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Open Access Journal
DOI No. https://doi.org/10.63665

ISSN 0368-4636
e-ISSN 2347-2537

Journal of the TEXTILE Association

VOL. 86 NO.4 NOVEMBER-DECEMBER, 2025


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Journal of the TEXTILE Association
TEXTILE SCIENCE | TECHNOLOGY | ENGINEERING | MANAGEMENT
ISSN 0368-4636
e-ISSN 2347-2537
NOV-DEC, 2025 VOLUME 86 NO. 4

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Effect of Tariffs on the Indian Textile and Apparel Industry

Global textile trade continues to be shaped by evolving tariff regimes and strategic trade interventions. The United States, as one of the world's largest importers of textile and apparel products, has in recent years recalibrated its tariff and trade policies to protect domestic manufacturing and rebalance supply chains. These measures have had a direct bearing on exporting economies, including India, whose textile sector remains a vital contributor to employment, foreign exchange earnings, and industrial growth.

Across the value chain, the impact of U.S. tariffs is uneven. Fibre and yarn exporters, especially in the cotton and blended segments, face shrinking margins as buyers explore duty-advantaged alternatives. Fabric manufacturers supplying to global brands encounter sourcing realignments favouring countries with preferential trade arrangements. Garment manufacturers, largely MSMEs and export-oriented units, remain the most vulnerable, whereas technical textiles remain relatively insulated due to specialisation. India's competitive position is further tested by the preferential market access enjoyed by competing exporters.

Nevertheless, the changing global trade landscape also presents opportunities. The U.S. push toward supply-chain diversification and reduced dependence on China offers India a strategic opening. Rationalisation of input tariffs, efficient implementation of export incentive schemes, improved logistics infrastructure, and facilitation of scale and technology adoption are essential policy imperatives. From an industry perspective, the focus must shift toward value-added manufacturing, product innovation, sustainability compliance, and market diversification.

Looking from this perspective, The Textile Association (India), South India Unit, recently held its 78th All India Textile Conference on November 21-22, 2025, at Hotel Le Meridien, Coimbatore, focusing on "Global Textiles: Unearthing Opportunities," with key discussions on efficiency, sustainability, and industry challenges, featuring leaders from LMW, Pallavaa Group, and participation from machinery manufacturers

Warm regards,

Dr. Aadhar Mandot
Hon. Editor
JTA Editorial Board

T. L. PATEL, President

It gives me immense pleasure to connect with our esteemed members, industry colleagues, academicians, and students through this bimonthly issue of the Journal of the Textile Association. This platform has, over the decades, played a pivotal role in disseminating technical knowledge, encouraging innovation, and strengthening the bond between industry and academia—values that remain central to the mission of The Textile Association (India).

The Indian textile and apparel industry continues to stand at a crucial crossroads. On one hand, we are witnessing unprecedented opportunities driven by global supply chain realignments, policy support, and growing demand for sustainable and value-added products. On the other hand, the sector is navigating challenges such as volatile raw material prices, rising energy costs, skill gaps, and the urgent need to adopt environmentally responsible practices. It is during such transformative times that institutions like TAI assume even greater relevance.

Sustainability is no longer an option; it is an imperative. From fibre selection and processing to dyeing, finishing, and recycling, the entire textile value chain must embrace cleaner technologies and circular practices. Indian textile professionals have both the responsibility and the capability to lead this change. Through technical seminars, workshops, and publications, TAI remains committed to spreading awareness and facilitating the adoption of sustainable solutions that are practical, scalable, and economically viable.

Another critical area demanding attention is technology upgradation and digitalization. Automation, data-driven manufacturing, artificial intelligence, and smart textiles are redefining the future of our industry. While large enterprises have begun adopting these technologies, it is essential that small and medium units are also empowered to participate in this transformation. Knowledge sharing, training programs, and industry–academia collaboration will be key enablers in ensuring inclusive growth.

Skill development continues to be a cornerstone for long-term competitiveness. The industry requires not only skilled machine operators but also technologists, designers, and managers who can think globally and act innovatively. I strongly encourage our student members and young professionals to actively engage with TAI activities, attend conferences, publish technical papers, and interact with industry veterans. Your curiosity, creativity, and commitment will shape the future of Indian textiles.

TAI, through its various regional units and national initiatives, is striving to remain a vibrant knowledge-driven association. The enthusiastic participation of our members in conferences, plant visits, webinars, and technical meets is truly encouraging. I extend my sincere appreciation to all office bearers, committee members, authors, reviewers, and volunteers who contribute tirelessly to the success of our programs and to the quality of this journal.

As we move forward, collaboration will be the defining factor for success—collaboration between fibres and fabrics, tradition and technology, sustainability and profitability, and most importantly, between people. Let us work together to strengthen India's position as a global textile leader, not only in volume but in value, innovation, and responsibility.

I invite your continued support, suggestions, and active participation in the activities of The Textile Association (India). Together, let us weave a future that is resilient, sustainable, and globally competitive.

With warm regards,

T. L. PATEL
President
The Textile Association (India)

Journal of the TEXTILE Association

ISSN 0368-4636

Textile-to-Textile Recycling: Technologies, Sorting, and Management Pathways

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Abstract:

Background: *Choosing an effective textile-to-textile recycling route hinges on three things: Fibre composition, blend ratios, and the finishing chemistry applied to the fabric. With the industry's environmental footprint growing, this review pulls together both mature and next-generation options mechanical, chemical, and biological pathways along with the enabling tools for sorting and separation. We also discuss technologies such as electrostatic separation and laser-induced breakdown spectroscopy (LIBS) that aid feedstock identification, wastewater treatment, and material recovery.*

Methods: *We assess mechanical, chemical, and bio-based recycling approaches alongside the infrastructure that allows them to scale high-throughput sorting, reliable Fibre ID, and targeted decontamination. The analysis highlights where these interventions can curb fast-fashion externalities, reduce landfill reliance, and speed the shift to a circular textile economy.*

Outcome: *The evidence indicates that large-scale fabric recycling is a cornerstone solution to the textile waste problem. Broad, reliable deployment depends on coordinated action across the supply chain, supportive policy (including extended producer responsibility), and continuous innovation.*

Conclusion: *To make sustainability the default, the sector must design for recyclability simplifying blends, documenting finish chemistry, and investing in collection, sorting, and recovery systems so material loops can be closed at quality and at scale.*

Keywords: *Biological Recycling; Fabric Recycling; Mechanical Recycling; Textile Industry; Textile Waste*

Citation: Gautam Shivaraj, M. Gurusamy, Mohanraj. P., S. Thiruselvan, "Textile-to-Textile Recycling: Technologies, Sorting, and Management Pathways", *Journal of the Textile Association*, **86/4** (Nov-Dec'25), 365-369, https://doi.org/10.63665/jta.v86i4.2

Article History : Received : 02-09-2025, Revised: 26-10-2025, Accepted: 30-10-2025

1. Introduction

Textile waste is usually divided into two streams. Pre-consumer waste (cutting-room off-cuts, damaged yardage, and packaging) occurs before products are available, whereas post-consumer waste (discarded apparel and household textiles) occurs after products are not available. Because pre-consumer material is usually cleaner and more consistent, it is relatively easy to return to production, such as by re-spinning off-cuts into yarn or channeling them into insulation, reducing landfill pressure and reducing demand for virgin Fibre [2, 3]. Post-consumer flows are more difficult to manage: mixed Fibre content, multilayer constructions, trims and finishes, and different dye systems complicate recovery and often lower the quality of recycled output.

2. Literature Review

Mechanical recycling has been practiced for decades: mills open, shred, and re-spin waste Fibres a process that works for both natural and synthetic materials [14]. The trade-off is damage. Opening and carding shorten staple length and weaken yarn, so the output is usually downcycled into nonwovens, insulation, or carpet underlay rather than returned to apparel-grade fabrics.

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By contrast, chemical (advanced) recycling aims to restore quality by taking polymers back to monomers or dissolving them for purification before reforming. This route is especially promising for synthetics like polyester and nylon, where the re-polymerized material can approach virgin performance. For natural Fibres, bio-recycling offers a gentler option: enzymes or microbes selectively break down Fibres, cellulases for cotton, proteases for wool, and a growing body of evidence suggests these methods can scale. Beyond recycling, upcycling takes a design-first approach. By reworking waste and deadstock into higher-value products and using design-for-disassembly and modular construction, several brands are already extending material life and keeping textiles in circulation [4, 5].

3. Modern Fabric Recycling Technologies

Technological progress is making fabric recycling more viable, efficient, and diverse. Below we outline major modalities, their process logic, applications, advantages, and constraints [10].

3.1 Mechanical Recycling

Mechanical recycling physically opens, shreds, and cards waste textiles back to Fibre, which is then re-spun into yarn or formed into nonwovens. Process performance depends on input quality and sorting pure streams (e.g., 100% cotton or wool) yield better results than blends. Typical end-uses include:

i. Nonwovens and insulation for buildings and vehicles, sound-dampening panels, felts, and padding.

ii. Blended yarns (recycled plus virgin) for knit or woven fabrics when Fibre length/strength must be restored.

Advantages: Established, scalable, and comparatively low-cost. Works well for clean, single-Fibre streams and pre-consumer waste.

Limitations: Each pass shortens Fibres, reducing strength, handle, and spinnability; apparel-grade outputs usually require virgin blending. Mixed Fibres (e.g., poly-cotton) and finishing chemicals complicate processing and may carry over into new products, necessitating more intensive cleaning and sorting [9 & 11–13].

3.2 Chemical Recycling

Feedstock recycling, also referred to as chemical recycling, recovers near-virgin building blocks by depolymerization (for synthetics) or solvent-based separation of polymers. For example, polyester polymers can be depolymerized to monomers, purified, and re-polymerized into new PET Fibres with performance approaching that of virgin, as recycled synthetics increasingly fill the roles of apparel, packaging, and technical textiles.

Advantages: Restores material quality; handles color and many contaminants by purification; especially effective for synthetics.

Limitations: Sorting and pre-treatment remain critical and costly; solvent handling and emissions control require stringent environmental management; natural Fibres such as cotton or wool are less mature in chemical routes [1, 14].

3.3 Biological (Enzymatic) Recycling

Biological recycling employs enzymes to selectively break down natural Fibres into reusable constituents. Cellulases target cotton and other cellulose-based Fibres, while proteases act on protein Fibres like wool and silk. Properly managed, enzymatic treatments can yield high-quality pulp or oligomers suitable for re-spinning or for conversion into regenerated cellulosic.

Advantages: Lower chemical intensity and milder conditions; Fibre-specific selectivity; potentially smaller environmental footprint [15, 16].

Limitations: Finishes, dyes, and auxiliaries can inhibit enzymes; feedstock variability complicates control; most processes remain at pilot scale, with industrial scale-up the key challenge [17].

3.4 Microbial Recycling

Microbial pathways utilize engineered or natural bacteria and fungi to breakdown polymers (such as hard to recycle synthetics like polyester or nylon) and depolymerize them into monomers for repolymerization. Though conceptually robust for closing loops on synthetics, these technologies are currently limited by slow reaction rates, feedstock heterogeneity, and a requirement to engineer strains for mixed-Fibre realities [1, 18 & 19]. In summary: there is no silver bullet for textile waste; the most viable path to scale is a hybrid model that combines advanced sorting with a portfolio of mechanical, chemical, and bio-based processes tailored to material type.

4. Textual Remnants and Their Possibilities

Off-cuts from cutting rooms, end-of-roll yardage, and defective or surplus fabric are traditionally considered remnants, and are available for near-term value creation for both environmental and economic benefits. The challenge and opportunity is that scraps are heterogeneous, varying in size, color, Fibre content, and finishing, and blends (e.g., poly-cotton) are particularly challenging.

Enablers:

i. **Design-led upcycling:** Turning remnants into limited-run garments, accessories, and interiors supported by modular patterning and design-for-disassembly.

ii. **Advanced sorting:** Near-infrared (NIR) spectroscopy and digital identification help separate by Fibre and color, improving consistency and yield though capital costs can be prohibitive for small producers.

iii. **Process innovation:** Remnants can be mechanically opened and re-spun, chemically dissolved and re-formed, or incorporated into nonwovens and composites, depending on quality and composition.

While some brands worry about uniformity or perceived "second-best" quality, rising waste volumes and consumer interest in sustainability make remnant valorization a pragmatic step in circularity.

5. Market and Industrial Catalysts for Textile Recycling

Multiple forces are nudging the industry toward circularity.

i. Consumer demand and transparency: Buyers increasingly scrutinize supply chains, pushing brands to disclose materials, impacts, and end-of-life pathways. Programs like take-back, resale, repair, and recycled-content lines demonstrate that sustainability can be a competitive differentiator. Companies such as Patagonia (Worn Wear) and H&M (Conscious Collection) have mainstreamed these ideas.

ii. Policy and Extended Producer Responsibility (EPR): EPR frameworks assign end-of-life responsibility to producers, incentivizing design for recycling, investment in collection, and higher recycled content [13]. Countries with robust policies and public awareness e.g., Japan and South Korea show high textile recovery rates supported by incentives for technology adoption [30].

iii. **Circular business models:** Take-back and product-as-a-service models, rental, and certified recycled inputs align cost savings with impact reduction. Partnerships such as collaborations leveraging ocean-bound plastics or denim-to-denim Fibre loops illustrate how cross-sector coalitions can accelerate scale.

iv. **Technology platforms:** Innovation hubs (e.g., circular fashion coalitions) advance sorting (NIR), tagging, and Fibre-specific recycling. Industrial adopters report higher throughput and better purity in feedstock classification, improving economics across the recycling stack [31, 34].

The net effect is a tightening feedback loop: policy and consumer pressure stimulate corporate action; corporate pilots de-risk technologies; and scaled infrastructure lowers costs, encouraging broader participation.

6. Challenges in Fabric Recycling and Remnant Processing

Despite progress, several obstacles remain [28, 31, 35–37]:

i. **Feedstock complexity:** Mixed Fibres, multi-layer constructions, elastane, coatings, and trims complicate disassembly and reduce recovered Fibre quality.

ii. **Sorting at scale:** Accurate, high-speed sorting by Fibre and color is essential yet capital-intensive. Labels are unreliable; NIR and digital identifiers help but are not ubiquitous.

iii. **Chemistry carry-over:** Dyes, finishes (e.g., water repellents, anti-wrinkle agents), and flame retardants can contaminate recycled outputs or require costly purification.

iv. **Quality and perception:** Mechanical routes shorten Fibres; apparel-grade yarns often need virgin blending. Market perception can also equate "recycled" with "inferior," dampening demand for high-value uses.

v. **Economics and infrastructure:** In many regions, textile recycling infrastructure is sparse. Sorting, cleaning, and reprocessing can cost more than producing virgin Fibres, especially where landfill/incineration is cheap.

vi. **Scale-up of bio-routes:** Enzymatic and microbial processes show promise but face kinetics, inhibition, and scale-up hurdles before broad industrial deployment.

Addressing these gaps will require coordinated investment in collection systems, standardized labeling/identifiers, pre-competitive sorting facilities, and policies that reflect the true external costs of waste.

7. Conclusion

The apparel system will not reach true sustainability without substantial investment in fabric recycling, and it must be coupled with better design, smarter policy, and shifts in everyday behavior. In practice, that means designing for circularity: prioritizing single-Fibre fabrics or clearly separable blends, standardizing modular trims, and choosing finishes that align with end-of-life routes, while making high-speed, accurate identification and separation routine across sorting operations. A portfolio approach is essential for mechanical routes for clean mono-materials, chemical pathways for synthetics and complex colors, and bio-based methods for natural Fibres, so materials retain value over multiple loops. Responsibility is shared: brands, manufacturers, policymakers, and consumers must align through EPR frameworks, procurement standards, mindful purchasing, and robust take-back programs. With coordinated action and steady innovation, today's "waste" becomes tomorrow's feedstock, reducing environmental harm, strengthening supply resilience, and anchoring a truly circular textile economy.

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Journal of the TEXTILE Association ISSN 0368-4636

Enhancing Comfort and Functionality in Sports Textiles - Advances in Material Science and Fabric Engineering

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Abstract:

In recent years, advancements in active sportswear textiles have been driven by the pursuit of multifunctional performance combined with ergonomic comfort. The sports apparel industry has increasingly diversified its market through the use of advanced fibrous substrates and cutting-edge textile technologies, designed to meet the evolving demands of athletes and fitness enthusiasts. Progress in polymer science, Fibre engineering, and surface modification has enabled the creation of fabrics that address key performance needs such as thermoregulation, moisture control, flexibility, and durability.

