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DEVELOPMENT OF ANTIMICROBIAL AND UV-PROTECTIVE SMART TEXTILES FROM ERI SILK, TASAR SERICIN, AND MULBERRY-INFUSED FIBERS TREATED WITH MUNGA EXTRACTS

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ABSTRACT

The increasing demand for sustainable and multifunctional textiles has accelerated research into bio-based smart fabrics with inherent antimicrobial and ultraviolet (UV) protective properties. In this study, an eco-friendly approach was developed to fabricate antimicrobial and UV-protective smart textiles using Eri silk and mulberry-infused fibers functionalized with Tasar sericin and bioactive Munga (*Moringa oleifera*) extracts. Tasar sericin was extracted through aqueous degumming and employed as a natural binding and biofunctional agent, while Munga leaf extracts rich in polyphenols and flavonoids were applied as antimicrobial and UV-absorbing finishes via a pad–dry–cure process using citric acid as a cross-linker. The treated textiles were characterized by Fourier transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), ultraviolet protection factor (UPF) evaluation, and quantitative antibacterial assays against *Staphylococcus aureus* and *Escherichia coli*. Results indicated strong chemical interactions between sericin, plant bioactives, and silk fibers, leading to durable functionalization. The treated fabrics exhibited significant antibacterial activity against both Gram-positive and Gram-negative bacteria and demonstrated a substantial increase in UV protection compared to untreated controls. Moreover, the functional properties showed good durability after multiple laundering cycles. The findings highlight the synergistic role of Tasar sericin and Munga extracts in imparting multifunctionality to silk-based textiles and demonstrate the potential of this sustainable strategy for developing next-generation smart textiles for medical, protective, and eco-conscious apparel applications.

KEYWORDS: Eri silk; Tasar sericin; Mulberry silk; Munga (*Moringa oleifera*) extract; Antimicrobial textiles; UV-protective textiles; Smart textiles; Bio-functional finishing; Sustainable textiles; Pad–dry–cure process

1. INTRODUCTION

The rapid expansion of functional and smart textiles has been driven by increasing public health concerns, environmental awareness, and demand for high-performance materials in medical, protective, and daily-wear applications. Among these, **antimicrobial and ultraviolet (UV) protective textiles** have gained significant attention due to their potential to reduce microbial contamination, prevent skin infections, and protect against UV-induced skin damage and premature aging.[1,2] Conventional textile finishing techniques rely heavily on synthetic antimicrobial agents and UV stabilizers, many of which are associated with toxicity, environmental persistence, and regulatory restrictions.[3] This has led to a paradigm shift toward **bio-based, sustainable, and biodegradable functional finishes**, particularly those derived from natural fibers and plant-based extracts.[4] Silk, a natural protein fiber composed mainly of fibroin and sericin, exhibits excellent biocompatibility, moisture management, and mechanical properties. While fibroin provides structural integrity, **sericin**, a globular protein rich in polar amino acids, has demonstrated intrinsic antioxidant, antimicrobial, UV-absorbing, and moisturizing properties.[5–7] Tasar sericin, obtained from wild silkworm species (*Antheraea mylitta*), has shown higher phenolic content and bioactivity compared to mulberry sericin, making it especially suitable for biomedical and textile functionalization.[8] Eri silk (*Samia ricini*) is a non-mulberry silk known for its thermal insulation, softness, and sustainability, as it allows silk harvesting without killing the silkworm. Mulberry silk, on the other hand, offers superior tensile strength and uniformity. Blending Eri silk with mulberry fibers provides a hybrid substrate with enhanced mechanical and comfort properties suitable for functional finishing.[9,10] Plant-derived bioactive extracts have been extensively studied as natural antimicrobial and UV-protective agents in textiles. Polyphenols, flavonoids, alkaloids, and tannins present in plant extracts exhibit strong antibacterial activity by disrupting microbial cell membranes and inhibiting enzyme systems.[11,12] In addition, many plant chromophores absorb UV radiation, thereby improving the ultraviolet protection factor (UPF) of treated fabrics.[13] *Moringa oleifera*, locally referred to as Munga in several regions, is a medicinal plant rich in phenolics, flavonoids, ascorbic acid, and isothiocyanates, all of which possess antimicrobial, antioxidant, and UV-absorbing properties.[14,15] Previous studies have demonstrated the antimicrobial efficacy of *Moringa* leaf and seed extracts against a broad spectrum of pathogenic bacteria and fungi.[16] However, its application as a multifunctional finishing agent in silk-based smart textiles remains largely unexplored.

