, structure, and physicochemical properties vary significantly based on the species of origin and the silk’s functional role (Altman *et al.,* 2003; Craig *et al.,* 1999). The inherent qualities of silk such as its natural sheen, luster, water absorbency, dye affinity, thermal insulation, and continuous filament nature make it distinct among natural fibers (Sheikh *et al.,* 2006). Silk is also valued for being lightweight, soft, elastic, flexible, and glossy, making it highly desirable for textile applications (Khan *et al.,* 2010; Ude *et al.,* 2014). Moreover, silk is a mechanically robust biomaterial with excellent environmental stability, biocompatibility, and biodegradability, expanding its potential beyond textiles into biomedical and industrial applications (Reddy and Prasad, 2011).

Silk is secreted by silkworms during the final larval stage to construct cocoons for pupal protection. Among commercially produced silks, four major types are recognized: mulberry, tasar, muga, and eri produced by Bombyx mori, Antheraea mylitta, Antheraea assamensis, and Samia ricini, respectively (Saikia and Saikia, 2022). Of these, tasar, muga, and eri are classified as non-mulberry or wild silks, collectively known in India as Vanya silk. India holds a global monopoly in the production of the rare and highly esteemed golden-yellow Muga silk, which is uniquely produced in Assam and its adjoining regions (Choudhury, 1992).

Silk production is not limited to lepidopteran insects; it is also observed in spiders and other arthropods. However, silkworms of the Bombycidae (B. mori) and Saturniidae (A. assamensis, A. mylitta, and S. ricini) families are the principal sources for commercial silk (Kundu *et al.,* 2008; Mori and Tsukada, 2000). Wild silks such as tasar, muga, eri, and fagaria mainly produced by Saturniidae tribes such as Antheraea and Attacini exhibit structural and functional differences from domesticated mulberry silk, offering a broader palette of material properties for diverse applications (Mahendran *et al.,* 2006; Vepari and Kaplan, 2007; Rockwood *et al.,* 2011).

Among the various natural silks, Muga silk holds a particularly special status due to its exclusive origin and exceptional properties. Secreted by the semi-domesticated silkworm Antheraea assamensis, endemic to Assam in northeastern India, Muga silk is admired for its natural golden sheen, high durability, and resistance to ultraviolet radiation (Kar *et al.,* 2013; Padaki *et al.,* 2015). These features have earned it the moniker “golden silk.” Unlike the widely cultivated Bombyx mori, which produces mulberry silk, A. assamensis belongs to the Saturniidae family and contributes to the wild silk industry (Padaki *et al.,* 2014).

Despite India’s unique position as the sole global producer of Muga silk, the scientific exploration of this remarkable fiber remains relatively sparse. Muga silk fibers are characterized by a distinctive composition and microstructure, exhibiting high crystallinity, superior tensile strength, and excellent thermal stability (Table 1) (Devi *et al.,* 2011; Saikia and Saikia, 2022). These features not only set it apart from other silk types but also make it a promising candidate for novel applications beyond conventional textile use. Recent investigations have shown that Muga fibroin possesses mechanical integrity, hydrophobicity, and biocompatibility comparable or even superior to mulberry silk fibroin, making it suitable for biomedical applications including tissue engineering and regenerative medicine (Kar *et al.,* 2013; Dutta *et al.,* 2013).

However, the industrial scalability and broader adoption of Muga silk are currently hindered by challenges such as limited production, absence of standardized processing protocols, and heavy dependence on a specific geographical region. These constraints underscore the urgent need for scientific attention and innovation in Muga silk research. This review aims to consolidate and critically assess the structural, physicochemical, and biomedical studies conducted on Muga silk to date. By highlighting its unique features and untapped potential, the review seeks to stimulate further interdisciplinary research and encourage sustainable innovation involving this exceptional biopolymer.

