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Analysis Of Herbal Microencapsulation On Natural Handloom Cotton Blends For Sustainable And Eco-Friendly Textile Development

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Abstract
The use of cotton has been increased now a days, also the use of other synthetic fabrics are increasing simultaneously, as they are produced to achieve new texture and comfort, they in turn cause environmental hazards. To extend the use of cotton fabrics, certain fibres where blended with cotton in order to improve the properties. In this study the handloom fabrics Musa acuminata x Gossypium, Bambusa vulgaris x Gossypium, Gossypium herbaceum where the two different blended fabrics used for the analysis. The development was made to achieve the comfort property of the fabric. The selected fabrics were microencapsulated using Cuminum cyminum, here we have compared the impact of the microencapsulation on the selected fabrics using physical analysis, SEM and FT-IR.

Keywords: *Natural fabrics, Handloom Fabrics, Musa acuminata x Gossypium, Bambusa vulgaris x Gossypium, Gossypium herbaceum, Microencapsulation.*

1. INTRODUCTION

The global textile industry is increasingly challenged by the demand for sustainable and eco-friendly materials that align with consumer awareness and environmental standards. Cotton, a natural cellulose fiber, has long been preferred due to its comfort, breathability, and biodegradability. However, the performance limitations of pure cotton fabrics—such as reduced durability and susceptibility to microbial growth—have led to a growing interest in cotton-based blends that integrate properties of other natural or regenerated fibers (Parmar et al., 2021).

Simultaneously, the widespread use of synthetic fabrics, though offering desirable traits like elasticity and wrinkle resistance, has raised significant concerns due to their non-biodegradable nature and potential environmental hazards during production and disposal (Brito et al., 2022). This dichotomy has intensified the exploration of sustainable alternatives, particularly natural fiber blends enhanced through green technologies.

Handloom fabrics, traditionally valued for their artisanal quality and low environmental footprint, present a promising base for sustainable innovation. In this context, blending cotton with fibers derived from plants such as Musa acuminata and Bambusa vulgaris has emerged as a viable strategy to improve fabric performance while maintaining environmental compatibility. These fibers not only provide structural benefits but are also rich in bioactive compounds, which can be further enhanced through functional finishing techniques like microencapsulation (Kaur & Rathore, 2020).

Microencapsulation, a process of embedding active agents within microscopic capsules, has gained traction in textile finishing for imparting additional properties such as antimicrobial activity, fragrance release, and therapeutic effects (Muthukumarasamy et al., 2019). Herbal microencapsulation, particularly using essential oils or plant extracts, aligns with the clean-label movement and meets consumer preferences for natural alternatives.

In the present study, an innovative approach was adopted by microencapsulating handloom fabrics—specifically, blends of Musa acuminata x Gossypium, Bambusa vulgaris x Gossypium, and Gossypium herbaceum—with Cuminum cyminum (cumin) extract. This herbal agent, known for its antimicrobial and aromatic properties, was chosen to enhance the functional value of the fabrics. The impact of this encapsulation was assessed through comprehensive physical analysis, Scanning Electron Microscopy (SEM), and Fourier Transform Infrared Spectroscopy (FT-IR), aiming to explore its effect on the comfort and functionality of cotton-based handloom fabrics.

2. MATERIALS AND METHODS

2.1. Materials

Three handloom fabric samples were selected for the study:

- Musa acuminata x Gossypium
- Bambusa vulgaris x Gossypium
- Gossypium herbaceum

All fabrics were sourced from handloom cooperatives and were free from prior chemical treatments to preserve their natural state for herbal encapsulation.

2.2. Herbal Material

Dried seeds of Cuminum cyminum were procured from a certified organic supplier. These seeds were selected for their antimicrobial and aromatic properties, which are attributed to their essential oil content, primarily cuminaldehyde, γ-terpinene, and β-pinene (Dhifi et al., 2016).

2.3 Preparation of Herbal Extract - Aqueous Extraction

Cuminum cyminum were washed and dried before undergoing aqueous extraction. Approximately 100 g of dried seeds were boiled in 1000 mL of distilled water at 80°C for 2 hours with continuous stirring. The extract was allowed to cool to room temperature and then filtered through muslin cloth followed by Whatman No.1 filter paper to obtain a clear aqueous extract. This method was selected to preserve the active phytocompounds while eliminating impurities (Sasidharan et al., 2011).