Therefore, the present study aims to develop and evaluate **eco-friendly antimicrobial and UV-protective smart textiles using Eri silk and mulberry-infused fibers functionalized with Tasar sericin and Munga (*Moringa oleifera*) extracts**. The study focuses on sustainable processing, physicochemical characterization, antimicrobial performance, UV protection, and durability of the functional finishes, thereby contributing to the advancement of green smart textile technologies.

2. MATERIALS AND METHODS

2.1 Materials

Raw Eri silk (*Samia ricini*) cocoons and mulberry silk (*Bombyx mori*) yarn were procured from certified sericulture farms in Bihar, India. Tasar silk (*Antheraea mylitta*) cocoons were obtained from wild sericulture units, and sericin was extracted from degumming liquor as described in Section 2.2. Fresh Munga (*Moringa oleifera*) leaves were collected locally, shade-dried, and milled into fine powder.

Citric acid (≥99%), sodium hypophosphite, ethanol, and all microbiological media were of analytical grade (Merck, India). *Staphylococcus aureus* (ATCC 6538) and *Escherichia coli* (ATCC 25922) were used as model Gram-positive and Gram-negative bacteria, respectively.

2.2 Extraction of Tasar Sericin

Tasar cocoons were cut into small fragments and degummed in distilled water at 95°C for 60 min (liquor ratio 1:40). The degumming solution was filtered and centrifuged at 8000 rpm for 15 min to remove insoluble impurities. The supernatant containing sericin was freeze-dried to obtain sericin powder. The extracted sericin was stored at 4°C until use. This method preserves the bioactivity and molecular weight distribution of sericin better than alkaline degumming.[17,18]

2.3 Preparation of Munga (*Moringa oleifera*) Extract

Dried leaf powder (50 g) was subjected to Soxhlet extraction with 70% ethanol for 6 h. The extract was concentrated under reduced pressure using a rotary evaporator and dried to constant weight. The extract was reconstituted in distilled water (10 g/L) for textile finishing. This solvent system efficiently extracts phenolics and flavonoids responsible for antimicrobial and UV-absorbing activity.[19,20]

2.4 Fabric Preparation and Functionalization

Eri silk and mulberry silk yarns were blended (50:50) and woven into plain-weave fabric (120 GSM). Fabrics were scoured using a non-ionic detergent (2 g/L) at 50°C for 30 min and rinsed thoroughly. Functional finishing was carried out by the **pad–dry–cure technique**. Fabrics were padded in an aqueous solution containing Tasar sericin (5 g/L), Munga extract (10 g/L), citric acid (6 g/L), and sodium hypophosphite (4 g/L) as catalyst. Padding was performed at 80% wet pick-up, followed by drying at 80°C for 5 min and curing at 140°C for 3 min. Citric acid was used as a green crosslinker to enhance durability of bioactive finishes.[21]

2.5 Characterization

2.5.1 FTIR Analysis

FTIR spectra were recorded using an ATR-FTIR spectrometer in the range 4000–500 cm^{-1} to identify chemical interactions between sericin, plant extract, and silk fibers.

2.5.2 Scanning Electron Microscopy (SEM)

Surface morphology of untreated and treated fabrics was observed using SEM after gold sputter-coating.

2.5.3 Antimicrobial Activity

Quantitative antibacterial activity was assessed using the AATCC 100 method. Percentage bacterial reduction was calculated after 24 h incubation at 37°C.

2.5.4 UV Protection Factor (UPF)

UPF values were measured according to AS/NZS 4399:2017 standards using a UV-Vis spectrophotometer equipped with an integrating sphere.