**Table 1. Comparative characteristics of Mulberry Silk (Bombyx mori) and Muga Silk (Antheraea assamensis)**

|  |  |  |
| --- | --- | --- |
| **Character**  **Silk variety** | ***Bombyx mori* (Mulberry silk)** | ***Antheraea assamensis* (Muga silk)** |
| **Native land** | Japan, China, India, Italy | Assam and NE states of India |
| **Host plant** | Mulberry (*Morus* spp.) | Som (*Machilus bombycina*), Sualo (*Litsea polyantha*) |
| **Rearing method** | Indoor | Outdoor |
| **Voltinisim** | Uni, bi-multi | Multi |
| **Diapause stage** | Egg | Pupal (wild form) |
| **Cocoon colour** | Various (generally white) | Dark brown (Amber) |
| **Length of filament (m)** | 800–900 | 500–600 |
| **Size (denier)** | 2.5–3.0 | 4.5–5.0 |
| **Dyeing** | Easy | Very difficult |
| **Cross- section of thread** | Triangular with white colour | Rectangular with golden-brown colour |
| **Gloss** | Weak | Strong |

(Devi *et al.,* 2011)

1. **TAXONOMY AND ECOLOGY OF MUGA SILK**

Taxonomic position of muga silkworm:

Kingdom – Animalia

Phylum – Arthropoda

Class – Insecta

Order – Lepidoptera

Family - Saturniidae

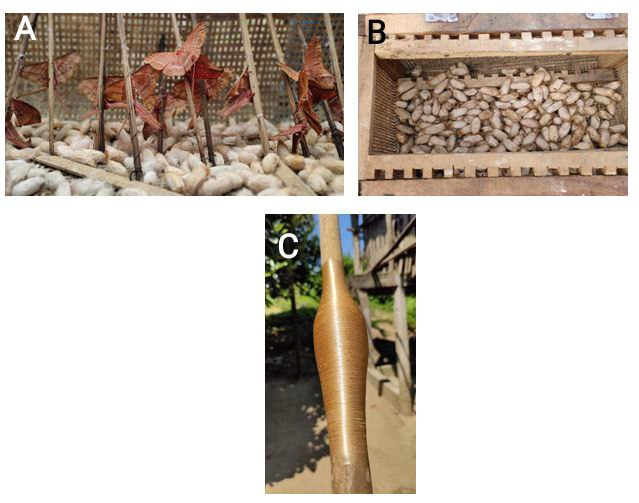
Genus – *Antheraea*

Species –*A.* *assamensis*

Antheraea assamensis is indigenous to the northeastern region of India and is primarily distributed across the Brahmaputra valley in Assam. Additionally, its presence has been reported in the East, West, and South Garo Hills of Meghalaya, as well as in Mokokchung, Tuensang, Kohima, and Wokha districts of Nagaland. In Arunachal Pradesh, it is found in the Lohit and Dibang valleys, and the Changlang and Papumpare districts. Other Indian regions include the Tamenglong district of Manipur and the Coochbehar district of West Bengal (Baruah and Kalita, 2023). Beyond India, this silkworm species is also found in parts of Northern Myanmar, the Kumaon and Kangra valleys of the Western Himalayas, and in regions of Sikkim, Himachal Pradesh, Uttar Pradesh, Gujarat, Puducherry, Bangladesh, Indonesia, and Sri Lanka (Kalita and Dutta, 2020).

The Muga silkworm is a **holometabolous** insect, undergoing complete metamorphosis through four distinct developmental stages: egg, larva, pupa, and adult. It is **multivoltine**, typically completing up to six generations annually. The duration of its life cycle varies with seasonal changes approximately **50 days during summer** and extending up to **120 days in winter**. The larva spins its cocoon within **3 to 7 days**, depending on environmental conditions (Fig. 1).

Rearing of A. assamensis is predominantly an **outdoor practice**, and the success of rearing is influenced by multiple ecological and managemental factors. This species exhibits a polyphagous nature, feeding on a variety of host plants. Among these, **Som (**Machilus bombycina**)** is the principal host in the plains, while **Soalu (**Litsea polyantha**)** serves as the major host in hilly regions. The **quality of the muga cocoon** is largely influenced by factors such as the genetic quality of seed cocoons, season of rearing, climatic conditions, hygiene of the rearing environment, and most critically, the **nutritional quality of the host plant leaves** (Sarmah *et al.,* 2010).



**Fig. 1. Key Stages in Muga Silkworm Rearing and Silk Production A) Muga moths B) Stored muga cocoons C) Reeled golden Muga silk thread**