The development of next-generation performance fabrics is shaped by several interrelated parameters. At the polymer and Fibre level, innovations include polyester microFibres, polyamide composites, elastomeric spandex, aramid Fibres, and bio-derived materials, which provide high tensile strength, elasticity, and lightweight resilience. In yarn and fabric construction, techniques such as micro-denier yarn production, warp and weft knitting, 3D spacer fabrics, and seamless knitting are employed to improve breathability, stretch recovery, and structural integrity. Finishing and coating approaches, including plasma treatment, nanotechnology-based finishes, phase change materials (PCMs), hydrophilic–hydrophobic surface engineering, antimicrobial treatments, and UV-protection coatings, further contribute to fabric functionality, durability, and wearer comfort.

This paper presents a comprehensive review of Fibre categories and their physicochemical properties, fabric structures and their influence on performance, and recent technological innovations that enhance sportswear. Particular attention is given to comfort-oriented features such as breathability, moisture-wicking, thermal regulation, quick-drying efficiency, odor resistance, and compression support, which define the standards of modern active wear textiles

Keywords : *Active sportswear fabrics, leisurewear fabrics, Sportswear, Sport tech, Technical textiles*

Citation: Sandeep Reen, Smriti Agarwal, "Enhancing Comfort and Functionality in Sports Textiles - Advances in Material Science and Fabric Engineering", *Journal of the Textile Association*, **86/4** (Nov-Dec'25), 370-375, https://doi.org/10.63665/jta.v86i4.15

Article History : Received : 30-08-2025, Revised: 06-10-2025, Accepted:10-10-2025

1. Introduction

The sports textile sector is among the fastest-growing domains within the global textile industry, integrating Fibre science, polymer engineering, and advanced fabric technologies to meet the evolving needs of both professional athletes and recreational users. In India, this segment contributes nearly 7% of the technical textiles market, underlining its role in driving industrial progress and innovation [1]. Sports textiles encompass more than basic apparel, extending into performance-oriented clothing, equipment, and accessories, all designed to enhance athletic efficiency, safety, and comfort. The transition from conventional cotton-based garments to engineered synthetic and composite Fibres marks a significant material innovation, transforming fabrics from passive coverings into active interfaces that regulate physiological responses and optimize performance.

The choice of textile materials plays a decisive role in sports applications, as it directly impacts thermos physiological comfort, durability, and biomechanical support [2]. Natural Fibres such as cotton and wool offer softness and breathability, whereas man-made Fibres like polyester, nylon, aramids, and elastane provide advanced attributes including moisture management, tensile strength, elasticity, and abrasion resistance [3]. Furthermore, modified synthetic Fibres treated with Nano coatings and functional finishes are now extensively employed in jerseys, shorts, footwear, and protective gear. These innovations cater to a wide spectrum of sports ranging from swimming and running to cycling and team-based disciplines. The rising popularity of outdoor and adventure activities such as mountaineering, paragliding, and cycling has further expanded the demand for active wear and performance textiles.

In elite performance domains such as sprinting, speed skating, skiing, and cycling, textiles play a pivotal role in aerodynamic optimization. Critical parameters including surface morphology, yarn geometry, seam orientation, fastener placement, and air permeability are meticulously engineered to reduce drag and maximize speed [4]. Simultaneously, the emergence of smart textiles and wearable technologies has introduced new functionalities

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such as integrated sensors, conductive Fibres, and phase-change materials, which enable garments to monitor physiological signals, regulate body temperature, and adapt to environmental changes [5]. These advancements reframe sports textiles as multifunctional systems, wherein Fibre chemistry, fabric structure, and garment design collectively determine performance outcomes.

Beyond the athletic sphere, sports textiles also contribute to broader technological and economic domains, with applications extending into medical textiles, defense gear, and protective clothing. Nonetheless, the sector continues to face challenges in reconciling sustainability with affordability and scalable production of high-performance materials [6]. This paper therefore aims to evaluate recent developments in sports textiles including Fibre and fabric innovations, functional finishing technologies, and emerging smart applications while highlighting research gaps that must be addressed to meet rising global and domestic demand for next-generation performance apparel.

2. Scope of the Review

This review brings together recent advancements in Fibre systems, fabric architectures, functional finishing technologies, and smart innovations in the field of sportswear. It explores both core performance parameters such as thermos physiological regulation, ergonomic comfort, and durability and emerging trends in intelligent textile applications. By linking the scientific principles that govern fabric functionality with their practical technological applications, the review seeks to identify key research gaps and propose potential directions for the development of next-generation sports textiles that are adaptive, sustainable, and responsive to user needs.

3. Need High Performance Sportswear

With the growing engagement in sports and fitness activities, the demand for advanced performance apparel is steadily increasing. This trend has pushed researchers, manufacturers, and designers to create innovative textile solutions that meet the rising expectations for both functionality and comfort. The surge in consumer spending on specialized sportswear fabrics has intensified market competition, making it essential to deliver products that combine high performance with aesthetic appeal and user comfort. To achieve this, industry and academia work collaboratively to design textiles that transform conventional fabrics into technically enhanced active wear. The fundamental requirements of such fabrics can be broadly classified into several categories:

4. Properties Required in Sportswear

4.1 General Performance Properties

A fundamental requirement of active sportswear is lightweight construction, which helps minimize unnecessary energy expenditure during physical activity. Equally important are elasticity and stretch recovery, which ensure freedom of movement and an optimal fit. Fabrics used in sportswear must also retain dimensional stability even when exposed to perspiration or environmental moisture, as distortion in garment shape can compromise performance. High tensile strength and abrasion resistance are essential to withstand the physical stress of intense training and competition. In addition, functional attributes such as quick-drying capacity prevent discomfort from accumulated moisture, while easy-care properties including shrink resistance, anti-pilling behavior, and wrinkle resistance contribute to garment durability and long-term consumer satisfaction.

4.2 Skin-Sensorial Comfort Properties

The tactile experience of sportswear plays a decisive role in user acceptance. Fabrics must be soft to the touch and engineered with smooth surface characteristics to reduce chafing and skin abrasion during continuous motion. Non-irritant and hypoallergenic finishes are increasingly applied to ensure compatibility with sensitive skin. Advances in Fibre cross-sectional modifications and surface treatments enable the creation of textiles that feel soft, dry, and comfortable even during extended use, thereby enhancing wear ability in demanding sports environments.

4.3 Ergonomic and Functional Properties

Sportswear design must also align with the biomechanics of the human body to improve efficiency and adaptability. Body-mapped garment structures and smart textile integrations provide localized muscle support while facilitating unrestricted motion. Compression fabrics are particularly valued for improving circulation and enhancing proprioceptive feedback. In outdoor sports, materials with waterproof, windproof, and breathable properties are vital to protect athletes from harsh weather while ensuring comfort. Similarly, advancements in footwear design such as lightweight construction, enhanced breathability, and improved traction reduce fatigue and improve safety during high-performance activities.

4.4 Psychological Comfort Properties

Beyond physical performance, psychological comfort significantly affects athlete confidence and focus. Aesthetics such as innovative designs, appealing fabric textures, and strategic use of colors play a motivational role. Color psychology, for instance, has been shown to influence mood and competitive spirit. The integration of smart textiles and wearable sensors further supports psychological assurance by enabling real-time monitoring of physiological functions, thereby fostering a sense of control and preparedness. In this way, psychological and functional elements intersect to enhance athletic performance.

4.5 Thermo-Physiological Comfort Properties

Among all requirements, thermo-physiological comfort is the most critical determinant of sportswear effectiveness. Efficient regulation of heat and moisture ensures athletes can perform without thermal strain. Advanced textile engineering enables fabrics to balance insulation and heat dissipation. High air permeability and vapor transmission facilitate ventilation, while low liquid absorption in skin-contact layers prevents dampness. Moisture-wicking technologies, such as microchannel Fibres and hydrophilic finishes, actively transport sweat away from the body. Emerging approaches including breathable membranes and phase-change materials (PCMs) further enhance thermal regulation by storing and releasing heat in response to body or environmental temperature fluctuations.

Thermo-physiological comfort occurs when a person is in thermal equilibrium, meaning the rate of heat loss matches the rate of heat generated by the body due to metabolic activity. Inadequate heat loss leads to a feeling of heat and humidity, causing heat stress, while excessive heat loss results in a sensation of cold. Hence, textiles need to be designed to facilitate optimal water vapor transmission while maintaining the necessary thermal insulation [7] For example; incorporating empirical studies on thermo-physiological regulation would substantiate claims regarding heat and moisture management in sportswear. Similarly, research on the performance evaluation of compression garments could provide evidence for their role in enhancing circulation, muscle recovery, and proprioceptive feedback. Furthermore, scholarly investigations into the applications of smart textiles in athletic contexts would reinforce discussions on functional integration, including real-time monitoring of physiological parameters. Such references not only validate the theoretical framework but also strengthen the academic rigor of this section.

4.6 Sustainability Considerations in Sportswear

Sustainability has emerged as a defining criterion in the evaluation of modern sportswear, influencing both material innovation and production processes. With increasing environmental awareness among consumers and regulatory bodies, the textile industry is compelled to adopt eco-friendly practices that reduce ecological impact without compromising performance. One prominent development is the incorporation of recycled Fibres such as polyester derived from post-consumer plastic bottles, ocean waste, and textile scrap. These materials offer comparable strength, elasticity, and durability to virgin Fibres while significantly lowering carbon emissions and resource consumption.

Equally important are low-impact dyeing and finishing techniques, including waterless dyeing methods, enzymatic treatments, and plasma finishes. These approaches minimize water and chemical usages, addressing the environmental burden associated with conventional wet processing in textiles. To objectively quantify such innovations, researchers increasingly rely on Life Cycle Assessment (LCA) methodologies. LCA enables a comparative evaluation of the environmental footprint of sustainable sportswear fabrics versus traditional materials, considering factors such as raw material sourcing, energy consumption, emissions, and end-of-life recyclability. Findings from such studies underscore the long-term benefits of transitioning to circular design models in sportswear. By explicitly embedding sustainability within the framework of performance, comfort, and aesthetics, contemporary sportswear design responds not only to the physiological and psychological needs of athletes but also to the global imperative for environmental responsibility.

5. Advanced Materials and Market Expansion

The scope of modern sports textiles encompasses innovations in materials, structures, and finishing techniques that improve ergonomics, comfort, and adaptability. Synthetic Fibres such as polyester and polypropylene are widely employed due to their outstanding dimensional stability, resistance to chemicals, and ease of care. Polyester, with its thermal stability, low moisture absorption, and affordability, is the most common foundation Fibre for active wear [2]. Polypropylene, with its hydrophobic nature and excellent insulation properties, has proven effective in managing moisture and maintaining thermal comfort across varying climates.

Globally, the sports textile market has expanded rapidly, driven by increased health awareness, raising participation in recreational and professional sports, and a surge in demand for versatile performance clothing [8]. The rise of athleisure has further blurred the boundary between sportswear and everyday fashion, while the integration of smart textiles has transformed garments into multifunctional systems. Market evolution now includes specialized apparel categories such as training gear, competition wear, and recovery clothing [9]. Importantly, the sector's influence extends beyond sports: advancements in Fibre technology, fabric engineering, and finishing techniques have stimulated innovation in medical textiles, protective clothing, and daily wear [10].

6. Interdisciplinary Performance Considerations

The requirements of sports textiles involve a dynamic interplay of physical, physiological, and psychological dimensions, all of which directly impact athlete performance [Fig. 1]. Developing effective sportswear therefore demands a holistic approach that integrates Fibre science, fabric engineering, and human-centered design. Understanding these factors is keys to producing garments that not only meet the technical requirements of various sports but also ensure comfort, safety, and confidence for the wearer.

Recent progress in specialized texturing techniques has played a pivotal role in advancing sports textile production. These techniques modify the microstructure of synthetic yarns, enabling improvements in both comfort and performance characteristics. Modern texturing methods have made it possible to engineer yarns with greater elasticity, enhanced moisture-wicking abilities, and better thermal regulation.

For instance, [11] introduced a rubber-blended Fibre strain sensor featuring a dual-sheath buckling configuration

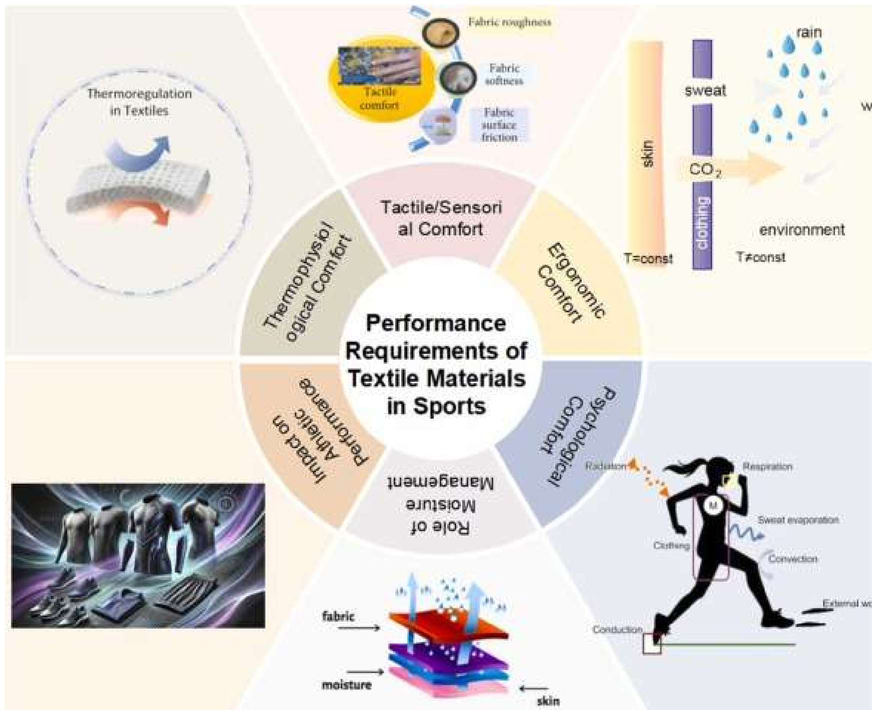

Figure 1: Scheme of performance requirements of textile materials in sports [12]

fabricated via a pre-stretching method. This design achieved an impressive strain detection capability of up to 600 %, though its sensitivity remained relatively modest. In a different strategy [12] produced CNT-ink/polyurethane (PU) yarns with a wrinkle-assisted crack architecture, resulting in ultralow detection thresholds and outstanding repeatability.

Further innovations in yarn architecture have led to notable enhancements in sensor responsiveness.[13] developed a sensor using braided stretchable yarns embedded with silver nanowires, capable of reliably detecting multiple forms of mechanical deformation including stretching, twisting, and bending while maintaining a high gauge factor (GF = 65) within a strain range of up to 100 %. Similarly [14] created an ultra-stretchable conductive helical yarn composed of a CNT/PU nanocomposite Fibre, demonstrating a maximum elongation capacity of 1700 %.

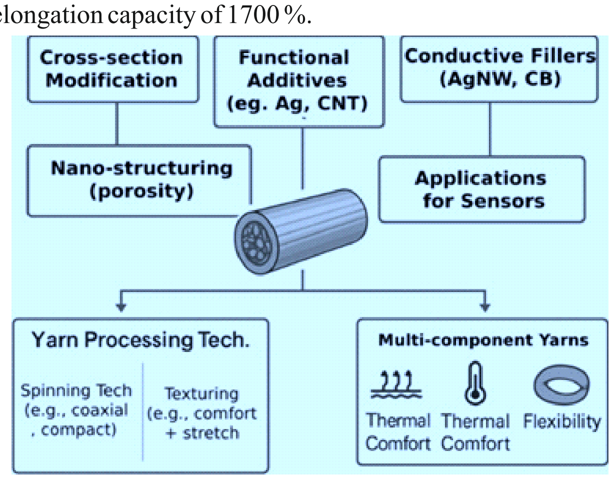

Figure 2: Overview of advanced Fibre and yarn processing technologies for sports textiles [14]

Collectively, these advancements in Fibre modification, yarn structuring and smart material integration have substantially broadened the design landscape for high-performance sports textiles. They offer a pathway toward garments that combine durability, functionality, and wearer comfort while seamlessly incorporating wearable sensing technologies.