2.5.5 Wash Durability

Treated fabrics were laundered up to 20 cycles following ISO 6330, and antimicrobial and UPF properties were re-evaluated.

2.6 Statistical Analysis

All experiments were conducted in triplicate. Results are presented as mean ± standard deviation. Statistical significance was determined using one-way ANOVA with $p < 0.05$ considered significant.

3. RESULTS AND DISCUSSION

3.1 Antimicrobial Performance

The antibacterial activity of untreated and functionalized silk fabrics was evaluated against *Staphylococcus aureus* and *Escherichia coli* using the AATCC 100 quantitative method. The percentage bacterial reduction values are presented in Table 1.

Table 1: Antibacterial activity of treated silk fabrics.

Sample	*S. aureus* (%)	*E. coli* (%)
Control	4.8 ± 0.9	5.2 ± 1.1
Sericin-treated	56.3 ± 2.1	53.4 ± 1.9
Munga-treated	61.5 ± 2.4	58.7 ± 2.0
Sericin + Munga	93.2 ± 1.3	90.6 ± 1.5

The untreated control fabric showed negligible antibacterial activity, confirming the absence of inherent antimicrobial functionality after scouring. Sericin-treated samples exhibited moderate bacterial reduction due to the presence of bioactive peptides and polar amino acid residues capable of disrupting microbial membranes.[22, 23]

Munga-treated samples showed slightly higher activity owing to the presence of phenolics and flavonoids that damage microbial cell walls and inhibit enzymatic systems.[24] Notably, the combined sericin + Munga treatment exhibited a synergistic enhancement with >90% bacterial reduction against both strains, indicating cooperative interaction between the silk protein matrix and plant bioactives.

3.2 Ultraviolet Protection Properties

UPF values were measured according to AS/NZS 4399:2017 standards and are summarized in Table 2.

Table 2: UV protection of functionalized silk fabrics.

Sample	UPF	Protection Category
Control	7.9 ± 0.5	Insufficient
Sericin-treated	26.1 ± 1.2	Good
Munga-treated	29.4 ± 1.3	Good
Sericin + Munga	47.6 ± 1.8	Excellent

The increase in UPF after treatment is attributed to UV-absorbing aromatic compounds in sericin and phenolic chromophores in Munga extract that effectively absorb UV-A and UV-B radiation.[25,26] The combined treatment showed excellent protection, surpassing the threshold for UV-protective textiles.

3.3 Wash Durability

Wash durability was assessed after 20 laundering cycles (ISO 6330). The retention of antibacterial activity and UPF is shown in Table 3.

Table 3: Durability of functional properties after washing.

Sample	Antibacterial retention (%)	UPF retention (%)
Sericin-treated	72	75
Munga-treated	68	71
Sericin + Munga	88	84

The superior durability of the combined finish is due to ester crosslinking between sericin, citric acid, and silk fibroin, which stabilizes the bioactive compounds on the fiber surface.[27]

3.4 Morphological and Chemical Evidence

SEM images showed uniform deposition of bioactive layers on treated fibers, whereas untreated fibers exhibited smooth surfaces. FTIR spectra confirmed the formation of ester linkages and hydrogen bonding between sericin, Munga extract, and silk fibers.

3.5 Mechanism of Synergistic Action

The enhanced multifunctionality arises from:

1. **Chemical anchoring** via citric acid crosslinking.
2. **Electrostatic interactions** between sericin and plant polyphenols.
3. **Sustained release** of antimicrobial agents from the sericin matrix.

This combination ensures high performance, durability, and eco-compatibility.

4. Observations

The following observations were recorded during the functionalization, testing, and analysis of Eri silk and mulberry-infused fabrics treated with Tasar sericin and Munga (*Moringa oleifera*) extract.

1. Visual and Physical Observations

1. Untreated silk fabrics appeared smooth, lustrous, and cream-white in color.
2. Sericin-treated fabrics exhibited a slight increase in surface roughness and a faint yellowish tone, indicating deposition of the sericin layer.
3. Munga extract-treated fabrics showed a pale greenish to light brown tint due to natural plant pigments.
4. Fabrics treated with both sericin and Munga extract showed uniform coloration and no patchiness, suggesting even uptake of the finishing agents.
5. No significant stiffness or loss of drape was observed after treatment, indicating good preservation of fabric comfort.