1. **INFLUENCE OF ENVIRONMENTAL AND REGIONAL FACTORS**

The quality and quantity of Muga silk production are significantly influenced by environmental and regional parameters. Numerous studies have reported that seasonal changes significantly affect the growth and productivity of various silkworm species, including mulberry, tasar, eri, and muga. Researchers have observed that these fluctuations directly or indirectly influence the commercial traits of silkworms such as cocoon weight, shell ratio, and silk yield, by altering physiological responses and rearing outcomes (Kamili *et al.,* 2014; Sarkar, 2018; Bhatia and Yousuf, 2014; Chattopadhyay *et al.,* 2017; Alam *et al.,* 2022; Sarma *et al.,* 2025; Barman and Rana, 2011; Padaki *et al.,* 2014). Unlike Bombyx mori, which has been extensively domesticated and standardized across rearing environments, Antheraea assamensis, the Muga silkworm, remains highly sensitive to climatic conditions, host plant availability, altitude, and seasonal variation. This environmental dependence plays a crucial role in determining the physical characteristics of cocoons and the properties of the silk fiber. The outdoor rearing practice, although traditional, makes the silkworm susceptible to abiotic fluctuations, which in turn affect its growth, cocoon yield, and silk quality.

#### 3.1 Seasonal Cropping and Climatic Sensitivity

Muga silkworms are reared in multiple seasons, traditionally categorized into six commercial and seed crop cycles per year: Jaruwa, Chatuwa, Jethuwa, Aheruwa, Bhodia, and Kotia. Among these, Kotia and Jethuwa are the most economically significant commercial crops due to their better climatic compatibility and cocoon yield (Table 2) (Padaki *et al.,* 2014). Temperature, humidity, rainfall, and photoperiod play crucial roles in influencing the development of Muga silkworms. The insect, being poikilothermic, is sensitive to even slight fluctuations in climatic conditions during different broods. For instance, Kumar *et al.* (2024) observed that the Kotia (autumn) crop exhibited significantly higher Effective Rate of Rearing (ERR) compared to the Jethua (spring) crop in the Garo Hills region, with a pooled t-value of 20.79 indicating statistically robust results. This improved performance was attributed to stable temperature and moderate rainfall during Kotia, as opposed to the heavy pre-monsoon showers and hailstorms often encountered during Jethua.

The seasonal effect on silk quality is further confirmed by Padaki *et al.* (2014), who reported superior cocoon qualities in Kotia compared to Jethua, with higher shell weight and silk reeling performance from the former. Kotia cocoons recorded average weights of up to 7.5 g with shell weights of 0.6 g, while Jethua cocoons were lighter with shorter filament lengths. Dutta *et al.* (2013) and Padaki *et al.* (2014) documented that cocoon characteristics such as weight, shell ratio, reelability, and raw silk recovery are highly variable between these crops. For instance, Kotia crop cocoons produced significantly higher raw silk yields (up to 13.9%) compared to the Jethuwa crop (approx. 10.5%) due to better cocoon compactness and filament continuity. Furthermore, the **average shell weight** during the Kotia crop was recorded at **0.26 g**, while in Jethuwa it was **0.21 g**, which directly affects the reeling efficiency and silk quality (Padaki *et al.,* 2014).

**Table 2. Seasonal cropping pattern of Muga Silkworm (Antheraea assamensis)**

|  |  |  |  |
| --- | --- | --- | --- |
| **Crop** | **Month** | **Nature of crop** | **Contribution in Yield** |
| **Bhadia** | August-September | Seed | 60% |
| **Kotia** | October-November | Commercial-I |
| **Aghania** | December-January | Seed / Commercial |
| **Jarua** | February-March | Seed | 40% |
| **Jethua** | April-May | Commercial-II |
| **Akharua** | June-July | Seed / Commercial |

#### (Padaki *et al.,* 2014; Das *et al.,* 2010)

#### 3.2 Regional Variation and Host Plant Influence

Geographical location also plays a vital role in cocoon morphology and silk fiber properties. Studies conducted in Assam, Meghalaya, and Arunachal Pradesh have shown considerable variation in cocoon characteristics based on altitude and microclimatic conditions (Padaki *et al.,* 2014). In a comparative study of three districts in Assam, Jorhat, Kamrup, and Lakhimpur, Saikia *et al.* (2022) demonstrated that Kamrup yielded the best cocoon metrics across both commercial seasons. Specifically, Kamrup recorded average cocoon weights of 5.73 g, shell weights of 0.51 g, and a shell ratio of 8.74%, while Jorhat lagged with values of 5.27 g, 0.43 g, and 8.20% respectively. These differences highlight the significance of localized microclimates and the nutritional profile of host plants across regions.