7. Fabric formation techniques

The evolution of fabric formation technologies has resulted in increasingly sophisticated textile structures tailored for sports applications, fundamentally transforming both performance and comfort in active wear. Among these, advanced knitting techniques such as computerized flat knitting and seamless knitting systems enable the development of garments with integrated functional zones and anatomically optimized fit. These technologies make it possible to incorporate varied fabric structures within a single garment, thereby optimizing performance for different body regions. For example, studies on single jersey knitted fabrics created from non-traditional yarns demonstrated notable improvements in thermal regulation, moisture vapor transmission, wicking efficiency, and antimicrobial activity [15]. Coolmax polyester yarns showed excellent moisture transport capabilities, Airflo polyester hollow Fibres provided effective thermal insulation, and Sea cell viscose yarns retained antimicrobial activity even after repeated laundering. Such innovations in knitting have accelerated the development of high-performance sportswear capable of regulating body temperature, managing perspiration, and providing antimicrobial protection.

Parallel progress has also been achieved in weaving technologies, where modern high-speed looms equipped with electronic jacquard systems facilitate the creation of multilayered and engineered weave structures. These designs enhance specific performance attributes such as tensile strength, flexibility, and moisture management. The advent of 3D weaving techniques has further expanded possibilities by enabling fabrics with integrated compression zones and enhanced mechanical stability. In sportswear, such innovations have given rise to waterproof yet breathable textiles, which are vital for maintaining athlete comfort. Various categories of waterproof breathable fabrics such as densely woven constructions, microporous membranes and coatings, and hydrophilic membranes have been developed to protect against environmental factors while still allowing sweat vapor to escape [16].

Nonwoven technologies have also gained prominence in the sports textile domain due to their ability to produce lightweight yet high-performance materials. Advanced methods like electrospinning and melt blowing allow for the fabrication of structures with unique morphologies, making them particularly effective for thermal insulation layers and moisture management components.

In recent years, the incorporation of nanomaterials into textile substrates has further advanced sportswear functionality. Graphene, silver nanoparticles, and eco-friendly green nanomaterials have been integrated into polyester fabrics, yielding improvements such as enhanced wicking efficiency, superior UV protection, and improved electrical conductivity [17]. Reported outcomes included a 25% increase in moisture management, 30% improvement in UV shielding, and a 20% reduction in heat retention. These results underscore the potential of nanotechnology to elevate both performance and protective features in sports textiles.

Overall, advancements in knitting, weaving, and nonwoven processes, combined with the integration of nanomaterials, are driving the next generation of sportswear design. These developments are enabling garments that not only optimize athletic performance but also deliver exceptional comfort,

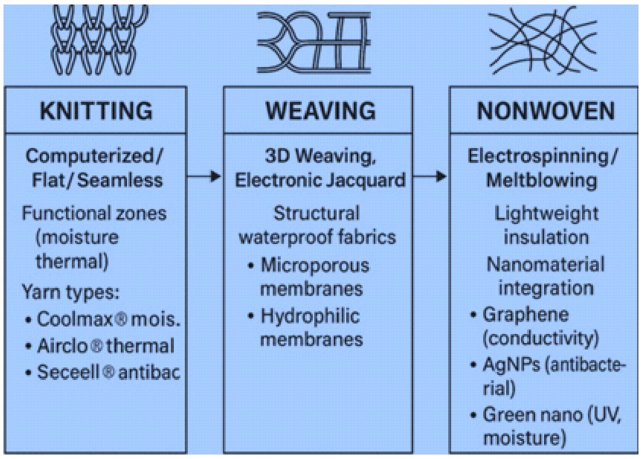

Figure 3: Schematic overview of advanced fabric formation techniques for sports textiles, highlighting key technologies, structure types, and performance-enhancing applications [17]

durability, and protection across diverse environmental conditions. A schematic overview of these three primary fabric formation methods knitting, weaving, and nonwoven is presented in Fig. [3]. Summarizing their key structures, functionalities, and performance applications in sports Textile.

8. Future trends and challenges in sports wear

The sports textile industry is at a critical crossroads, where rapid technological advancements intersect with urgent sustainability imperatives. This convergence presents both opportunities and challenges for the next phase of development.

8.1 Sustainability Imperatives

Sustainability has become a defining factor in the evolution of sports textiles. Stakeholders across the value chain face mounting pressure to adopt eco-friendly practices throughout the product lifecycle, from raw material selection to end-of-life management. Current strategies include the use of bio-based alternatives to conventional synthetics, closed-loop manufacturing, and designing products for recyclability. The major challenge lies in balancing environmental responsibility with high-performance standards, requiring innovations in material science and manufacturing processes that do not compromise athletic functionality.

8.2 Smart Textile Integration

The integration of smart technologies represents one of the most transformative trends in sports textiles. With advancements in sensing systems, real-time data analytics, and wireless connectivity, garments are increasingly capable of monitoring physiological parameters and athletic performance. However, barriers such as power supply limitations, durability of electronic components, and seamless textile–hardware integration remain unresolved. Future breakthroughs are expected in self-powered systems, flexible electronics, and robust embedding methods, which will be critical for widespread adoption.

8.3 Customization and Personalization

Consumer demand for individualized sportswear continues to rise, fueled by advances in digital manufacturing technologies such as 3D printing, automated cutting, and body-mapped knitting. These tools enable garments with personalized fit and function. The key challenge is scalability developing cost-effective systems that can deliver customization on a mass scale. Solutions will likely include advanced digital sizing platforms, automation in manufacturing, and streamlined supply chains.

8.4 Environmental and Lifecycle Considerations

The environmental footprint of sports textiles extends beyond production into their use phase and end-of-life disposal. Issues such as microFibre shedding, chemical-intensive finishing processes and waste accumulation demand urgent solutions. Future directions point toward biodegradable synthetics, waterless dyeing, and advanced textile recycling technologies, which remain underdeveloped for complex, multi-material garments.

9. Conclusion

This review has presented a comprehensive analysis of the critical role of textile materials in modern sports applications. Beginning with the physiological and ergonomic needs of athletes, we examined how engineered Fibres and fabric architectures provide essential functions such as moisture management, thermal regulation, compression support, and tactile comfort. Advancements in materials ranging from Nano coatings and multifunctional composites to sensor-embedded smart textiles demonstrate how innovation extends beyond fabrics into fully integrated performance systems.

Our discussion of manufacturing processes highlighted the technical challenges of scaling advanced methods such as electrospinning, precision spinning, and seamless knitting, while maintaining wear ability and durability. Sustainability was emphasized as a central consideration, particularly the need for bio-based Fibres, circular recycling strategies, and solutions to microFibre pollution.

Finally, by identifying current research gaps were including the long-term reliability of smart functions, integration of energy-harvesting systems, and eco-friendly processing techniques we provide a roadmap for future exploration.

In conclusion, the sports textile sector is transitioning toward a future defined by adaptive functionality, sustainability, and intelligent integration, positioning it as a leading driver of innovation across both the textile industry and broader material sciences.

Acknowledgements

I would like to express my sincere gratitude to Department School of Design, Mody University of Science and Technology for providing the necessary facilities and a supportive research environment that enabled me to carry out this study.

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Journal of the TEXTILE Association
ISSN 0368-4636

AI-Powered Transformation in Home Textiles: Efficiency, Sustainability, and Consumer Experience

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Abstract :

Background

The home textile sector, including bed linens, towels, and curtains, is under pressure from rising consumer expectations, stricter sustainability standards, and supply chain uncertainties. Artificial intelligence (AI) is emerging as a strategic enabler, offering innovative solutions across design, production, quality control, logistics, and customer interaction.

Methods

The scope includes a scoping review (2015–2025) of peer-reviewed literature and reputable industry reports, supplemented by documented corporate cases in home textiles. Inclusion required explicit metrics (e.g., yield %, energy or water usage, forecast error) or reproducible descriptions of AI workflows.

Results

Analysis shows that AI improves efficiency and competitiveness through multiple pathways: (i) trend forecasting and generative design tools; (ii) optimized color matching and dyeing via machine learning and spectral systems; (iii) automated defect detection and predictive maintenance using computer vision and IoT; (iv) cutting-room efficiency through AI nesting algorithms; (v) supply chain resilience with demand sensing and drone-assisted inventory checks; and (vi) blockchain-based platforms that ensure cotton traceability. On the consumer side, AI enhances personalization and supports the growth of "smart" bedding products. These applications reduce waste, improve product quality, and reinforce sustainability initiatives.

Conclusion

AI complements rather than replaces human creativity and craftsmanship. Organizations in the home textile industry that embrace AI strategically across design studios, mill operations, and retail channels can achieve measurable improvements in productivity, sustainability, and consumer trust, positioning themselves for long-term competitive advantage.

Keywords: *Artificial Intelligence, Home Textile Industry, Smart Manufacturing, Sustainability, Supply Chain Optimization*

Citation: M. Gurusamy, Seranmadevi R, D. Barani, M. Iswarya, "AI-Powered Transformation in Home Textiles: Efficiency, Sustainability, and Consumer Experience", *Journal of the Textile Association*, **86/4**(Nov-Dec, 2025), 376-381, https://doi.org/10.63665/jta.v86i4.14

Article History : Received :28-07-2025, Revised: 23-08-2025, Accepted: 27-08-2025

1. Introduction

Home textiles are quietly becoming one of the most tech-infused corners of consumer goods, from bedsheets and bath towels to curtains and cushions. This article examines how artificial intelligence is reshaping the entire value chain from trend and pattern design to dyeing, weaving, cutting, quality control, logistics, retail, sustainability, and even "smart" bedding in our homes using concrete, recent examples.

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2. Importance of AI in Home Textiles

If the organization stands on a mill floor today, the organization sees the same timeless machinery: carders, spinners, looms, dye ranges, finishing lines. However, if the organization steps closer, it will notice cameras where human inspectors used to stand, dashboards that predict faults before the organizations happen, and cutting rooms that squeeze extra yield from the same fabric roll. In addition, the retail side AI tools predict what colors will sell, help shoppers design rooms, and keep inventory in the right place at the right time, during a transformation in the industry.

Three pressures are making AI non-optional in home textiles:

i. Margin pressure (cotton and energy volatility, retailer demands).
ii. Sustainability mandates (water, chemicals, traceability, especially for cotton).
iii. Customer expectation (fast trend cycles, personalization, and omnichannel convenience).

Home textiles are ideal for AI because the organizations combine repeatable patterns (literally, in printed repeats and cutting layouts) with high-volume processes and rich data from cameras, sensors, and ERP systems. When organizations feed that data into computer vision, forecasting, and optimization models, it results in fewer defects, faster response times, and less waste.

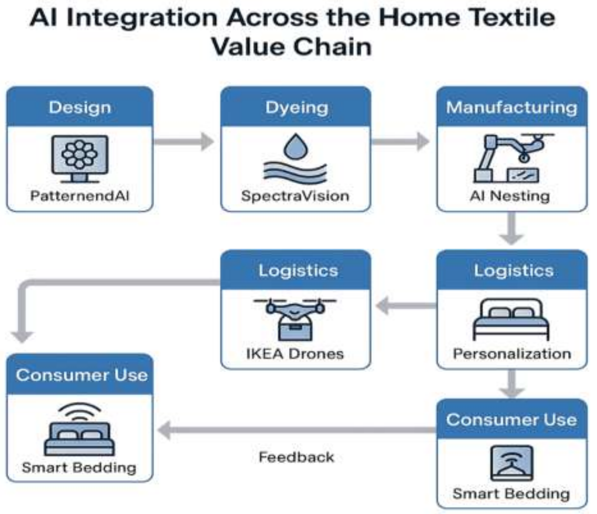

Figure 1 - AI Integration Across the Home Textile Value Chain

Source: Authors' framework and synthesis based on peer-reviewed and industry sources referenced in this paper

3. Research Gap and Contributions

Despite the rapid diffusion of AI tools in textile design, dyeing, inspection, finishing, logistics, traceability, and retail, peer-reviewed syntheses focused specifically on home textiles remain limited. Prior publications frequently aggregate apparel, technical textiles, and home textiles without comparable metrics (e.g., right-first-time dyeing %, stenter energy kWh/kg, defect ppm), constraining capital-budgeting decisions. This article contributes by (i) outlining an integrated AI-in-home-textiles value-chain view; (ii) applying three decision lenses: ROI, sustainability impact, and implementation feasibility; and (iii) using quantitative indicators such as water (L/kg), energy (kWh/kg), waste (%), and defect rates (ppm) to enable benchmarking and transparent comparison.

4. Methodology

The scope includes a scoping review (2015–2025) of peer-reviewed literature and reputable industry reports, supplemented by documented corporate cases in home textiles. Inclusion required explicit metrics (e.g., yield %, energy or water usage, forecast error) or reproducible descriptions of AI workflows.

4.1 Analytical approach

The analysis combined (i) case synthesis to aggregate convergent findings; (ii) thematic categorization across value-chain stages; and (iii) benchmarking against normalized indicators such as RFT dyeing, stenter energy intensity, inspection-stage waste rates, and demand MAPE. Extraction sheets captured variables, units, and context; when studies reported ranges, indicative mid-points were computed with citations to support reproducibility.

4.2 Bias mitigation for vendor-driven evidence

Vendor examples were included only with independent corroboration, quantitative baselines, and disclosure of limitations. Qualitative-only claims are treated as illustrative rather than evidentiary.

5. AI in design & trend capture: from inspiration to print-ready repeats

Generating a fresh wallpaper or bed linen repeated a decade ago meant a designer's careful hours in Illustrator. That human craft is still central, but AI accelerates ideation and helps teams test more concepts before committing to print.

5.1 AI pattern generation at the concept stage

AI tools create seamless, print-ready repeat tiles from text prompts, which are helpful for brainstorming motifs and building seasonal mood boards faster. The organization still needs a designer's eye, but can explore a more expansive search space in minutes [1].

5.2 On-demand printing platforms

Marketplaces let independent designers and brands upload designs to be printed on fabric, wallpaper, and home décor, an ecosystem where AI-assisted artwork increasingly shows up and can be bought in small lots for sampling or short runs [2].

5.3 Enterprise color & pattern workflows

Beyond inspiration, enterprise AI tools and others streamline creating tiled repeats and production-ready assets (e.g., Illustrator's pattern/repeat features). AI here speeds cleanup and iteration even when final art is hand-crafted [3].

5.4 Live example (workflow)

A bedding brand's studio uses Patterned AI to explore 50 floral variations around a “botanical dusk” theme, selects five promising repeats, refines them in Illustrator, then posts the finalists to an internal portal where merchandising and planning teams can A/B test colorways with past sales data. The result: more options in less time, and better odds of landing the winning print.

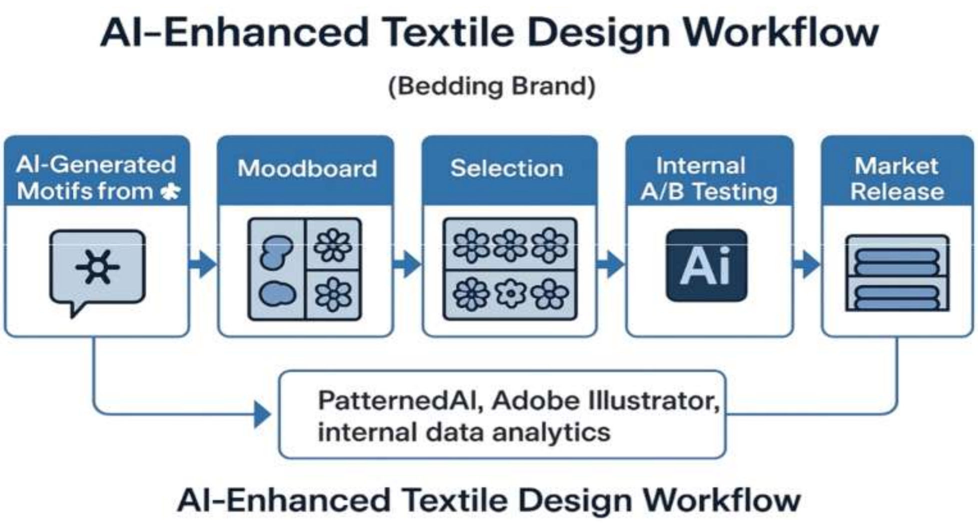

Figure 2 - AI-Enhanced Textile Design Workflow

Source: Authors' framework and synthesis based on peer-reviewed and industry sources referenced in this paper

6. Color science & dyeing: where AI saves water, chemicals, and time

Color is unforgiving in home textiles (imagine a duvet set whose pillowcases don't match the quilt after laundering). AI and spectral measurement are driving real gains:

6.1 Measuring the "unmeasurable"

AI Spectra Vision couples a hyperspectral spectrophotometer with software to measure and communicate color on complex materials, think textured terry towels, jacquards, or multi-colored prints, where classic spectro methods struggle. Better measurement + formulation reduces re-dyes and rejected lots [5].