2. Observations During Processing

1. Sericin solutions formed a stable coating on silk fibers without precipitation.
2. The addition of citric acid improved fixation and reduced leaching of finishes during rinsing.
3. No foam formation or fiber damage was observed during pad–dry–cure processing.
4. Treated fabrics showed minimal shrinkage (<2%) and no visible degradation.

3. Microstructural Observations (SEM)

1. Untreated fibers displayed smooth, clean surfaces with clearly visible fibrillar structures.
2. Treated fibers showed a thin, uniform coating over the surface.
3. Combined sericin + Munga treated fibers exhibited the most continuous and homogeneous surface layer, confirming effective functionalization.

4. Chemical Observations (FTIR)

1. New absorption bands corresponding to ester (–COO–) and hydrogen bonding were observed in treated samples.
2. The appearance of peaks around 1720 cm^{-1} indicated ester linkage formation due to citric acid crosslinking.

3. Enhanced intensity of amide I and II bands confirmed the presence of sericin on silk fibers.

5. Biological Observations (Antimicrobial Tests)

1. Clear inhibition zones were observed around treated samples on agar plates, while untreated samples showed no inhibition.
2. The combined sericin + Munga treated samples consistently showed the largest inhibition zones and highest bacterial reduction.
3. Gram-positive bacteria (*S. aureus*) were slightly more sensitive than Gram-negative bacteria (*E. coli*).

6. UV Protection Observations

1. Untreated fabrics transmitted a high proportion of UV radiation and showed low UPF values.
2. Treated fabrics significantly reduced UV transmission.
3. The highest UV blocking was observed in sericin + Munga treated samples.

7. Wash Durability Observations

1. Slight fading of color was observed after multiple wash cycles, especially in Munga-only treated fabrics.
2. The combined treatment showed better retention of functional properties after laundering.
3. No peeling or cracking of the finish was observed after washing.

Summary of Observations

- The finishing process was stable, uniform, and did not damage the silk fibers.
- The combination of Tasar sericin and Munga extract produced the most effective and durable antimicrobial and UV-protective performance.
- The treatment preserved fabric comfort while imparting multifunctional properties.

5. CONCLUSION

The present study successfully demonstrated the development of eco-friendly, antimicrobial and UV-protective smart textiles through the functionalization of Eri silk and mulberry-infused fabrics using Tasar sericin and Munga (*Moringa oleifera*) extract. The integration of these bio-based materials resulted in a synergistic enhancement of textile functionality while maintaining sustainability, biodegradability, and fabric comfort.

Tasar sericin acted not only as a natural antimicrobial agent but also as an effective bio-binder that facilitated strong attachment of plant bioactives onto the silk fiber surface. The incorporation of Munga extract, rich in phenolic compounds and flavonoids, significantly improved antibacterial performance and UV absorption capacity. The combined sericin + Munga treatment exhibited superior antimicrobial activity against both Gram-positive and Gram-negative bacteria (>90% reduction), along with excellent UV protection (UPF >45), outperforming individual treatments. The functional finishes also demonstrated good durability after repeated laundering, indicating the effectiveness of citric acid crosslinking in stabilizing the bioactive compounds on the fiber matrix. Importantly, the processing method preserved the aesthetic, mechanical, and comfort properties of the silk fabrics, making them suitable for wearable and biomedical applications.

Overall, this work highlights the strong potential of using wild silk proteins and medicinal plant extracts to develop next-generation smart textiles that are safe, sustainable, and high-performing. The approach offers a promising alternative to synthetic chemical finishes and supports the advancement of green textile technologies for applications in healthcare, personal protective clothing, and environmentally conscious fashion.

Future research may focus on optimizing formulation concentrations, scaling up the process for industrial application, evaluating long-term stability under real-use conditions, and exploring additional bioactive plant sources to further enhance multifunctional textile performance.

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