**3.3 Host Plant-Environment Interactions**

Host plant quality, a function of both environmental condition and plant species, was shown to contribute approximately 38.2% to successful crop harvest, as compared to 37% from climate alone (Choudhury, 1992). Som (*Persea bombycina*) and Soalu (*Litsea monopetala*) are the two primary host plants; however, their efficacy varies with seasons and geography. Borpuzari *et al.* (2022) found that Som-fed larvae consistently outperformed others in terms of shell weight and shell ratio, particularly during Kotia, suggesting that Som offers superior nutrition under favorable seasonal conditions. Any fluctuation in host plant phytochemistry due to soil health, rainfall, or pest pressure directly affects larval growth, cocoon shell development, and the biochemical composition of the silk.

The influence of host plants on the economic traits of silkworms is not limited to Muga silk. Several studies have also documented similar impacts in other silk-producing species. Literature on mulberry silkworms and other non-mulberry species has shown that the biochemical and nutritional composition of leaves significantly affects parameters such as larval duration, cocoon weight, shell thickness, and silk filament length (Bahar *et al.,* 2011; Singh and Goswami, 2012; Deka and Kumari, 2013; Subharani *et al.,* 2017).

#### 3.4 Temperature and Humidity Thresholds

Optimal temperature and relative humidity are essential for successful larval development and cocoon spinning. Muga silkworms thrive best in ambient temperatures ranging between **24–28°C** and relative humidity between **70–85%** (Padaki *et al.,* 2014). Extreme weather events like unseasonal rainfall or high temperatures during late instars can disrupt spinning, induce disease outbreaks, and decrease cocoon quality. Unfavorable conditions, such as extreme temperature, unseasonal rainfall, and high wind velocity, particularly during seed crop seasons (Aherua and Bhodia), were found to reduce productivity by up to 20% (Saikia *et al.,* 2016). Such stresses not only affect larval development but also increase vulnerability to diseases and predators, making crop scheduling a critical management strategy.

#### 3.5 Reeling and Post-Cocoon Performance

Environmental factors influence not only cocoon yield but also post-cocoon processing efficiency. Kotia crop cocoons have consistently shown higher **reelability (38-44%)** and **non-breaking filament length (NBFL) of up to 103-164 meters**, whereas Jethuwa crop cocoons exhibit a reelability of **33-42%** and lower NBFL (Padaki *et al.,* 2014). These variations are crucial for industrial spinning processes and determining the market value of the raw silk (Table 3).

**Table 3. Comparative analysis of cocoon and reelability parameters between Kotia and Jethua muga crops**

|  |  |  |
| --- | --- | --- |
| **Parameter** | **Kotia crop** | **Jethuwa crop** |
| **Cocoon wt, g** | 5.85 – 6.5 | 5.4 – 6.3 |
| **Shell wt, g** | 0.54 – 0.6 | 0.48 – 0.57 |
| **SR, %** | 9.2 – 9.5 | 8.9 – 9.1 |
| **FL, m (Filament length)** | 338.4 – 399.5 | 294.8 – 376.3 |
| **NB (Breaks)** | 1.3 – 1.6 | 1.4 – 2.0 |
| **NBFL, m** | 103.7 – 163.7 | 97.7 – 133.9 |
| **Fil wt, g** | 0.20 – 0.23 | 0.17 – 0.22 |
| **Fil. Denier** | 5.2 – 5.3 | 5.1 – 5.27 |
| **Reelability, %** | 38.5 – 43.5 | 33.3 – 41.7 |
| **RSR, %** | 35.3 – 38.5 | 34.2 – 38.2 |
| **Renditta** | 4332 – 5085 | 4591 – 5849 |

(Padaki *et al.,* 2014)

1. **STRUCTURAL AND MOLECULAR CHARACTERISTICS OF MUGA SILK**

Silk is primarily composed of two key proteins: fibroin, which forms the structural filament, and sericin, a glue-like glycoprotein that encases the fibroin filaments. In the raw silk strand, known as the “bave,” fibroin filaments called “brins” are bundled and held together by sericin. At the molecular level, fibroin is made up of microfibrils, which are ordered assemblies of amino acid chains arranged in bundles. These microfibrils determine the fiber’s mechanical integrity and flexibility. The cross-sectional morphology also distinguishes mulberry and non-mulberry silks as mulberry silk fibers exhibit a triangular cross-section, whereas non-mulberry fibers such as those of Muga and Tasar are closer to rectangular in shape and exhibit characteristic surface striations (Gupta *et al.,* 2000).