6.2 Machine learning in dyeing

Recent research from NC State shows that ML models map [4] color shifts during the dyeing process more accurately, helping mills cut waste and get closer to target shades faster with less water, fewer chemicals, and fewer lab dips.

6.3 Live example (dyehouse)

A towel mill ingests historical lab-dip results, recipe cards, and in-process spectro readings into a regression model that predicts final ΔE by fabric construction and bath conditions. The team trims the organization's corrective re-dye per 10 lots, resulting in tangible savings in water and auxiliary chemicals while maintaining brand standards for color fastness.

7. Smart manufacturing: spinning, weaving, finishing watched by AI

7.1 Computer vision quality control at loom and finishing

Historically, trained inspectors scanned for knots, slubs, misses, and stains at 30–60 m/min. Now, vision systems watch every centimeter and flag defects instantly:

i. Uster Technologies offers automated inspection [6] and data platforms to analyze and classify defects that used to take teams hours. Their 2024 update highlights moving mills from manual to automated fabric inspection with rapid integration and real-time data capture.

ii. At the weaving stage, on-loom monitoring [6] uses high-resolution cameras to detect issues as fabric forms, improving first-quality yield, which is essential for bed and table linens where long, clean runs are the norm.

iii. Vision on the line and in packaging is maturing fast. 3D AI vision system shows how inspection moves from 2D images to combining depth and AI classification applicable for folded towel packs, sheet sets, and carton QC before shipping [7].

7.2 Spinning and prep with digital intelligence

While home textiles are sold as fabric and finished goods, yarn quality drives everything. Vendors embed Industry 4.0 [8] features (data acquisition, optimization, predictive maintenance) across the spinning line, with new machines and software suites showcased through 2023–2025. These tools allow mills to monitor critical parameters and stabilize yarn even with variable cotton lots.

7.3 Predictive maintenance (PdM)

Unplanned stops during weaving/finishing are costly. IoT + AI PdM is now mainstream in textiles:

i. An India-based case study describes AI-driven condition monitoring for a legacy textile operation: sensorized assets, cloud models predicting faults, and less downtime for maintenance teams [9].

ii. Academic work continues to refine PdM architectures for manufacturing, with 2024–2025 reviews covering trustworthy AI, explainability, deployment, and helpful guardrails for mills rolling out PdM at scale.

iii. Live example (mill uptime): A jacquard weaving plant tags motor vibration, temperature, and stop code streams to detect precursors of rapier misalignment. A gradient-boosting model predicts a fault window 8–12 hours ahead; planned micro-stoppages replace catastrophic halts, lifting loom utilization by 2–3% in peak weeks.

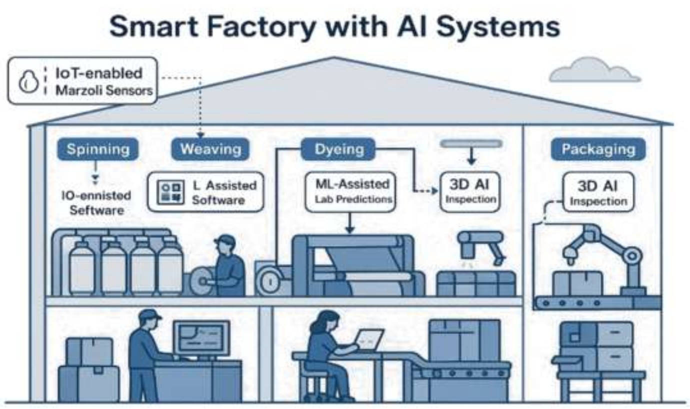

Figure 3 - Smart Factory with AI Systems

Source: Authors' framework and synthesis based on peer-reviewed and industry sources referenced in this paper

8. Cutting-room AI: yield, speed, and small-batch economics

Once the fabric passes inspection, AI can convert meters into margin in the cutting room.

8.1 AI-assisted nesting in furniture/upholstery & home décor.

The cutting ecosystem (Vector cutters + Valia and Furniture On Demand) and AI nesting algorithms help brands plan, prioritize, and maximize fabric utilization, which is critical for large-pattern repeats or costly upholsteries [10]. Recent coverage highlights customers using AI nesting to estimate usage precisely and avoid overspending on fabric while speeding order processing.

8.2 Automated nesting for technical and home textiles

It has long used advanced algorithms to search layout solutions and increase material yield, especially when cutting sheet sets with directional prints or matching pillowcase stripes across SKUs [11].

8.3 Live example (curtains & cushions)

A made-to-measure drapery shop processes 150 custom orders/day. With AI-assisted nesting and a rule set for face/lining direction, the organizations ' yield lifts by ~3–5% and removes a planning bottleneck during seasonal peaks, giving customers faster ETAs without buying extra rolls.

9. Supply chain, inventory & logistics: the quiet superpower

Home textiles are bulky, color-sensitive, and space-hungry. AI demand sensing and robotic/vision inventory are transforming availability and carrying cost:

9.1 Demand forecasting and drones

AI tools are improving forecast accuracy and store planning, and AI-enabled inventory drones (via Verity) are being developed to count stock and spot misplaced items even alongside workers. Better forecasts + always-on counts = fewer stockouts and less dead stock [10].

9.2 Retail demand planning in home goods

Home retailers have adopted AI capabilities [11] to automate planning and upgrade forecasting; a pattern the study sees across homeware and soft goods to match stock to local tastes and seasonal swings.

9.3 Agentic AI in logistics

Warehousing and transport increasingly use AI agents for slotting, routing, and exception handling, improving on-time delivery for bulky home categories.

9.4 Live example (sheet sets)

A North American retailer splits "cooling percale" colors by climate region using an AI demand model trained on local weather, returns, and social signals. It reduces inter-store transfers by 18% and cuts end-of-season markdowns on outlying colors, freeing open-to-buy for on-trend SKUs.

10. Traceability & trust: following cotton from farm to bed

Home textiles, especially cotton traceability, have moved from "nice to have" to "license to operate." One of the most visible on a scale:

10.1 Digital & Third-Party Verification

A blockchain-enabled, AI-supported traceability platform that tracks Fibre back to farms and provides digital/third-party verification to retailers and consumers [12]. It's a blueprint for combining supply-chain data with AI checks to catch anomalies, underpinning claims like "Egyptian cotton" or "organic."

10.2 Live example (towels): A US retailer's private-label towels arrive with QR-backed traceability records. When a sustainability auditor requests proof of a campaign, the brand pulls Wel-Trak data to validate farm origin and chain of custody in minutes instead of weeks.

11. Marketing, personalization & retail UX: design help and discovery

Consumers don't shop for "fabric GSM"; the organizations shop for rooms and feelings. AI helps translate catalog logic into inspiration:

11.1 GenAI-powered Inspiration

A GenAI-powered inspiration and visual browsing experience that ties style prompts to shoppable products, bridging the gap between a Pinterest mood and a cart full of items [13]. Coverage in early 2025 underscores promise and limits as retailers learn what shoppers want from AI imagery.

11.2 AI Assistant

Rolled out via OpenAI's GPT ecosystem to guide room design, recommend products, and link to checkout, think of it as a digital design associate that learns a shopper's vibe [10].

11.3 Live example (bedding bundle builder)

A retailer's chatbot asks: "Warm sleeper? Preferred palette? Pets on bed?" It then auto-builds a summer set (percale sheets, lightweight duvet, washable shams) in two color ways, explains the trade-offs (cooling vs. coziness), and checks local inventory for same-week delivery.

12. Smarter products at home: "textiles" that sense and adapt

Strictly speaking, "smart beds" blend textiles with embedded tech, but the organizations illustrate where AI meets comfort: Eight Sleep's Pod [15] learns user preferences and automatically adjusts bed temperature through the night; newer systems add elevation and snore-reduction features, all driven by ambient data and algorithms.

Sleep Number [14] has moved steadily toward AI-infused beds that respond to sleepers' biometrics and offer active cooling/warming programs covering the whole sleep surface ecosystem (mattress + temperature-balancing bedding).

While the organization's bed sheets aren't running neural nets, the category halo matters: customers primed by AI-assisted sleep expect temperature and moisture management in sheets and duvets, and the organizations search accordingly.

13. Sustainability: less water, less energy, less waste measured, not promised

Sustainability is where AI quietly pays for itself:

13.1 Inspection → less scrap

Automated defect detection [6] catches flaws earlier, improves quality, and prevents packaging/shipping defects that result in returns.

13.2 Color right-first time

ML-assisted dyeing and better spectral tools (Datacolor) mean fewer lab dips and re-dyes, directly cutting water/chemicals [4].

13.3 Energy optimization & PdM

AI predictive maintenance and energy management frameworks let mills run closer to optimal loads, especially as India and others push to decarbonize thermal processes and adopt renewables [9].

13.4 Policy & macro push

India's textile sector, projected to scale dramatically by 2030, faces growing pressure to halve emissions, spurring innovations like near-net-zero factory blueprints and greener process choices. AI underpins many of the measurements and optimization steps needed to get there.

13.5 Live example (energy & waste)

A bed linen finisher uses a reinforcement-learning controller to tune stenter temperature/line speed against moisture readings and fabric weight. Gas use falls ~6–8% at steady quality; over a year, that's six figures in savings at current prices.

14. Comparative assessment (ROI – Sustainability – Feasibility):

14.1 Dyeing/Color

ML recipe prediction and lab-dip optimization. ROI: fewer re-dyes, faster cycles.

14.2 Sustainability: RFT improvements can reduce water use by ~10–30% depending on baseline [16]. Feasibility: requires spectral data and historical records.

14.3 Fabric Inspection

Computer-vision defect detection/segmentation. ROI: higher first-quality, fewer returns. Sustainability: double-digit reductions in scrap/rework are frequently reported [17]. Feasibility: camera retrofits and SOP change management.

14.4 Finishing

Model-based stenter control (humidity/temperature). ROI: energy savings and quality stability. Sustainability: ~5–30% energy savings in documented programs [18]. Feasibility: moisture sensing and operator training.

14.5 Supply Chain

Demand sensing and drone-assisted cycle-counting. ROI: lower stockouts/markdowns. Sustainability: reduced dead stock and transport emissions. Feasibility: ERP/WMS integration ad data governance.

14.6 Traceability

Blockchain with anomaly checks. ROI: risk mitigation and potential premium pricing. Sustainability: faster verification and fewer audit cycles [19]. Feasibility: multi-tier partner alignment.

15. Quantitative Sustainability Evidence

15.1 Water

Dyeing/printing water intensity commonly ~35–215 L/kg depending on substrate and process; improving RFT and rinse-water reuse materially reduces loads [16].

15.2 Energy

Stenter frames often draw ~40–55 kWh/h electricity and ~50–60 kg/h fuel; humidity/temperature control and heat recovery show ~5–30% savings in documented programs [18].

15.3 Waste

Computer-vision inspection is associated with double-digit reductions in rework/scrap and shorter lead times in published deployments [17].

15.4 Traceability

Wel-Trak 2.0 demonstrates blockchain-enabled farm-to-shelf verification in home textiles, accelerating audits and strengthening ESG disclosures [19].

16. Future research directions:

16.1 Workforce Reskilling

Measure productivity and quality uplift from hybrid inspector-plus-AI roles; define competency frameworks for dyehouse and finishing technologists using AI decision support.

16.2 Circular economy

Quantify AI's role in design-for-disassembly, Fibre identification for automated sorting, and closed-loop flows for cotton/poly blends in home textiles.

17. Conclusion

The soft-goods revolution will be measured in complex numbers. AI doesn't replace the weaver's wisdom or the designer's taste. It's giving both bigger levers: seeing defects earlier, predicting demand smarter, cutting cloth tighter, and telling the truth about where cotton came from. The brands and mills that win in home textiles will be the organizations that blend craft + code and measure progress not in buzzwords but in first-quality %, yield %, MAPE, on-time delivery, water per kg, and verified claims.

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Journal of the TEXTILE Association

ISSN 0368-4636

Chemical Processing of Natural and Synthetic Fibres: Environmental Impact, Challenges and Sustainable Alternatives

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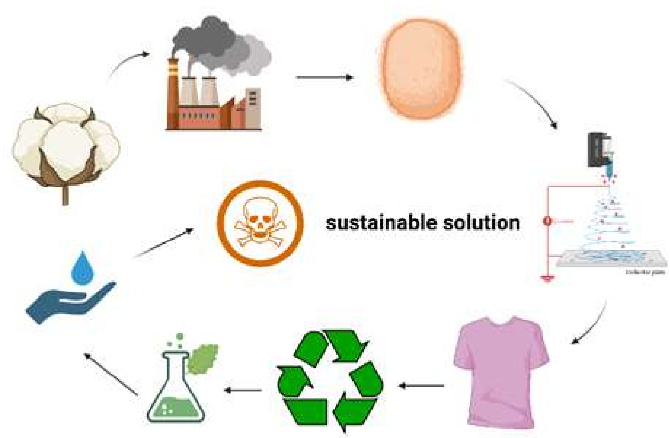
Abstract :

The textile industry is one of the most resource-intensive and chemically driven manufacturing sectors worldwide, significantly contributing to both global economic output and environmental degradation. Chemical processing of fibres –covering pretreatment, dyeing, printing, and finishing-play a vital role in giving functionality, color, and performance to natural and synthetic textiles. However, these quantities of water, energy, and chemicals, often leading to high levels of effluent toxicity, air emissions, and solid waste. Conventional wet processing methods, especially those involving reactive and disperse dyes, release hazardous organic compounds, heavy metals, and salts into aquatic environments, posing long-term ecological and human health risks. This review critically examines the environmental impact of chemical processing across fibre types such as cotton, wool, silk, polyester and nylon. It highlights sources of pollution, degradation pathways, and their persistence in ecosystems. The study also explores recent advances in sustainable processing, including enzymatic desizing, plasma and supercritical CO_2 treatment, low-liquor-ratio dyeing, and nanomaterial-assisted finishing. Life cycle assessments and green chemistry approaches are discussed as essential tools for reducing environmental burdens. The review concludes that adopting clean technologies, process automation, and circular economy principles can markedly lessen the ecological impacts of textile chemical processing. Transitioning toward closed-loop, energy-efficient, and biodegradable systems is vital for aligning the textile industry with sustainable development goals and safety standards.