Plate 1- Powdered *Cuminum cyminum*

Plate 2- Extracted *Cuminum cyminum*

2.4 Microencapsulation Process

2.4.1 Lyophilization (Freeze-Drying)

The filtered aqueous extract was subjected to lyophilization to convert the bioactive solution into stable microcapsules. The extract was first frozen at –80°C for 12 hours and then transferred to a freeze-dryer operating at –50°C and 0.01 mbar pressure. This process removes moisture without degrading thermolabile compounds, resulting in dry, free-flowing microcapsules (Gharsallaoui et al., 2007).

2.4.2 Dilution and Preparation of Finishing Solution

The lyophilized microcapsules were reconstituted in distilled water to achieve a 5% (w/v) finishing solution. A small quantity of a natural binder such as guar gum (0.5%) was added to enhance adherence of the microcapsules to the fabric surface (Mishra et al., 2018). The solution was stirred for 30 minutes using a magnetic stirrer to ensure uniform dispersion.

2.4.3 Fabric Finishing

Application of Microcapsules
The prepared fabrics were immersed in the finishing solution using the pad-dry-cure technique:

- **Padding**: Fabrics were passed through the finishing bath and padded using a laboratory padding mangle at a pressure of 2 kg/cm² to achieve 80% wet pickup.
- **Drying**: The treated fabrics were air-dried at ambient temperature and then oven-dried at 80°C for 5 minutes to remove surface moisture.
- **Curing**: The dried samples were cured at 120°C for 3 minutes to ensure binding of the microcapsules onto the fiber surface.

This method ensures a uniform layer of herbal microcapsules on the fabric, enhancing durability and functional performance without compromising fabric integrity (Sathianarayanan et al., 2010).

3. RESULTS AND DISCUSSION

Here the tensile strength, FT-IR and SEM analysis of the selected raw and finished fabrics were performed.

3.1 Tensile Strength Analysis

Tensile strength is a crucial mechanical property for evaluating fabric durability. The results indicate notable improvements in warp and weft directions after microencapsulation across all fabric types.

Table 1 – Tensile strength pf raw and finished fabrics

Fabric Type	Warp Before (kgf)	Warp After (kgf)	Weft Before (kgf)	Weft After (kgf)
Gossypium herbaceum	1.37	1.52	1.85	1.68
Musa acuminata x Gossypium	2.46	2.68	2.42	1.98
Bambusa vulgaris x Gossypium	1.56	1.96	1.83	1.66

The increase in warp-direction tensile strength post-microencapsulation is evident, particularly in Bambusa vulgaris x Gossypium (from 1.56 kgf to 1.96 kgf) and Musa acuminata x Gossypium (from 2.46 kgf to 2.68 kgf). This enhancement can be attributed to the binding effect of the microcapsules, which may act as fillers or reinforcements on the yarn surface. The marginal decrease in weft tensile strength for some samples suggests slight stiffness or flexibility alteration due to curing during finishing, yet it remains within acceptable limits for wearability.