Muga silk, secreted by Antheraea assamensis, is structurally complex due to the coexistence of both α-phase (crystalline) and β-phase (amorphous) regions within its fibroin. The rigidity of the fiber is attributed to the α-phase, while its extensibility arises from chain mobility in the β-phase. Devi *et al.* (2011) investigated the structure of degummed Muga silk fibers and reported a crystalline arrangement consisting of four molecular chains in a primitive tetrahedral unit cell with edge dimensions of a₀ = b₀ = 746 pm and c₀ = 738 pm (Devi et al., 2011). The distance between the planes of the α-phase was found to be one-fourth the unit cell edge, a structural constraint that hinders the penetration of dye molecules, thus explaining the challenges in bleaching and dyeing Muga silk. The dual presence of α-helical and β-sheet conformations confers both strength and flexibility, contributing to Muga silk's unique mechanical resilience.

Further insights into Muga silk fibroin were provided by Kar *et al.* (2013), who extracted fibroin from the silk glands of fifth instar A. assamensis larvae and characterized it using SDS-PAGE, FTIR, and X-ray diffraction (XRD). Their findings revealed that Muga fibroin consists of two polypeptide chains, each approximately 250 kDa, connected via disulfide bonds. Initially, the fibroin exists in a random coil conformation but transitions to a β-sheet structure upon ethanol treatment. This transformation enhances crystallinity and insolubility, key attributes for biomedical applications such as scaffold and film development.

Dutta *et al.* (2013) corroborated these findings through the fabrication and characterization of fibroin films from Muga silk gland extracts. Their SEM, FTIR, and XRD analyses revealed that the films retained an amorphous character with predominant random coil structures. These films were hydrophobic, thermally stable, and resistant to organic solvents, reinforcing the fiber's potential for use in durable biopolymer products. The thermal resistance of Muga fibroin was found to be superior to that of mulberry fibroin, indicating its enhanced stability under processing and usage conditions. Additionally, Ye *et al.* (2017) studied silk-silk blend films, particularly blends of Bombyx mori and Muga fibroins. Their work showed that Muga fibroin is highly miscible with B. mori fibroin in aqueous solution and contributes significantly to increasing the glass transition temperature and thermal degradation resistance of the blends. This compatibility opens up new avenues for creating composite materials with tailored structural and functional properties.

Collectively, these studies highlight the intricate structural and molecular framework of Muga silk, establishing it as a fiber with high thermal resilience, structural adaptability, and excellent mechanical performance. Such attributes underscore its promise as a versatile and high-performance biomaterial suitable for both traditional textiles and emerging biomedical applications.

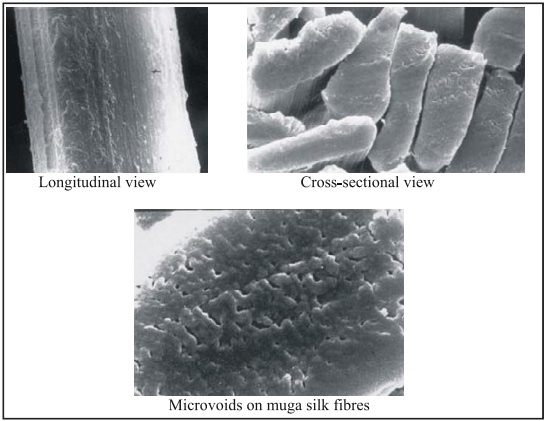
1. **PHYSICOCHEMICAL AND THERMAL PROPERTIES OF MUGA SILK**

Muga silk possesses distinct physicochemical characteristics that set it apart from other natural silk fibers. These include its golden-brown color, high tensile strength, moderate luster, and remarkable thermal resistance. The physicochemical traits of Muga silk are a function of its amino acid composition, crystalline structure, and surface morphology. The physicochemical and thermal properties of Muga silk are crucial determinants of its utility in textiles, biopolymers, and biomaterials. These properties stem from its protein composition, crystalline morphology, and unique molecular arrangements, setting it apart from both mulberry silk (*Bombyx mori*) and other non-mulberry silks.

**5.1 Physical and Morphological Properties**

Muga silk fibers are composed mainly of fibroin, the core filament protein, and sericin, a hydrophilic glycoprotein that encases fibroin during cocoon formation. Morphologically, Muga silk exhibits a near-rectangular cross-section and longitudinal striations on the fiber surface, features that contrast with the triangular cross-section of *B. mori* silk (Gupta *et al.,* 2000). These surface striations and cross-sectional shape influence the fiber's reflectance, enhancing its natural golden sheen and making it suitable for premium fabrics.