Graphical Abstract

Keywords: *Effluent toxicity, Environmental impact, Fibre Pre-treatment, Green chemistry, Sustainable dyeing, Textile Processing*

Citation: Jothi Jerald, Pachiyappan KM, Manikandan Dhayalan, "Chemical Processing of Natural and Synthetic Fibres: Environmental Impact, Challenges and Sustainable Alternatives", *Journal of the Textile Association*, **86/4** (Nov-Dec'25), 382-389, https://doi.org/10.63665/jta.v86i4.17

Article History : Received :23-10-2025, Revised: 03-11-2025, Accepted: 07-11-2025

1. Introduction

The global textile industry is a major and growing sector, contributing significantly to employment, industrial growth, and international trade [1, 2]. In 2023, global production of textile fibres exceeded 120 million tonnes, a figure that continues to increase due to rising consumer demand and urbanization [3]. The industry is characterized by its diverse raw materials and heavy reliance on chemical processing to turn raw fibres into functional, aesthetic, and value-added products. The two main fibre categories- natural fibres (such as cotton, jute, wool, silk, and flax) and synthetic fibres (such as polyesters, nylon, acrylic, and polypropylene)- undergo several wet and dry processing steps that use substantial water, energy, and chemicals. While these processes improve fibre performance, they pose significant challenges [4]. Chemical processing includes operations such as pre-treatment, dyeing, priming, and finishing, each engineered to add specific desired properties. Pretreatment steps like desizing, scouring, bleaching, and mercerization remove impurities, improve hydrophilicity, and prepare textiles for dyeing [5]. The subsequent dyeing and finishing processes use a wide range of dyes, mordants, surfactants, oxidizers, formaldehyde resins, and heavy metal catalysts to enhance color, stability, flame retardance, and antimicrobial qualities [6]. However, conventional methods produce large volumes of toxic effluents rich in chemical oxygen demand (COD), biological oxygen demand (BOD), total dissolved solids (TDS), and dyes, which can cause significant environmental harm if not properly treated before discharge [7]. Globally,

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textile dyeing and finishing account for up to 20% of industrial water pollution, consuming about 80-150L of water per kilogram of fabric. The effluents often contain complex mixtures of dyes, auxiliaries, and finishes that contain recalcitrant organic molecules resistant to biological breakdown [8]. Persistent dyes such as azo, reactive, and halogenated agents can form toxic aromatic amines and mutagenic intermediates upon partial degradation. Synthetic fibres like polyester and nylon, when processed chemically, can release microplastics and oligomers, adding further environmental concerns. These pollutants impact aquatic life, reduce light for photosynthesis, and bioaccumulate in the food chain, ultimately threatening human health through contaminated water and food [9]. The environmental impact extends beyond water pollution. Energy-intensive processing emits greenhouse gases, while volatile organic components (VOCs) from solvent-based finishes degrade air quality [10]. The use of chlorine-based bleaches, formaldehyde resins, and perfluorinated chemicals like PFOA and PFOS raises further concerns due to their toxicity and persistence. As the textile and apparel sector is projected to grow annually by 3-4%, these impacts highlight the urgent need for cleaner, sustainable alternatives. Over the past decade, sustainability principles have gained momentum in textile manufacturing. Principles from frameworks such as the United Nations Sustainable Development Goals SDG 6 (Clean Water and Sanitation) and SDG 12 (Responsible Consumption and Pollution)-focus on reducing pollution and resource use. Research and innovation now emphasize green chemistry, low-impact technologies, and circular economy models. Technologies like enzyme-based scouring and bleaching, ozone and plasma treatments, and supercritical CO_2 dyeing show promising results for reducing water and chemical consumption. Similarly, nanotechnology enables advanced finishes that improve durability and performance while lessening resource use. Advance Oxidation Processes (AOPs), and zero-liquid discharge (ZLD) systems being implemented in textile hubs like Tirupur (India) and Jiangsu (China) [11]. Use of bio-based auxiliaries, natural mordants, and plant-derived surfactants is expanding as alternatives to petroleum chemicals. Life cycle assessments (LCAs) provide valuable insights on environmental performance, guiding industry and policy [12]. Despite these advancements, challenges remain, including the high cost and scaling difficulties of eco-friendly technologies, variability in raw materials, differences in fibre properties, and data gaps on long-term environmental impacts [13]. A thorough understanding of fibre chemistry, chemical interactions, and effluent treatment is necessary for effective solutions. This review focuses on the chemical processing of natural and synthetic fibres, examining their environmental effects and recent sustainable innovations. It discusses fibre classification, processing chemicals, pollution mechanisms, and emerging eco-friendly methods like enzymatic, nanomaterial-assisted, and solvent-free techniques. The goal is to connect process chemistry with environmental sustainability, offering practical insights for researchers, industry, and policymakers. It systematically reviews the chemical processing of various fibres, emphasizing their structures, processing needs, and environmental impacts. Then evaluates emerging green technologies through case studies and performance metrics. The review aims to identify key research gaps and propose strategies for sustainable textile manufacturing. Achieving this requires not only technological innovation but also systemic changes in industry practices, policies, and consumer behaviour. Incorporating green chemistry, circular production, and life-cycle thinking can transform the textile sector into a resource- efficient industry that meets future demands without harming the environment.

2. Classification of Textile Fibres

Textile Fibres, the fundamental building blocks of all textile materials, are broadly categorized based on their origin and chemical composition into natural, regenerated, and synthetic types, each exhibiting distinct physiochemical behavior during chemical processing Table 1. Understanding fibre classification and structure helps evaluate their interactions with agents like alkali, acids, dyes, and chemicals. Fibre groups include natural, regenerated, and synthetic Fibres, each with unique compositions, surface morphologies, and reactivity, influencing wettability, dyeability, and environmental impact [14].

2.1 Natural Fibres

Derived from plants, animals, or minerals, mainly composed of polymers like cellulose in cotton, jute, and flax, and proteins in silk and wool. Cotton, mainly cellulose (~88-96%), is hydrophilic due to hydroxyl groups but prone to alkaline degradation, requiring careful chemical control [15]. Its structure favors reactive dyes but demands extensive water and chemicals. Jute and flax contain more lignin and hemicellulose, making them stiffer and harder to dye, needing harsher pretreatments. Silk and wool, protein fibres, have distinct reactivity, with wool's scaly surface complicating processing, often generating hazardous waste [16].

2.2 Regenerated Fibres

Made form chemically modified natural polymers like cellulose, they include viscose, modal, and lyocell, differing in production and properties. Viscose involves dissolving cellulose in chemicals, risking pollution, modal improves strength lyocell uses a non-toxic solvent, offering environmental benefits [17]. Their porosity and hydrophilicity enhance dyeability but may cause swelling or fibrillation, requiring special finishes.

2.3 Synthetic Fibres

Man-made form petroleum-based monomers, including polyester, nylon, acrylic, and polypropylene. Polyester is strong and resistant but hydrophobic, needing high-temperature dyeing and contributing microplastic pollution [18]. Nylon is tough and elastic, with moderate dyeing ease

Table 1: Classification of Textile Fibre s Based on Origin, Composition, Key Characteristics and Environmental Processing Considerations

Fibre type	Subclass examples	Primary chemical composition	Key characteristics	Environmental processing/considerations
Natural Fibres	**Plant Based:** cotton, jute, Flax	Cellulose (88-96%) hemicellulose, lignin, waxes	Hydrophilic, good dye uptake, alkali sensitive	High water and chemical demand; generates alkaline wastewater
	Animal-Based: Silk, wool	Proteins (fibroin keratin)	Sensitive to pH; scaly surface (especially wool); good affinity for acid dyes	Hazardous by-products form degumming and scouring: difficult waste management
	Mineral-based: Asbestos	Silicate minerals ($Mg_3 Si_2O_5 (OH)_4$)	Fire-resistant, non-combustible	Health hazards (fibrosis, carcinogenic); limited modern use
Regenerated fibre	Viscose, modal, Lyocell	Chemically modified cellulose	Hydrophilic and porous; good dyeability, risk of fibrillation	Pollution form viscose process; lyocell more ecofriendly (non-toxic solvent)
Synthetic fibre	Polyester (PET)	Polyethylene terephthalate	Strong hydrophobic, thermoplastic	Requires high-temperature dyeing; microplastic pollution
	Nylon (PA)	polyamide	Tough, elastic abrasion-resistant	High energy input; greenhouse gas emissions
Comparative composition Features		Cellulosic: -OH groups; Protein: -COOH, $-NH_2$; Synthetic: C-C, C-C-O,-CN bonds	Reactivity depends on functional groups and surface morphology	Governs fibre-chemical interactions, dye affinity, and sustainability impact

but environmental concerns form greenhouse gases. Acrylic mimics wool but requires hazardous solvents. Polypropylene is lightweight and inert, challenging to dye [19].

2.4 Composition and Surface

Cellulosic Fibres have hydroxyl groups for chemical reactions but risk damage under harsh conditions. Protein fibres are pH-sensitive; synthetics are inert but can be modified chemically. Surface treatments improve dyeability, morphology influences chemical, penetration, with natural Fibres being more irregular and synthetic Fibres smoother [20].

2.5 Environmental Impact

Each fibre type influences processing resource use and waste. Natural Fibres need water, alkali, and oxidants, generating wastewater, protein Fibres produce hazardous by products synthetics demand high energy and shed microplastics. Regenerated Fibres pose hazards form chemicals used in production. Understanding these aspects helps develop sustainable processing strategies and reduce ecological footprints [21].

3. Conventional Chemical Processing

Chemical processing of textiles involves preparatory, colouration, and finishing stages each using water, chemicals, and energy, impacting the environmental through pollution, resource depletion, and effluents. Processes like scouring remove impurities with alkali, producing effluents that can pollute water. Alternatives like enzymatic scouring are limited commercially. Bleaching improves whiteness using chemicals like hydrogen peroxide, but creates toxic residues and energy use. Mercerization treats cellulose Fibres for better properties, demanding large water volumes and complex waste treatment [22]. Dyeing the most chemical-intensive stage, uses dyes, salts and auxiliaries, incomplete fixation causes water contamination. New methods like waterless dyeing exist but face cost barriers [23]. Printing uses dyes and solvents, emitting VOCS and waste; digital printing reduces environmental impact. Finishing adds functional traits with chemicals like PFCs, which are persistent pollutants, though eco-friendly methods are emerging. These processes result in high water and energy use and toxic waste, highlighting the need for sustainable practices, green chemistry and closed-loop systems to lessen environmental impact [24].

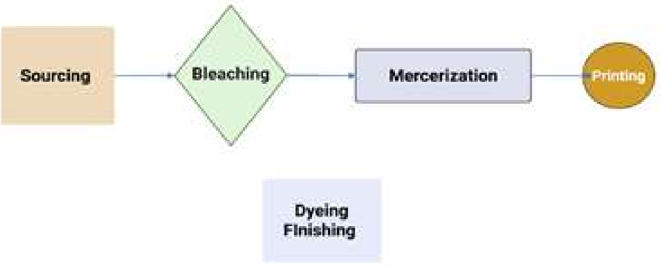

Figure 1: Conventional Chemical Processing

4. Environmental Impacts

Processing textiles exerts significant environmental pressure through resources use and hazardous waste, affecting ecosystems and climate change. Each stage-from fibre prep to finishing-contributes to pollution via effluents, air emissions and residues. These pollutants harm aquatic life, soil quality, and contribute to climate issues [25].

4.1 Water consumption and effluent

The textile industry uses 200-250 Liters of water per kg of fabric, producing effluents rich in dyes, salts, metals, and chemicals that challenge wastewater treatment and harm aquatic ecosystems [26].

4.2 Chemical Toxicity and Bioaccumulation

Effluents contain toxic substances like azo dye, formaldehyde resins, chlorinated agents, and heavy metals that bioaccumulate and pose health risks, including mutagens and carcinogens [27].

4.3 Energy Use and Emissions

Wet processing is energy-heavy, producing 1.2 billion tonnes of CO_2 annually, driven by fossil fuels. Improving energy recovery and adopting renewable energy can reduce impact [28].

4.4 Microfibre and Waste Pollution

Synthetic Fibres release microplastics that contaminate oceans and carry toxins, while sludge and chemical residues from treatment create waste disposal issues [29].

4.5 Air Pollutants and VOCs

Thermal treatments and coating emit VOCs like toluene and formaldehyde, causing smog and health risks. Combustion releases gases that degrade air quality. Understanding these pollutants guides eco-friendly processing [30].

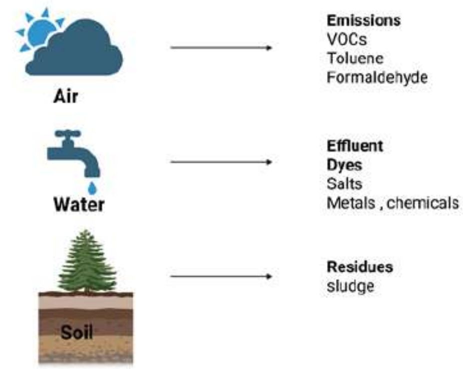

Figure 2: Environmental Impacts

5. Fibre-Specific Impacts

The environmental footprint varies by fibre type. Cotton, the most used, is resource-intensive, requiring vast water and chemicals, and produces effluents high in alkalinity and TDS. Sustainable practices are needed. Polyester, from petroleum, consumes less water but creates microplastics and has a high carbon footprint due to energy-intensive processing. Wool's scouring produces effluents during rich in organic matter and solids, complicating treatment. Silk releases organic effluents during degumming; natural alternatives are emerging. Blended textiles pose recycling challenges due to heterogeneity, often ending as waste, representing a major sustainability hurdle [31].

6. Sustainable and Green Alternatives

The textile industry is adopting eco-friendly technologies to reduce chemicals, water, and energy use. Enzymatic treatment like pectinase cellulase, and lipase cut chemical needs and wastewater, while enzymatic bleaching lowers hydrogen peroxide use and effluent COD, preserving fibre strength and whiteness [32]. Low-liquor and supercritical CO_2 dyeing cut water and energy consumption, the latter for

Table 2: Major Pollutants Form Textile Chemical Processing, Their Sources, and Associated Ecological and Health Effects

Pollutant Type	Source/Process	Major chemicals	Ecological/Health effects
Water Pollutants	Scouring, bleaching, dyeing	Surfactants, dyes, salts, metals	High COD/BOD, eutrophication, aquatic toxicity
Toxic organics	Dyeing finishing	AZO dyes formaldehyde, phenols	Mutagenicity, bioaccumulation, endocrine disruption
Heavy metals	Mordanting, pigment, printing	Cr, Cu, Ni, Zn	Sediment contamination, food chain transfer
Air emissions	Heat curing, solvent finishing	VOCs, SO_2, NO_x	Smog formation, respiratory irritation
MicroFibre s/solids	Synthetic, fibre washing, ETP sludge	Polyester, nylon sludge, residues	Microplastics pollution solid contamination

polyester and hydrophobic Fibres eliminates water, enabling solvent recovery and near-zero discharge, despite high costs. Bio-based auxiliaries form natural oils and microbes replace harmful chemicals, improving biodegradability. Advance wastewater treatments with nanocomposites and photocatalysts degrade dyes and toxins faster and can recycle water, reducing freshwater use and effluent waste. Using renewable energy and techniques like solar dyeing, microwave heating, and plasma treatments Further lowers the carbon footprint and boosts efficient. These strategies shift the industry toward resources-efficient, pollution-free, regenerative production [33].

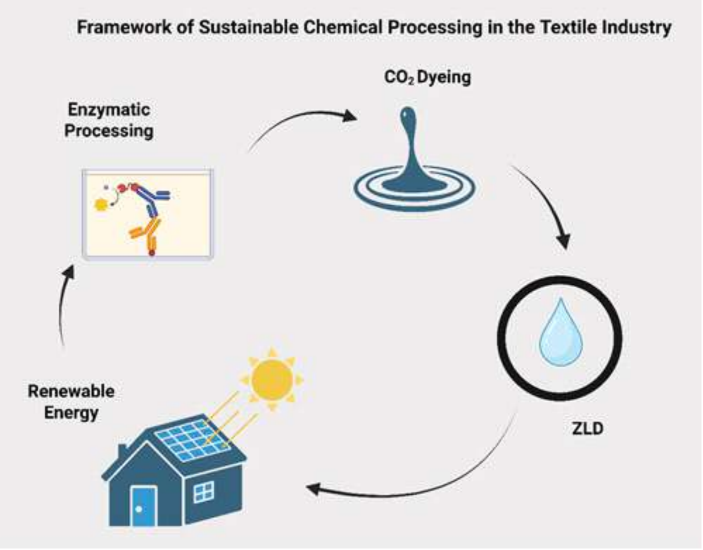

Figure 3: Schematic Illustration of Sustainable Chemical Processing in The Textile Industry

7. Policies, Regulations and Standards

The addressing environmental issues form textile chemical processing through international and national frameworks. The ZDHC initiative sets strict guidelines to eliminate hazardous chemicals, with industry benchmarks like the MRSL and wastewater guidelines promoting safer processes [34]. In the EU, REACH regulates hazardous substances, requiring disclosure of chemical info, while certifications like OEKO_TEX and GOTS ensure textile are free of harmful substances and produced sustainably. National regulations, such as India's CPCB norms for zero-liquid discharge and the Eu's IPPC directive for emission reduction, complement these efforts. Voluntary initiatives like Higg index and ISO 141001 further advance sustainability. These measures collectively foster responsible chemical management, resource conservation, and cleaner production, aligning with UN SDGs [35].

8. Future Perspectives

There are tremendous advancements in the implementation of radical-evasive green chemistry within the textile chemical processing industry. This implementation focuses on emphasizing the minimization of toxic chemical use, maximization of efficient use of resources, and renewal of inputs. Recent advances of green chemistry in wet processing within the textile industry include the use of enzymes and eco-friendly substitutes in replacement of traditional alkalis, acids, and oxidants. This advancement aids in the reduction of energy and water use [36]. Biocatalytic scouring, laccase or peroxidase enzyme-mediated bleaching, and natural dye mordanting are remarkable advances in using green chemistry. The use of ionic liquids, eutectic solvents, and microwave-assisted methods are advances that improve the selective use of chemicals and decrease the potential for polluted wastewater [37]. Biodegradable and biosustainable green chemistry aids in the reduction of textile waste through circular design and fibre recycling textile waste recovery methods like polyester depolymerisation and enzymatic hydrolysis of cotton. The integration of hybrid recycling systems aids in achieving circularity and reducing waste pollution. The replacement of chemically modified textiles with self-cleaning and wastewater treatment modified textiles is an advancement. Compliance with the principles of green chemistry is enhanced with the use of biosurfactants and plant softeners. The application of smart sensors, digital twins, and machine-learning algorithms within AI and Industry 4.0 systems aids in the real-time monitoring and reduction of discharges. These systems are engineered to optimise systems and reduce energetic requirements. The efficiency and preciseness with which data-driven models enhance predictive maintenance, liquor ratios, and dye uptake is improving the eco-friendly manufacturing process [38]. In unison with the decline of ecological impacts and the rise of global competitiveness sustainable textile manufacturing, the convergence of green chemistry, circular economy, and digital innovation is unprecedented.