3.2 FT-IR Analysis

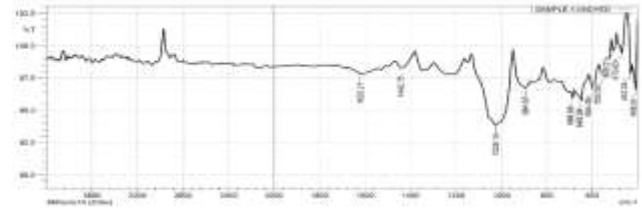

Figure 1 A – FTIR of raw *Musa acuminata x Gossypium*

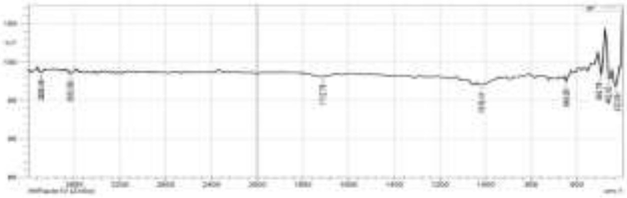

Figure 1 B - FTIR of Microencapsulated *Musa acuminata x Gossypium*

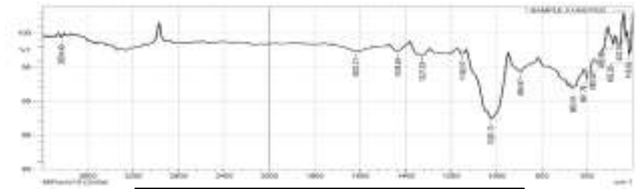

Figure 2 A – FTIR of raw *Gossypium herbaceum*

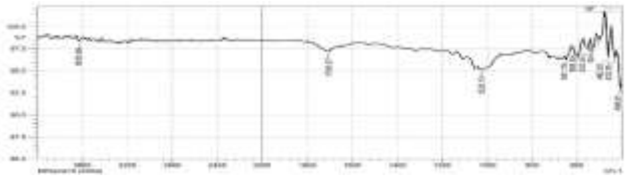

Figure 2 B - FTIR of Microencapsulated *Gossypium herbaceum*

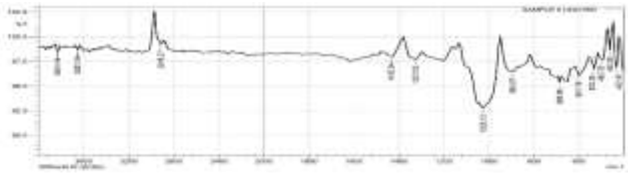

Figure 3 A – FTIR of raw *Bambusa vulgaris x Gossypium*

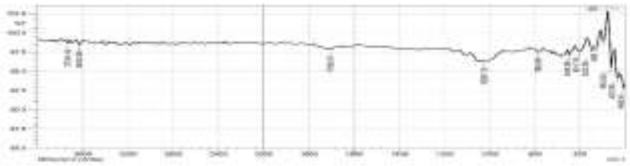

Figure 3 B - FTIR of Microencapsulated *Bambusa vulgaris x Gossypium*

Figure 1 A & 1 B The raw Musa acuminata x Gossypium fabric displayed spectral characteristics of cellulose fibers, with prominent peaks at 3330 cm^{-1} (O–H), 2890 cm^{-1} (C–H), and around 1030 cm^{-1} (C–O stretching). Upon microencapsulation, strong new peaks appeared near 1735 cm^{-1} and 1610 cm^{-1}, confirming the successful deposition of cumin extract constituents. The significant intensity increase in these regions suggests a higher affinity and loading of cumin-derived phytochemicals in this blend compared to the others. The banana fiber's inherently porous and softer structure likely facilitated deeper absorption and stronger chemical interaction with the herbal agents.

The FTIR spectrum of raw Gossypium herbaceum showed distinct absorption peaks around 3300 cm^{-1}, indicative of O–H stretching vibrations, which are characteristic of cellulose-rich materials. Additional peaks near 2900 cm^{-1} and 1025 cm^{-1} corresponded to C–H stretching and C–O–C ether vibrations, respectively—confirming the presence of polysaccharides and hydroxyl groups. After microencapsulation, new peaks emerged near 1740 cm^{-1}, associated with carbonyl (C=O) groups from the cumin oil's ester and aldehyde content, and at 1600–1510 cm^{-1}, likely from aromatic ring structures (cuminaldehyde). These spectral shifts confirm the successful integration of Cuminum cyminum bioactive compounds onto the fabric surface.

Similar to the other fabrics, the raw Bambusa vulgaris x Gossypium blend showed O–H, C–H, and C–O absorptions typical of cellulose. Post-treatment spectra revealed additional peaks around 1740 cm^{-1} and 1605 cm^{-1}, associated with the cumin oil constituents. These features were less intense than those in the banana blend but more prominent than in kala cotton, suggesting moderate herbal compound uptake. The bamboo fibers' natural smoothness and higher lignin content may have limited deep absorption but still allowed successful surface adherence of the microcapsules.