The denier (thickness) of Muga silk ranges between 4 and 7, whereas mulberry silk typically ranges from 2 to 3 denier, indicating that Muga is inherently coarser and more robust (Padaki *et al.,* 2015). The fiber density of Muga silk is approximately 1.30 g/cm³, slightly lower than that of mulberry silk (1.34 g/cm³), which affects the feel and drape of the resulting fabric (Padaki *et al.,* 2015). In terms of filament length, the non-breaking filament length (NBFL) of Muga silk is around 150 meters, and the total filament length extracted from a single cocoon ranges from 500–600 meters. In contrast, *B. mori* silk cocoons yield a longer NBFL of 700–800 meters and a total filament length of 1200–1600 meters (Table 4) (Padaki *et al.,* 2015). Despite this difference, Muga compensates with greater mechanical strength and structural integrity (Fig 2).



**Fig. 2 SEM Images of Muga silk fibres**

(Das *et al.,* 2010)

**Table 4. Comparative physicochemical and mechanical properties of commercially important silk fibers**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Characters** | **Muga** | **Mulberry (bi)** | **Eri** | **Tasar** |
| **Total filament length (m)** | 600-800 | 1200-1600 | 400-500 | 750-900 |
| **NBFL (m)** | 150-250 | 700-800 | 0.05-2.0 | 100-250 |
| **Fiber fineness (denier)** | 4-7 | 2-3 | 3-4 | 8-12 |
| **Fiber density (g/cm3)** | 1.30 | 1.34 | 1.30 | 1.31 |
| **Fibroin (%)** | 80–86 | 66–72 | 82–88 | 78–85 |
| **Sericin (%)** | 12–16 | 25–32 | 11–13 | 14–17 |
| **Tenacity (gf/den)** | 4.2 | 4.5 | 3.1 | 3.9 |
| **Elongation at break (%)** | 30 | 19 | 22 | 28 |
| **Toughness (gf/den)** | 1.1 | 0.6 | 0.5 | 0.9 |

(Dewangan, 2013; Padaki *et al.,* 2015; Saikia and Saikia, 2022)

**5.2 Chemical Composition and Dyeability**

Muga silk is composed of a complex sequence of amino acids, including glycine, alanine, serine, and tyrosine, arranged in alternating hydrophilic and hydrophobic regions (Table 5). These regions allow the silk to exhibit amphoteric behavior, enabling interactions with both acidic and basic dyes. However, due to the tightly packed crystalline structure especially the dominance of α-helical and β-sheet domains dye molecules have limited access, making Muga silk difficult to bleach or dye effectively (Devi *et al.,* 2011; Saikia and Saikia, 2022).

**Table 5. Comparative amino acid composition (mol %) of silk fibroin from major silkworm species**

|  |  |  |  |
| --- | --- | --- | --- |
| **Amino acid** | **Amino acid composition (mol %)** | | |
| **Mulberry (bi)** | **Mulberry (cross)** | **Muga** |
| Aspartic acid | 1.64 | 1.49 | 4.97 |
| Glutamic acid | 1.77 | 1.53 | 1.36 |
| Serine | 10.38 | 10.85 | 9.11 |
| Glycine | 43.45 | 43.73 | 28.41 |
| Histidine | 0.13 | 0.15 | 0.72 |
| Arginine | 1.13 | 1.16 | 4.72 |
| Threonine | 0.92 | 0.76 | 0.21 |
| Alanine | 27.56 | 28.36 | 34.72 |
| Proline | 0.79 | 0.76 | 2.18 |
| Tyrosine | 5.58 | 5.76 | 5.12 |
| Valine | 2.37 | 2.89 | 1.5 |
| Methionine | 0.19 | 0.11 | 0.32 |
| Cystine | 0.13 | 0.12 | 0.12 |
| Isoleucine | 0.75 | 0.78 | 0.51 |
| Leucine | 0.73 | 0.75 | 0.71 |
| Phenylalanine | 0.14 | 0.18 | 0.28 |
| Tryptophan | 0.73 | 0.75 | 2.18 |
| Lysine | 0.23 | 0.25 | 0.24 |

(Sen and Babu, 2004 a,b; Saikia and Saikia, 2022)

**5.3 Thermal Properties**

One of the most remarkable properties of Muga silk is its thermal stability. Dutta *et al.* (2013) observed that Muga silk fibroin films, prepared from gland extracts, retained structural integrity under thermal stress and were highly resistant to degradation by organic solvents. These films displayed a random coil structure that transitioned into a β-sheet conformation upon ethanol treatment, which enhanced their crystallinity and insolubility, essential attributes for biomedical scaffolds. Kar *et al.* (2013) also reported superior thermal performance of Muga fibroin compared to mulberry silk. In thermogravimetric analysis, Muga fibroin exhibited a higher onset of thermal degradation, confirming its enhanced resistance to heat-induced denaturation. The ethanol-treated β-sheet conformation provided thermal stability suitable for biomedical applications such as tissue scaffolds and drug delivery matrices.