On top of all that, the use of clean technologies, textile processing is now sustainable and with low environmental footprints. Ozonation, supercritical CO_2 dyeing, ultrasonic-assisted treatment, and enzymatic desizing are low impact processes that use far less chemicals and reduce the use of water, alkali, and surfactants. New and sustainable techniques such as plasma-based surface modifications, photocatalytic oxidation, and MBRs are energy efficient with waste water and provide finishing. The techniques lower the formation of sludge, enhance process selectivity, and allow the recovery of resources for reuse, improving closed-loop sustainability. As much as process automation is integral to optimizing the use of chemicals, so is digital process control and predictive maintenance. AI-driven feedback systems and smart sensors are the apex of real time monitoring of temperature, pH, and other effluent qualities. Waste minimization, efficiency stabilization, and the elimination of human error in processes of Industry 4.0 are improvements to processes that are automation. Predictive maintenance and resource management are other attributes Industry 4.0 improvements provide.The application of zero liquid discharge (ZLD), water and chemical recycling, and waste valorisation into pigments or regenerated fibres as the last sustainable techniques of the circular economy guarantees lasting compliance for the eco-friendly requirements. The holistic design also incorporates solar-assisted dryers and biogas heating units as renewable energy systems, contributing to a lowered carbon footprint. These systems, in synergy with the predominant automated and circular techniques, form a robust and eco-friendly textile ecosystem that mitigates the adverse impacts of textile production on the environment and allows the sector to stand as an exemplary sustainable model for industrial innovation to the rest of the economy [39].

9. Life Cycle Assessment (LCA) and Environment Metrics

Life Cycle Assessment (LCA) measures environment effects of textile manufacturing from raw materials to disposal. It considers energy, emissions, water, toxicity, and waste at all stages-Fibres creation, spinning, weaving, dyeing, finishing, use and disposal. LCAs help improve sustainability by identifying key stages and comparing materials or technologies. For natural Fibres like cotton and wool, agriculture and wet processing mainly impact the environment due to irrigation, pesticides, and wastewater. Synthetic Fibres like polyester and nylon have the greatest impact during polymer synthesis and extrusion, driven by fossil fuels, high-temperature polymerization, and greenhouse gases [39]. Recent studies show bio-based polymers such as PLA and PHA, or regenerated cellulose like lyocell, can reduce global warming and chemical toxicity, though they may use more energy in some stages. The LCA framework supports eco-design, process improvements, and circular manufacturing, ensuring credible sustainability claims.

10. Comparative Assessment: Naturals vs. Manufacturing Fibres

Natural and synthetic Fibres differ in environmental impact, chemical makeup, and processing Table 3 [40]. Natural Fibres like cotton, jute, wool and silk come from renewable, biodegradable sources, but their cultivation needs large water, fertilizer, and pesticide use, producing wastewater with high chemical demand. Wool and silk processing also result in organic pollutants. Manufactured Fibres includes synthetic (like polyester, nylon) from petrochemicals, which are strong but non-biodegradable and release microplastics, and regenerated once like viscose and lyocell. Viscose uses hazardous chemicals, while lyocell is eco-friendlier with a closed -loop process. Synthetic Fibres consume more energy but are durable and recyclable. Nature Fibres are biodegradable but require more land, water and chemicals. Sustainable production combines strategies like bio-based polymers, closed-loop processes, enzymatic scouring, and eco-friendly dyeing, balancing eco-friendliness and performance [41].

11. Carbon Footprint Analysis

The carbon footprint reflects the total greenhouse gas (GHG) emission, measured as CO_2, equivalents, associated with textile manufacturing. Major sources include energy use during spinning and chemical processing, raw materials derived from fossil fuels, and transportation [42]. Typically, producing 1kg of cotton fabric results in 15-20kg CO_2-eq emissions, mainly from irrigation, fertilizer production, and thermal energy used in dyeing and finishing processes. In contrast, polyester fabric generates around 9-12 kg CO_2-eq, with over 70% of emission originating from polymer synthesis. Wool carries a higher footprint of 30-35kg CO_2 -eq per kilogram of Fibre due to methane emission from sheep. Regenerated Fibres like lyocell and modal generally have lower footprints (~6-8 kg CO_2-eq/kg), especially when made using solvent recovery system. Implementing renewable energy, heat recovery, and low-temperature dyeing can reduce emissions by up to 40%. Digital and CO_2- based waterless dyeing method also substantially cut energy consumption and emission. Incorporating carbon accounting into lifecycle assessments (LCAs) and adopting carbon-neutral certification schemes help textile producer's better tract and reduce their climate impact [43].

12. Water Consumption and Scarcity Concerns

Water is essential in textile manufacturing, used notably in pre-treatment, dyeing and finishing stages. The water footprint encompasses both direct process water and indirect water from Fibre cultivation. Cotton textiles are the most water- intensive, consuming approximately 7000-10,000 litres per kilogram of Fibre, primarily due to irrigation and wet processing rinsing. Conversely synthetic Fibres like

Table 3: Comparative Characteristics of Natural and Manufactured Fibre s

Fibre Category	Examples	Primary Composition	Key Advantages	Environmental Concerns
Natural Fibres	Cotton, Jute, Wool, Silk	Cellulose(Plant) Proteins(animal)	Renewable, biodegradable, good comfort and dye affinity	High water and chemical use; pesticide application; effluent toxicity from scouring /bleaching
Regenerated Fibres	Viscose, modal, lyocell	Chemically modified cellulose	Soft texture, good dyeability, renewable origin	Use of toxic solvents (viscose); energy-intensive production; solvent recovery issues
Synthetic Fibres	Polyester (PET), Nylon(PA)	Petrochemical polymers(C-C, C-O,C-N bonds)	High strength, durability, wrinkle resistance, low cost	Derived from fossil fuels; non – biodegradable; micro plastic release; high energy input

polyester and nylon require minimal direct process water but rely on high-energy water systems for cooling and steam, creating indirect water footprints. Regenerated cellulose Fibres such as viscose and lyocell have water use that depends on solvent recovery efficiency. Recent sustainability initiatives include waterless dyeing methods (e.g., supercritical CO_2 dyeing, plasma finishing), membrane filtration, and zero-liquid discharge (ZLD) system for wastewater reuse. Using closed – loop water systems can reduce freshwater consumption by up to 90%, especially in water-scarce textile centres like Tiruppur (India) and Jiangsu(China). Water conservation should be supported by real-time monitoring, green chemistry alternatives, and digital controls to ensure water use aligns with the UN SDG 6- clean and sanitation.

13. Conclusion

Textile chemical processing is vital for properties like whiteness and dyeability but causes environmental harm through water use, chemicals, and energy, leading to pollution and ecosystem damage. Advances in green tech, such as enzymatic and CO_2 dyeing, bio-based auxiliaries, nanotech, filtration, and zero-liquid discharge, aim to recue impacts. Renewable energy and process upgrades support carbon-neutral goals. Challenges include scalable, cost-effective methods, nanomaterial safety, fibre recycling, and supply-chain transparency. Collaboration among academia, industry, and policymakers is crucial to develop standards and eco-labels for sustainable transformation.

Acknowledgements

The authors gratefully acknowledge the management of PSG College of Arts& Science (PSG CAS) and the Department of Costume Design and Fashion, PSG CAS, Coimbatore, India, for their support.

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Journal of the TEXTILE Association ISSN 0368-4636

Development of Nonwoven Insulation Material using Hemp Fibre

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Abstract:
The increasing demand for sustainable and non-toxic insulation materials has emphasized the limitations of conventional glass wool, which is associated with skin irritation, respiratory issues, and environmental concerns. This study investigates the development of hemp Fibre -based thermal insulation as an eco-friendly and safer alternative. Hemp, being a renewable and biodegradable resource, provides excellent thermal insulation, breathability, moisture resistance, and non-toxicity. In this research, two types of nonwoven fabrics were prepared: a needle-punched nonwoven using 100% hemp fiber and a thermally bonded nonwoven using a hemp/polyester fiber blend. The study focuses on optimizing fiber treatment, exploring suitable nonwoven binding techniques, and evaluating the thermal and physical properties of both fabrics. The outcomes are expected to support sustainable construction practices by minimizing dependence on synthetic insulation and fostering the development of greener, healthier building materials. Results implies pure hemp offers better eco-friendliness, biodegradability, and compact insulation and the blend delivering enhanced flexibility, recovery, and air circulation, with reduced sustainability.

Keywords: *Biodegradable, Eco-friendly, Hemp Fiber, Sustainability, Thermal Insulation*

Citation: Manjunath Burji, Satish Aparaj, "Development of Nonwoven Insulation Material using Hemp Fibre", *Journal of the Textile Association*, **86/3**(Sept-Oct'25), 390-394, https://doi.org/10.63665/jta.v86i4.11

Article History : Received : 15-10-2025, Revised: 04-12-2025, Accepted: 08-12-2025

1. Introduction

The building and construction sector is one of the largest consumers of energy and materials globally, and insulation materials are central to reducing heating/cooling loads and associated greenhouse gas emissions. Conventional insulation materials such as glass wool, mineral wool, and polystyrene have been widely used, but they pose several challenges: skin and respiratory irritation, potential toxicity, non-biodegradability, and substantial embodied carbon [1]. These concerns have spurred research into natural, sustainable, and non-toxic insulation alternatives.

Among natural fibres, hemp (Cannabis sativa L.) has emerged as a promising candidate owing to its favourable thermal, hygrothermal, mechanical, and environmental properties [2]. Hemp fibre is renewable, fast-growing, biodegradable, and able to sequester carbon during growth. Its intrinsic structure with hollow or porous elements provides thermal and acoustic insulating potential, along with good moisture regulation [3].

Several studies have quantified the thermal performance of hemp-based materials. For example, loose bulk mixtures of hemp fibre and hurd show thermal conductivity values in the range 0.055–0.065 W/m·K, depending on bulk density and composition [4]. These values are higher (i.e., worse) than some conventional insulations like glass wool or polystyrene, but by increasing thickness or optimizing fibre-to-hurd ratio, equivalent thermal resistance (R-values) can be achieved [5].

Hemp shiv based composites (where "shiv" refers to the woody inner core) have also shown promise: composites with low density (~175–240 kg/m³) and matrices such as starch or silica achieved thermal conductivities around 0.05–0.058 W/m·K, while also exhibiting good mechanical strength and enhanced moisture buffering [6]. Similarly, measurements on raw hemp shives in low density ranges (~109–124 kg/m³) yielded thermal conductivities of ≈0.049–0.052 W/(m·K) [7].

Another approach is using hemp fibre in more composite or panel formats. For instance, gypsum panels reinforced with hemp fibres demonstrate reduced thermal conductivity with increasing fibre content, along with acceptable mechanical properties for use in building insulation [8]. Also, formulations combining hemp with sheep's wool show that thermal conductivity can be lowered (e.g. ~0.033–0.044 W/(m·K)) while still maintaining strength and reasonably low water absorption [9].

However, there are challenges. Hemp fibres are hydrophilic and thus absorb moisture; increased moisture content can degrade thermal insulation performance and durability. Air permeability and the potential for air filtration through the insulating layer pose further issues, especially for loose-fill forms [1, 10]. Variability in raw material (fiber diameter, hurd proportion, density) also causes performance inconsistency [2].

Another consideration is binding and composite formation (nonwoven, bonded, or in matrices) and treatments for moisture resistance, fire retardancy, and long-term stability. The choice of binder or bonding method (mechanical, thermal, chemical) can influence thermal and physical properties [6].

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2. Material and Methods

2.1 Material

For the production of nonwoven fabric, the hemp fibre was initially sourced from Weaving Wibes, Mumbai & Polyester fibre from PSG InduTech CoE, Coimbatore. Prior to manufacturing, the fiber properties were thoroughly tested to ensure compliance with quality standards. The table below presents the list of tests conducted, the respective testing standards, and the obtained results.

Table 1: Details of Hemp fibre

Parameter	Testing Machine	ASTM Standard	Results
Fibre Length	Grease Plate Method	D1447	81.53 mm
Fibre Strength	Instron 5565	D5034	243.71 grams
Elongation	Instron 5565	D5034	0.36 %
Moisture Content	Shirley Moisture Meter	D2496	4.32 %
Fibre Diameter	Microscope	D2130	49.47 micrometer

Table 2: Details of Polyester fibre

Parameter	Testing Machine	ASTM Standard	Results
Fibre Length	Grease Plate Method	D1447	51 mm
Fibre Denier	Cut and Weighing	D1577	2 Denier

2.2 Methodology

- **100% Hemp Needle Punched Nonwoven Manufacturing**

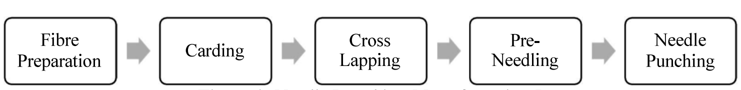


Figure 1: Needle Punching Manufacturing Process

The production of 100% hemp needle-punched nonwoven fabric (250 GSM) involves key steps, including fiber preparation, web formation, and mechanical bonding using a Dilo sample needle punching machine.

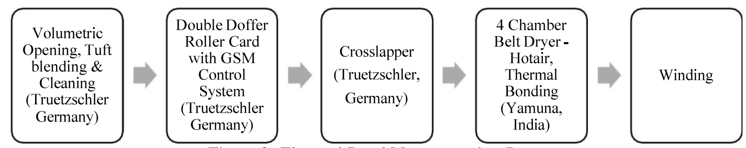
- **Hemp/Polyester Thermal Bonded Nonwoven Manufacturing**

Fibers in the required proportions are mixed, opened, and fed into the carding machine to produce a double web using a double doffer system. Both webs are collected at the machine's dead stock on a conveyor and then fed into a cross lapper, where the web is layered to achieve the desired GSM of the fabric.

The laid web is then processed using a heat flow meter machine, where controlled heat is applied to facilitate the bonding of low-melt fibers with recycled polyester fibers. This process ensures uniform adhesion, strength, and durability of the thermal-bonded nonwoven fabric. The final fabric, with a GSM of 180, is composed of hemp, polyester fiber, and low-melt fiber with a melting point of 120°C.

Table 3: Blend Proportion for Thermal Bonding

Material	Proportion
Hemp	50 %
Polyester	30 %
Low Melt Polyester	20 %



Fi ure 2: Thermal Bond Manu acturin Process

Products

Figure 3: Needle Punched Nonwoven & Hemp/Polyester Thermal Bonded Nonwoven

2.3 Testing

Testing of Nonwoven fabrics is carried out using following standards.

- Tensile Strength: ASTM D5034
- Elongation: ASTM D5034
- Density: ASTM D4052
- Thickness: ASTM D1777
- Air Permeability: ASTM D737
- Thermal Conductivity: ASTM D518
- Water Retention: ASTM D7365
- GSM (Grams per Sq. Meter): ASTM D3776
- Compressibility: ASTM D5729
- Compressional Recovery: ASTM D5729

3. Result & Discussion

The physical, mechanical, and thermal properties of two nonwoven samples 100% hemp needle-punched and hemp/polyester thermal-bonded were evaluated. The results reveal distinct performance characteristics influenced by fiber composition and bonding technique.