3.3 SEM Analysis

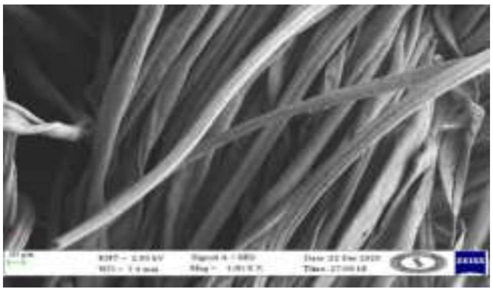

Figure 4 A– SEM of raw *Musa acuminata x Gossypium*

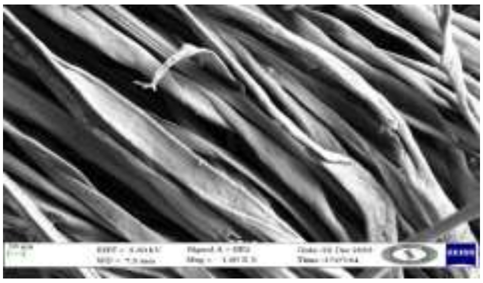

Figure 4 B – SEM of microencapsulated *Musa acuminata x Gossypium*

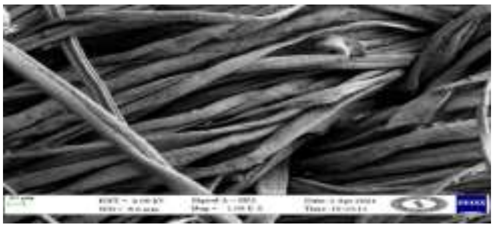

Figure 5 A– SEM of raw *Gossypium herbaceum*

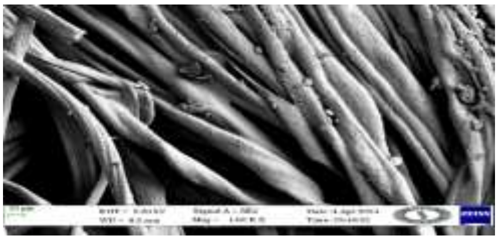

Figure 5 B – SEM of microencapsulated *Gossypium herbaceum*

Figure 6 A– SEM of raw *Bambusa vulgaris x Gossypium*

Figure 6 B – SEM of microencapsulated *Bambusa vulgaris x Gossypium*

The Figure 4 A & B images clearly demonstrated a clean, orderly fiber structure in raw Musa acuminata x Gossypium. After finishing, the fabric displayed extensive and evenly distributed microcapsules covering the fiber surfaces. The capsules adhered well, forming a thin, continuous layer without disrupting the textile's structural integrity. The high degree of surface coverage, minimal agglomeration, and consistent capsule size suggest excellent encapsulation efficiency and physical compatibility between the fiber and the cumin-based finish.

The Figure 5 A & B imaging of raw Gossypium herbaceum revealed a fibrous, uneven surface with microvoids and loose fiber alignment, typical of untreated cotton. Post-treatment images exhibited the appearance of distinct, spherical microcapsules adhering to the fiber surface. However, capsule distribution appeared less uniform compared to other blends, likely due to the higher coarseness of kala cotton fibers, which offer fewer binding sites. The microcapsules were still distinguishable, suggesting moderate adherence and coverage.

The Figure 6 A & B images of raw Bambusa vulgaris x Gossypium displayed fine, aligned fibers with a smoother surface compared to the other fabrics. After encapsulation, numerous microcapsules were visible across the fiber surfaces, though slightly clustered in certain regions. The overall capsule coverage was good, with clear attachment along the fiber walls. Compared to kala cotton, the bamboo blend showed better dispersion and attachment, though not as homogeneous as the banana blend.

4. CONCLUSION

This study demonstrates the effectiveness of microencapsulation using Cuminum cyminum extract in functionalizing handloom cotton-blend fabrics. Three natural fabrics—Gossypium herbaceum, Musa acuminata x Gossypium, and Bambusa vulgaris x Gossypium—were evaluated for mechanical and chemical improvements through tensile strength testing, FTIR analysis, and SEM imaging. Among the three, Musa acuminata x Gossypium exhibited the highest tensile strength post-treatment, indicating superior structural reinforcement through the encapsulation process. FTIR spectra of this fabric showed the most intense and well-defined absorption bands related to the cumin extract, confirming its efficient chemical binding. SEM images further validated these findings, showing dense, uniform distribution of microcapsules that adhered effectively without compromising fiber alignment. The Musa acuminata x Gossypium blend performed moderately well, showing noticeable improvements in tensile strength and consistent FTIR and SEM results. The fabric's smooth surface allowed capsule deposition, though the dispersion was slightly uneven. It still represents a viable alternative for herbal-functionalized textiles with good aesthetic and mechanical properties. On the other hand, Gossypium herbaceum demonstrated the lowest encapsulation efficiency among the three. While it showed increased tensile strength and spectral changes confirming herbal deposition, SEM revealed sparse microcapsule coverage. This could be attributed to the coarse, rough texture of the fibers and a limited number of binding sites for effective adherence.

In summary, the Musa acuminata x Gossypium outperformed the others in all three analytical dimensions—mechanical strength, chemical uptake, and microstructural encapsulation—making it the most suitable for applications in therapeutic, wellness, and aroma-retaining textiles. Its compatibility with natural herbal finishes and superior physical characteristics positions it as a leading sustainable textile for future eco-functional fashion.

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