In a comparative study of silk-silk blends, Ye *et al.* (2017) demonstrated that Muga fibroin significantly increased both the glass transition temperature (Tg**)** and the degradation temperature (Td) when blended with *B. mori* fibroin. The Tg of pure *B. mori* fibroin films was reported at approximately 178°C, while that of the Mori-Muga blend increased to 185–190°C, depending on the blend ratio. Similarly, the thermal degradation temperature of Muga blends exceeded 300°C, as opposed to around 280°C for pure *B. mori*. These findings highlight Muga fibroin’s potential role as a stabilizing component in composite materials. Taken together, Muga silk displays a robust set of physicochemical and thermal properties: high fiber strength, moderate elasticity, amphoteric dyeing behavior, and superior thermal resistance. Its morphological uniqueness and dense molecular structure contribute to both its aesthetic value and its performance under thermal and mechanical stress. These characteristics position Muga silk as a premium textile fiber and an emerging contender in the development of high-performance biopolymers and biomedical devices.

1. **BIOMEDICAL APPLICATIONS OF MUGA SILK**

The biomedical potential of silk fibroin has been well documented, primarily focusing on Bombyx mori. However, non-mulberry silks, particularly Muga silk (Antheraea assamensis), are now emerging as valuable biomaterials due to their superior thermal stability, mechanical resilience, and biocompatibility. Muga silk fibroin, owing to its higher molecular weight and β-sheet content, offers several advantages in regenerative medicine, scaffold design, and drug delivery systems.

#### 6.1 Biocompatibility and Cellular Interaction

Biocompatibility is a primary requirement for any biomedical scaffold. Kar *et al.* (2013) evaluated the in vitro cytocompatibility of Muga fibroin films using human osteoblast-like MG-63 cells. The cells adhered well to the fibroin surfaces and exhibited normal morphology and proliferation across a 7-day culture period. MTT assay results indicated over **90% cell viability**, demonstrating that Muga silk supports cell attachment and growth without cytotoxic effects. This performance was found to be comparable, and in some cases superior, to B. mori silk fibroin, which has long been considered the gold standard for biocompatible materials (Altman *et al.,* 2003; Vepari and Kaplan, 2007). The presence of RGD-like motifs (arginine-glycine-aspartic acid) in Muga fibroin, as inferred from its amino acid composition, likely contributes to enhance cell adhesion a desirable feature in tissue engineering scaffolds.

#### 6.2 Use in Scaffold and Film-Based Applications

The robust mechanical strength and stability of Muga silk make it particularly suitable for use as a base material for scaffolds and biofilms. Dutta *et al.* (2013) successfully fabricated 2D films from silk gland extracts of Muga fibroin and observed good resistance to thermal and organic solvent degradation. These films retained their structure under physiological conditions, suggesting their potential for long-term implantation. The ability of Muga fibroin to transition into β-sheet–rich, water-insoluble films upon ethanol treatment adds to its suitability in load-bearing or moist-tissue environments. Such film matrices are ideal for applications in wound dressings, ophthalmic inserts, and transdermal delivery systems. Their hydrophobic surface properties, combined with slow degradation, can offer controlled interaction with biological tissues, allowing for regulated healing or drug release.

#### 6.3 Thermal and Structural Advantages in Biomedical Contexts

Thermal stability is a critical requirement for sterilization and clinical utility. Kar *et al.* (2013) and Ye *et al.* (2017) both reported that Muga silk fibroin exhibits **higher thermal decomposition temperatures (>300°C)** than B. mori fibroin (~280°C). This not only ensures stability during autoclaving and other high-temperature processing methods but also supports structural integrity in vivo, where enzymatic degradation can compromise less crystalline materials.