Table 4 - Physical and thermal properties of Nonwoven fabrics

Parameter	100% Hemp Needle Punched	Hemp\Polyester Thermal Bonded
Tensile Strength (MD) (N)	17.31	15.41
Elongation (MD) (mm)	103.8	52.8
Tensile Strength (CD) (N)	24.65	26.62
Elongation (CD) (mm)	63.9	50.5
Density (Kg/m^3)	98.98	12.09
Thickness (mm)	2.647	14.2
Air Permeability (cm^3/cm^2/sec)	134	230
Thermal Conductivity (W/mK)	0.04717	0.04892
Water Retention (%)	138.60	193.69
GSM (g/m^2)	257.34	180.13
Compressibility %	66.11	50.00
Compressional Recovery %	32.45	80.00

3.1 Effect on Tensile Strength

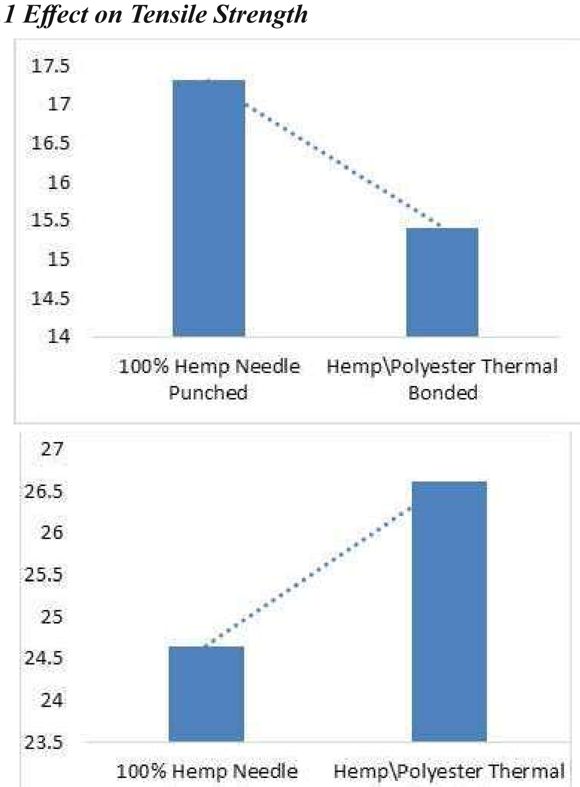


Figure 4: Effect on Tensile Strength (MD & CD)

*I*n the machine direction (MD), the 100% hemp nonwoven exhibited higher tensile strength (17.31 N) than the hemp/polyester blend (15.41 N). This indicates that pure hemp fibers, being naturally strong and stiff, can bear greater loads along the fiber orientation. Conversely, in the cross direction (CD), the blend (26.62 N) surpassed 100% hemp (24.65 N). The inclusion of polyester likely enhanced fiber entanglement, improving crosswise load distribution and flexibility.

These results suggest that needle-punched pure hemp offers superior directional strength, while polyester blending enhances isotropic strength.

3.2 Effect on Elongation

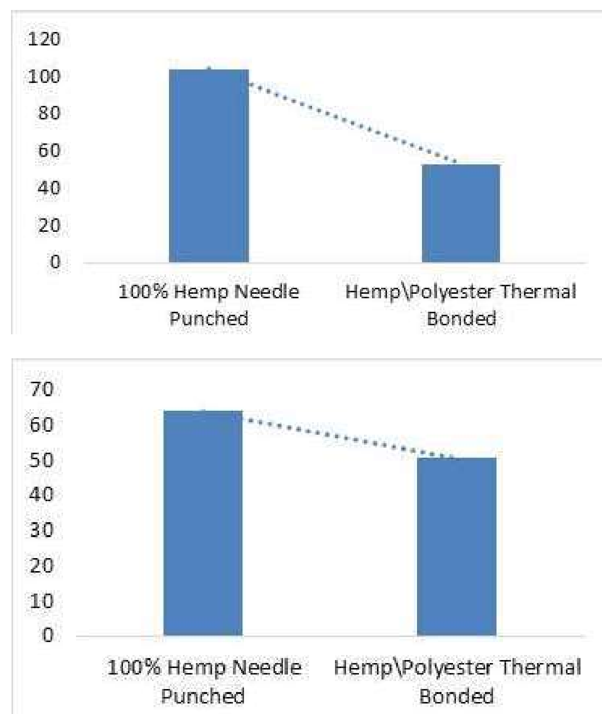


Figure 5: Effect on elongation (MD & CD)

The elongation at break in MD was significantly higher for 100% hemp (103.8 mm) than for the blend (52.8 mm), implying greater stretchability and ductility in the needle-punched structure. In CD, the blend (50.5 mm) showed reduced elongation compared to pure hemp (63.9 mm). The synthetic polyester fibers, although elastic, contribute to a stiffer bonded structure, thereby limiting overall deformation.

Hence, pure hemp fabric demonstrates better flexibility, while thermal bonding limits extensibility.

3.3 Effect on Density and Thickness

The density of the hemp sample (98.98 kg/m^3) was much higher than that of the blend (12.09 kg/m^3). This lower density in the thermal-bonded sample is attributed to the bulky nature of polyester fibers and the presence of low-melt

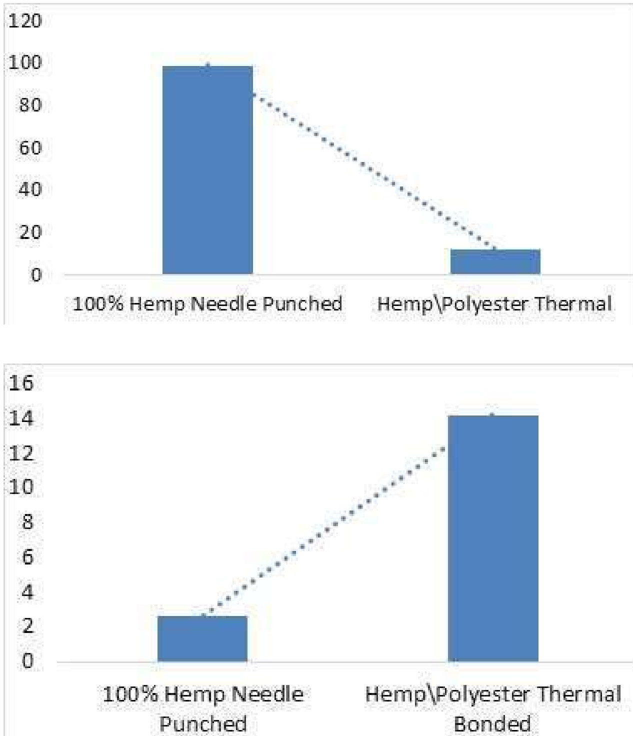


Figure 6: Effect on density and thickness

bonding fibers that introduce voids during heating. Conversely, the thickness of the blend (14.2 mm) exceeded that of 100% hemp (2.647 mm). This thickness increase contributes to higher loft, potentially beneficial for insulation, but the lower density can reduce overall compactness and mechanical stability.

3.4 Effect on Air Permeability

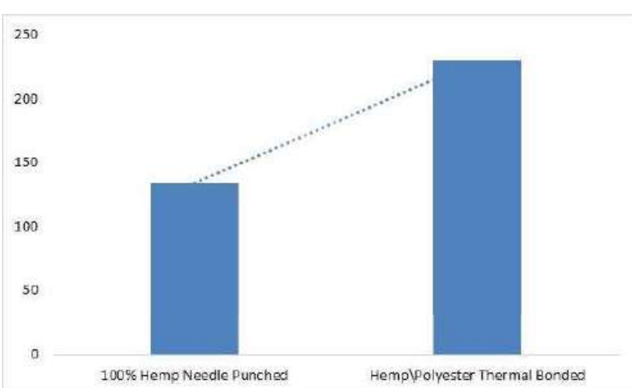


Figure 7: Effect on air permeability

Air permeability was greater in the blended sample (230 $cm^3/cm^2/s$) compared to 100% hemp (134 $cm^3/cm^2/s$). The more open fiber structure of polyester fibers facilitates airflow, while the denser hemp fabric restricts it. Controlled air permeability is desirable in insulation to balance breathability and thermal retention. Thus, while the blend supports ventilation, the pure hemp structure is better for minimizing convective heat loss.

3.5 Effect on Thermal Conductivity

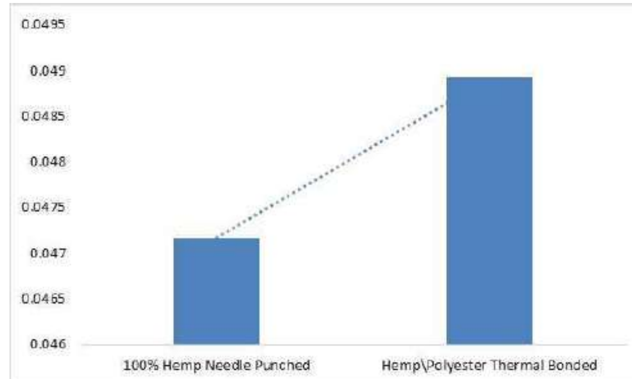


Figure 8: Effect on thermal conductivity

Both samples exhibited comparable thermal conductivity, with values of 0.04717 W/m·K (hemp) and 0.04892 W/m·K (blend). The small variation suggests that the inclusion of polyester did not significantly affect the insulation efficiency. These values are within the range reported for natural-fiber-based insulation materials [4–6]. Therefore, hemp fibers alone or blended demonstrate competitive thermal resistance compared to conventional glass wool or synthetic insulators.

3.6 Effect on Water Retention

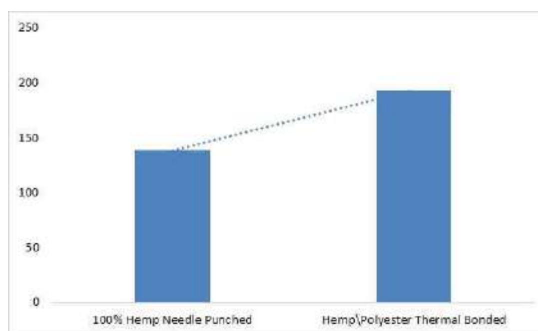


Figure 9: Effect on water retention %

The hemp/polyester blend displayed higher water retention (193.69%) than pure hemp (138.60%). This may result from the open, thicker structure of the blend that traps more moisture. However, excessive water absorption can compromise insulation performance, making moisture resistance treatment important for practical applications.

3.7 Effect on Fabric Mass (GSM)

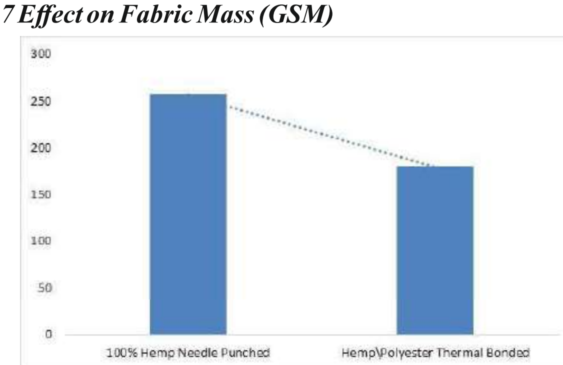


Figure 10: Effect on GSM

The GSM of 100% hemp (257.34 g/m²) exceeded that of the blend (180.13 g/m²). This indicates that needle-punched hemp forms a denser, heavier fabric, which enhances insulation capacity but may increase material usage. The lighter blend offers weight reduction at the cost of compactness.

3.8 Effect on Compressional Behavior

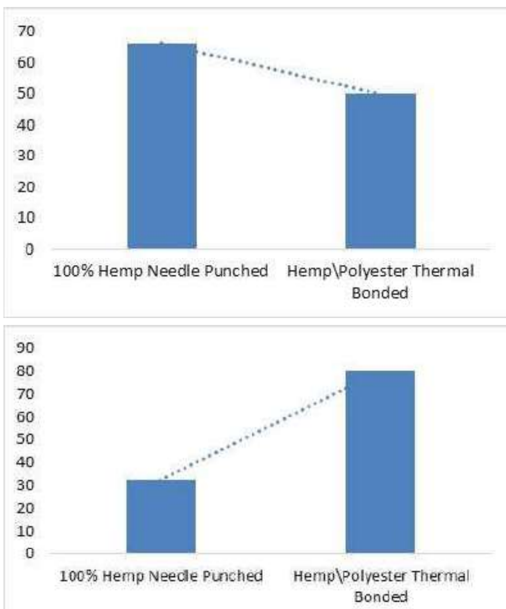


Figure 11: Compressibility % and Compressional recovery%

The compressional test results (Table 4.2) showed that 100% hemp had higher compressibility (66.11%) but lower compressional recovery (32.45%). Its natural hollow structure allows easy compression but limits rebound. The blend exhibited lower compressibility (50%) but superior recovery (80%), owing to polyester's elastic resilience. Thus, pure hemp is suitable for static insulation applications, while the blend may perform better under repeated loading or mechanical stress.

4. Conclusion

The comparative analysis indicates that 100% hemp needle-punched nonwoven provides better density, compactness, and heat retention, making it a strong candidate for sustainable thermal insulation. The hemp/polyester thermal-bonded fabric, while lighter and thicker, shows improved resilience and permeability, which may suit lightweight or breathable insulation needs. In short, pure hemp offers better eco-friendliness, biodegradability, and compact insulation. The blend delivers enhanced flexibility, recovery, and air circulation, albeit with reduced sustainability.

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Journal of the TEXTILE Association

ISSN 0368-4636

Development of Polyester and Cotton Fibres Reinforced Composite by using Wastes from Apparel Industry

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Abstract:

Background: *The apparel industry generates significant amounts of cut waste (10-30% of fabric), which is often used for low value applications. This study aims to develop a sustainable alternative to traditional wood-based materials by creating high-performance composite panels using recycled polyester, cotton, and blended fibers from garment cut wastes.*

Methods: *Composite materials were fabricated using a high-volume, high-pressure compression moulding process. Recycled polyester, cotton, and polyester/cotton blend fibers were used as reinforcement, either as loose fibers or as needle-punched nonwoven fabrics. These were combined with various matrices, including epoxy resin, kaolinite, and polypropylene sheets, at different reinforcement-to-matrix ratios. The resulting composites were evaluated for their thickness, mass per unit area, tensile strength, flexural strength, and impact strength according to ASTM standards.*

Results: *The mechanical properties of the composites were significantly influenced by the fiber and matrix composition. Samples with a 50/50% polyester/cotton blend (PC1 and PC2) showed the highest tensile strengths. The cotton fiber-reinforced sample (C2) exhibited the highest flexural strength at 142.53 MPa. For impact strength, the PC1 sample demonstrated the best performance.*

Conclusion: *The findings demonstrate that high-performance composites can be successfully produced from apparel waste fibers. The study confirms that the choice of reinforcement and matrix materials is critical for achieving desired mechanical properties. These composites offer a viable and sustainable alternative to wood-based products, promoting both environmental conservation and efficient waste utilization.*

Keywords: *Cutting waste, Epoxy MT, Kaolinite, Recycled Fibers, Reinforced composite*

Citation: J. Thanikai Vimal, K. Srinivasalu, Taruna Rajpurohit, K. Ramapraba, "Development of Polyester and Cotton Fibres Reinforced Composite by using Wastes from Apparel Industry", *Journal of the Textile Association*, **86/4** (Nov-Dec'25), 395-399, https://doi.org/10.63665/jta.v86i4.16

Article History : Received : 20-09-2025, Revised: 11-10-2025, Accepted: 15-10-2025

1. Introduction

The developments of number of composite materials for domestic and structural objects are being made from natural resources such as wood, clay, and dirt [1]. To respond to these requirements while also limiting natural resource use to benefit the environment, new concepts and practical commodities can be developed using a range of recycling techniques in present days [2]. This is initiative to imperative that we meet the growing demand for eco-friendly products in order to preserve our ecosystem while using the fewest amounts of natural resources possible for future development. In a range of industries, composite constituents are becoming huge demand for low and high performance applications [4]. The average cutting efficiency in the clothes industry ranges from a minimum of 70% to a extreme of 90%, liable to the diverse clothing product styles. As a result, 10 to 30 percent of the fabrics used to make clothing are wasted as garment cut wastes in the apparel sector cutting section [5]. The domestic textile industries mostly use these cut wastes for low performance applications like carpet manufacture and fiber fill. In addition to minimizing the unitization and consumption of various natural resources for the creation of new composite panels, we can improve the efficient exploitation of apparel cut wastes recycled fibers by employing them to develop high performance composite panels. The two unique structural components of composite materials are reinforcement and matrix [6–8]. When several materials are integrated as the reinforcement and matrix, the resulting composite material structure exhibits superior functional qualities compared to its individual components [9–11]. A composite is a material composed of two or more different substances, each with its own physical and chemical properties [12]. For the creation of composites, several new novel materials are favoured for a variety of reasons, including materials that are more cost-effective, lighter, or stronger than traditional composite materials [13]. Composite materials made of recycled natural and synthetic fibers are among the greatest ways to employ recycled fibers for a variety of end uses and applications [14]. These recovered fibers can be produced using waste from the textile manufacturing industry's cut panel products. Naturally occurring and synthetic fibers are already employed as successive reinforcing elements in a wide range of applications, such as structural composites and automotive applications [15]. Fiber-reinforced polymer (FRP) composites are advanced materials created by combining strong fibers like carbon, glass, aramid, or wood with a polymer matrix such as epoxy, polyester, thermosetting plastic, or phenol formaldehyde resins. These

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composites are primarily used in demanding sectors like aerospace, automotive, marine, and construction due to their exceptional performance [16]. This study's main goal is to produce composite materials from clothing cut wastes that can match or replace wood-based structural materials and applications. A crucial need is to decrease the reliance on wood for common commercial products. This includes items like partition boards, doors, furniture, electrical switchboards, and false roofing. By reducing wood consumption, the project aims to conserve natural resources [17]. With a willowing machine, reinforcement fibers can be individually removed from discarded clothing cut wastes. The fibers from the apparel cut waste fabric panels are separated, individualized, and released by the iron spikes inside a sizable drum in willowing machines. To achieve the desired characteristics, these fibers are then bonded with different matrices. These matrices, often referred to as resins, play a vital role in maintaining the correct orientation of the reinforcement throughout the composite's structure. The choice of matrix is as important as the fiber type and arrangement, as it contributes significantly to the overall performance of the finished composite. The link created by the reinforcement fibers and matrices effectively distributes applied loads throughout the entire composite structure while enhancing defence against chemical and external threats [18]. Using various garment cut wastes from cotton and polyester fibres, an attempt has been made to build a composite material in this research.