#### 6.4 Composite and Blend-Based Biomedical Materials

The blending of Muga fibroin with B. mori silk has been explored to develop composite biomaterials with tunable properties. Ye *et al.* (2017) fabricated films using Mori-Muga fibroin blends and observed a **glass transition temperature (Tg)** of approximately **190°C** in 50:50 blends, significantly higher than pure B. mori films. These blended films demonstrated improved mechanical strength, resistance to deformation, and thermal stability, making them suitable for use in orthopedic devices, surgical meshes, and guided tissue regeneration membranes.

The biomedical applications of Muga silk are supported by its biocompatibility, thermal resilience, and capacity for structural customization. Studies show that Muga fibroin is not only safe for use with human cells but also mechanically and chemically robust under physiological and processing conditions. Its ability to form stable, functional films and scaffolds, either alone or in combination with other silks, positions Muga silk as a next-generation material for regenerative medicine, drug delivery systems, and other clinical devices.

### ****CHALLENGES AND LIMITATIONS****

Despite the remarkable structural, mechanical, and biomedical potential of Muga silk (Antheraea assamensis), its broader scientific and industrial utilization is constrained by several challenges. These limitations span across production, processing, and application domains and must be addressed to unlock the full potential of this indigenous silk (Table 6).

**Table 6. Challenges and Limitations of Muga silk production and application**

|  |  |  |  |
| --- | --- | --- | --- |
| **Challenge** | **Description / Impact** | **Implications** | **References** |
| **Geographical Limitation** | Muga silkworms are endemic to Assam and adjoining regions; highly sensitive to environmental variations. | Limits mass-scale production; vulnerable to climate change. | Borpuzari *et al.,* 2022; Padaki *et al.,* 2014 |
| **Seasonal Yield Variability** | Silk yield and cocoon quality fluctuate significantly between rearing seasons (Kotia > Chotua). | Inconsistent supply; difficulty in meeting industrial demand. | Borpuzari *et al.,* 2022; Padaki *et al.,* 2014 |
| **Host Plant Dependence** | Silkworms rely on specific host plants (*Persea bombycina*, *Litsea monopetala*); leaf quality varies seasonally and regionally. | Affects cocoon quality and silk protein composition. | Borpuzari *et al.,* 2022; Kumar *et al.,* 2022 |
| **Processing and Dyeing Challenges** | High crystallinity and tight fibroin packing restrict dye penetration; bleaching is also difficult. | Limits fiber customization; increases processing cost. | Devi *et al.,* 2011; Saikia and Saikia, 2022 |
| **Lack of Standardized Protocols** | Few optimized or scalable methods for fibroin extraction, purification, or fabrication into biomaterials. | Hinders reproducibility, scalability, and industrial application. | Kar *et al.,* 2013; Dutta *et al.,* 2013 |
| **Outdoor Rearing Sensitivity** | Exposure to pests, pathogens, and harsh weather due to open-field rearing system. | Reduces survival rates and increases rearing losses. | Padaki *et al.,* 2014; Kalita and Dutta, 2020 |
| **Low Technological Investment** | Infrastructure, research funding, and industrial linkage lag behind that of *B. mori* silk industry. | Limits product diversification and global commercialization. | Dutta *et al.,* 2013; Kar *et al.,* 2013 |

1. **CONCLUSION**

Muga silk (Antheraea assamensis), with its exceptional mechanical strength, thermal stability, hydrophobicity, and biocompatibility, holds immense potential beyond traditional textiles, especially in biomedical and functional material applications. However, to realize its full potential, focused efforts are required across several fronts. Future research should emphasize detailed molecular and genetic characterization to understand fibroin biosynthesis and enable selective breeding for improved traits. Standardized, scalable protocols for fibroin extraction, solubilization, and fabrication are essential to transition from lab-scale to industrial-scale biomaterials such as 3D scaffolds, hydrogels, and films. Muga silk's integration into composite materials with other natural or synthetic polymers could yield advanced biofunctional materials with tailored properties, suitable for applications in tissue engineering, wound healing, and drug delivery. Additionally, its thermal and structural robustness make it an ideal candidate for development in bioelectronics, cosmetics, and sustainable packaging. However, the species’ geographic confinement to Assam, its dependency on specific host plants and climatic conditions, and the artisanal nature of production remain key limitations. Developing climate-resilient rearing systems, reforestation of host plants, and better infrastructure could enhance production and regional livelihoods. In conclusion, Muga silk is not merely a cultural asset but a scientifically valuable fiber poised to contribute meaningfully to the next generation of biomaterials and eco-friendly technologies.

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