2. Materials and Methods

2.1. Materials

Recycled Fibers: These fibers are sourced from waste garment cut fabric panels collected from South Indian

Table 1 - Ratio of reinforcement to matrices, fiber components, and sample proportions with sample code

Sr. No.	Sample Name	Identify Code	Reinforcement Ratio	Sample components	Molding Temperature & weight/sq.ft
1	**Sample - I** Reinforcement1: matrices 3.	C1	Cotton fibre 100%	1. Fibre RF-57g (RF-Reinforcement) 2. Kaolinite MT - 35g (MT-Matrice) 3. Epoxy MT - 135 g 4. Hardener - 16g- for better compression	135°C & 243g
2		P1	Polyester fibre 100%		135°C & 243g
3		PC1	Polyester/ Cotton fibre blend 50/50%		135°C & 243g
4	**Sample– II** Reinforcement 1: matrices 3.	C2	Cotton fibre 100%	1. Fibre RF - 131 g 2. Kaolinite MT - 110 g 3. Epoxy MT - 284 g 4. Hardener - 20 g - better compression	135°C & 525 g
5		P2	Polyester fibre 100%		135°C & 525 g
6		PC2	Polyester/ Cotton fibre blend 50/50%		135°C & 525 g
7	**Sample– III** Reinforcement 1: matrices 3. The four matrices layers were organized into three layers of reinforcement	C3	Cotton fibre 100%	1. Fibre RF - Needle punched non-woven fabric-30 g - 3 webs - 12 g/each lay 2. PolyPropylene sheet MT- 350 denier 8 sheets were used as 4 layers (2 sheets per lay)	160°C & 70 g
8		P3	Polyester fibre 100%		160°C & 70 g
9		PC3	Polyester/ Cotton fibre blend 50/50%		160°C &70 g
10	**Sample - IV** Reinforcement 1: matrices 3. The reinforcement's top and bottom were coated with matrices.	C4	Cotton fibre 100%	. Fibre RF - Non-woven fabric (Needle Punched) - 37 g 2. Epoxy MT - 72 g - 2 coatings top and bottom with 37 g/coating 3. Hardener - 4 g – for better compression	135°C &150 g
11		P4	Polyester fibre 100%		135°C & 150 g
12		PC4	Polyester/ Cotton fibre blend 50/50%		135°C & 150 g

**C-Cotton, P-Polyester, PC- Polyester/Cotton, RF-Reinforcement, MT-Matrices* apparel companies. They include:100% polyester,100% cotton, Blends of 50% cotton and 50% polyester. The waste fabric was processed into fibers using a willowing machine. These fibers were then used to create needle-punched nonwoven textiles for reinforcement.

Matrices: The following materials were used to bind the fibers: 1. Epoxy resin: Characterized by a dynamic viscosity of 10797 MPa at 25°C and a glass transition temperature (Tg) of 124.22°C. 2. Kaolinite: A type of clay powder. 3.Polypropylene sheet: With a weight of 120 gsm (grams per square meter) and a thickness of 0.2 mm.

Composite Formulation: The composites were created using 4 different ratios matrices, as detailed in Table 1. Within each ratio, 4 distinct types of composite samples were produced, varying in their reinforcement and matrix compositions and combinations. This approach allows for the investigation of how different recycled fiber types and matrix materials, in various proportions, affect the final properties of the composites

2.2. Methods

The composites in this study were engineered using four distinct reinforcing ratios involving cotton, polyester and cotton/polyester fibers, combined with 3 different matrix materials: epoxy resin, kaolinite, and polypropylene.

Reinforcement Methods: For the I and II sample preparation ratios, recycled fibers were directly incorporated as reinforcements. Conversely, for the III and IV sample preparation ratios, recycled fiber-made needle-punched nonwoven textiles served as the reinforcements. This approach allowed for an investigation into how both the fiber type and the form of reinforcement (loose fibers versus nonwoven textiles) influence the final composite properties. A high volume, high pressure compression moulding equipment was used to make the composites. The reinforcement and matrices were combined and stacked in different ratios, as indicated in Table 1. After that, it was squeezed in the compression moulding machine at the temperature and pressure specified in Table 1 for 50 kg/cm2. After 30 minutes of compression, the compressed composites were removed from the compression moulding machine and allowed to stand at room temperature for 24 hrs.

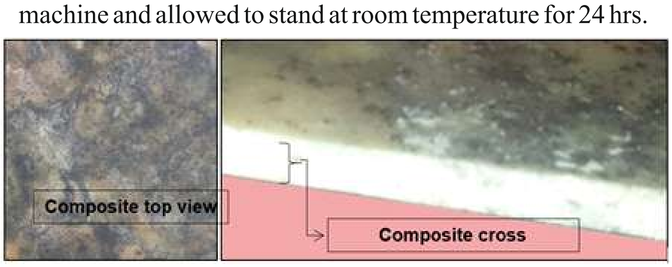

Figure 1 - Recycled fibre reinforced composite Sample

2.3 Evaluation methods

Tensile strength, flexural strength, impact strength, and water absorbency tests were performed on the twelve different produced composite samples that are displayed in Table 1 in order to assess and analyse their technical performance and characteristics. The technical properties of composites are evaluated by looking at their thickness, mass per unit area, tensile strength, and Impact strength and their respective standard methods are shown in table 2. Every sample was prepared with a standard room temperature of 24°C and a RH of 65% prior to testing. For every sample, 5 samples were tested; the results were shown as the mean of those samples.

Table 2 - Type of evaluations and their standards

S. No.	Type of test	Standard
1	Mass per unit area (GSM)	ASTM D3776
2	Thickness (mm)	ASTM D1777
3	Tensile strength (MPa)	ASTM D3039
4	Flexural strength test (MPa)	ASTM D 790
5	Impact strength test (MPa)	ASTM D7136

3. Results and Discussion

3.1 Thickness and Mass per unit area

The mass and thickness of the produced composite samples per half square foot are displayed in Table 3. The results show that the mass and thickness per unit area are always closely related to the reinforcement to matrix ratios. Consequently, the technical properties of composites are greatly influenced by the ratio of reinforcement to matrices.

Table 3 - Composite sample thickness and mass per unit area

Sample Ratio code	Samples	Avg. Thickness in mm	Avg. Weight in g
I	C1	4.5	256.93
	P1	4.8	255.62
	PC1	4.7	254.72
II	C2	6.9	523.26
	P2	6.8	525.31
	PC2	6.9	524.71
III	C3	0.9	69.33
	P3	1.1	69.52
	PC3	1.1	69.49
III	C4	2.5	153.51
	P4	2.4	155.62
	PC4	2.4	153.73

3.2 Tensile Strength

Figure 2 displays the tensile strength of the polyester, cotton, and Polyester/cotton reinforced composite samples. Based on the observation and analysis of these results, the tensile strength of samples PC1 and PC2 in ratios I and II is higher than that of all other samples. The tensile strength of the samples is significantly affected by the improved cohesion and bonding of the epoxy resin and kaolinite matrices with fiber reinforcement, which is primarily responsible for this. Because of the bonding between the synthetic resin and 100% synthetic polyester fiber, the P1 sample exhibits a greater tensile strength when associated to all the samples in the same ratio category ratios I & II. Sample P3 has good tensile strength due to the increased bonding between the polyester fiber and PP sheet. Because the samples C4, P4, and PC4 are composed of needle-punched non-woven fabric for reinforcement and pure epoxy resin as the matrix, their tensile strength is lower than that of the other samples. The reason for this was found to be the needle-punched non-woven reinforcement material; because of its well-packed needle-punched structure, which prevents the epoxy resin from penetrating completely, it results in a moderate bonding between the reinforcement and matrices, while in all other samples, the loose fibers are mixed directly with the matrices.

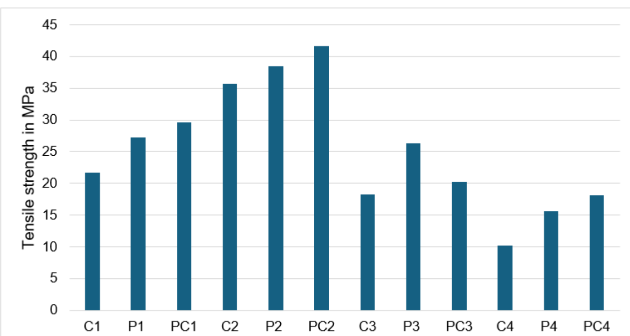

Figure 2 - Tensile strength comparison of blended composites made of polyester, cotton, and polyester/cotton

3.3 Flexural Strength

The flexural strength of composite samples reinforced with polyester, viscose, and polyester/viscose fibers is contrasted in Figure 3. The findings indicate that, in comparison to the other samples, the C2 material offers the greatest value of 142.53 MPa because of its superior blending, larger reinforcement content, and better matrix composition. Because Sample C1 was created with the same materials and composition as Sample C1, it also offers the second-best result of 104.12 MPa among all the samples. These observations suggest that the reinforcement's consistency and attachment with the kaolinite and resin matrices is superior, and these properties have a significant impact on the composite's increased flexural strength.

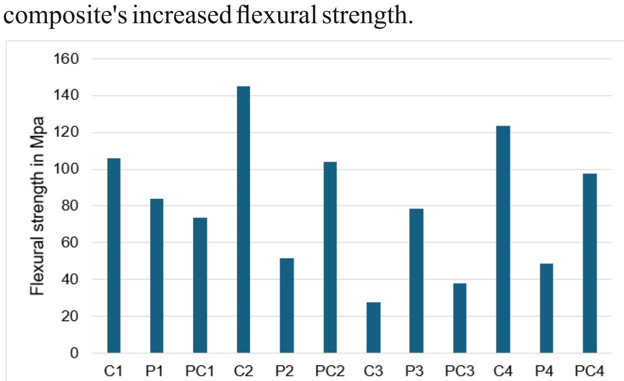

Figure 3 - Flexural Strength comparison of blended composites made of polyester, cotton, and polyester/cotton

3.4 Impact Strength

In comparison to the other samples, the sample PC1, which was created using epoxy and kaolinite as matrices, shows the best impact strength, as indicated by the impact strength data of cotton, polyester, and polyester/cotton as displayed in figure 4. According to analysis, the PC1 structure contains 50% reinforcement made of synthetic polyester fiber, which has a greater crystalline content and aids in better bonding with synthetic epoxy resin to provide better impact strength. The material P3 has a reasonable impact strength, and an efficient bonding between the reinforcement and matrices, two synthetic materials, was found to be present inside its structure.

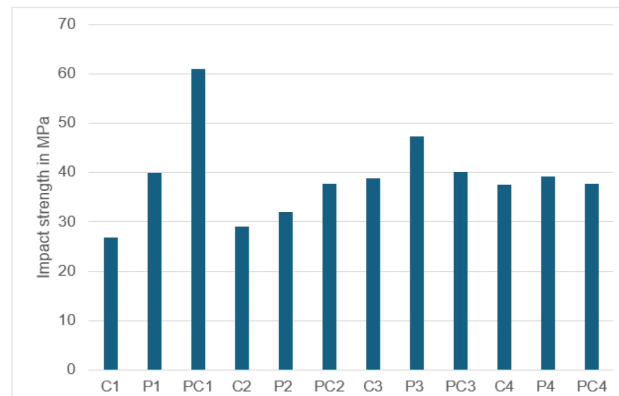

Figure 4 - Impact Strength comparison of blended composites made of polyester, cotton, and polyester/cotton

4. Conclusion

This study demonstrated promising results in terms of both mechanical performance and environmental sustainability. The comprehensive analysis of the composite samples revealed that the technical properties, such as tensile strength, flexural strength, impact strength, and water absorption, are significantly influenced by the type and ratio of reinforcement to matrix materials. According to the experimental data, samples PC1 and PC2 exhibited the highest tensile strengths among all tested combinations, attributed to the improved bonding between the epoxy resin and kaolinite matrices with the fibre reinforcements. In terms of flexural strength, the C2 sample achieved the highest value of 142.53 MPa, followed by C1 with 104.12 MPa, indicating that a higher reinforcement content and optimal matrix composition enhance the composite's structural integrity. For impact strength, the PC1 sample outperformed others, owing to the synergistic effect of polyester/cotton reinforcement and dual matrices. In summary, the study confirms that recycled fibre composites, especially those reinforced with polyester or polyester/cotton blends and paired with suitable matrices, can achieve desirable mechanical properties and moisture resistance. These materials present a sustainable alternative to traditional wood-based products, contributing to natural resource conservation and effective waste utilization in the textile industry.

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From Waste to Wearable: Repairing & Upcycling Uniforms for Circular Fashion

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Abstract:

Background

This case study is centred around a pedagogical initiative, 'From Waste to Wearable: Upcycling Uniforms for Circular Fashion', which was conducted as a three-week elective design course at the world University of Design. The course was introduced to twenty-one fashion design students of third-year. It encouraged them to reflect on sustainability through creative upcycling of discarded uniforms.

Methodology

The program followed a qualitative case study approach organized in three stages: raising awareness, skills building, and final reflection. It addressed theoretical topics related to circular fashion and offered practical workshops in deconstruction, repair, dyeing, appliqué, and structural manipulation. Qualitative information was collected through the form of reflective interviews and project products.

Results

Eight students used wearable prototypes, and 13 participated in achieving their own fashion projects to fulfil degree requirement. Thematic analysis provided key learning outcomes: heightened material consciousness, appreciation of craftsmanship, recognition of storytelling potential of textiles and re-interpreted sustainability concepts. Students reported a perceptual shift, from thinking of sustainability as a design trend, to embracing sustainability as a way of thinking focused on responsibility and creativity, with a long-term value of the garment. Many also demonstrated intentions to use sustainable approaches in future design work and to promote repair and upcycling.

Conclusion

This study shows how experiential and project-based pedagogy can be effectively used to develop an awareness of sustainability in fashion education. By working with discarded uniforms, students were inspired to take circular design practices and critically challenge the prevailing linear 'take-make-dispose' model of clothing production.

Keywords: *Economic stability, K-means clustering, Machine Learning, Quantitative Evaluation, Rural Weavers, Smart Textiles, Textile Technology*

Citation: Ambika Magotra, Vidushi, "From Waste to Wearable: Repairing & Upcycling Uniforms for Circular Fashion", *Journal of the Textile Association*, **86/4** (Nov-Dec'25), 400-405, https://doi.org/10.63665/jta.v86i4.12

Article History : Received :20-09-2025, Revised: 17-11-2025, Accepted: 21-11-2025

1. Introduction

The global fashion industry has become one of the economy's most resource-guzzling and environmentally damaging sectors. Characterized by quick production cycles, overconsumption, and mass waste of textiles, the industry is responsible for almost 10% of global carbon emissions. It creates large volumes of water pollution and landfill accumulation [1]. Fast fashion in particular has accelerated the rhythm of fashion garment production and disposal, resulting in a "take-make-dispose" model, the violation of the principles of ecological sustainability and social responsibility [2]. In the face of these challenges, circular fashion has gained popularity as a framework with a focus on resource efficiency, longevity, reuse and recycling of textiles [3].

Circular fashion rethinks the life cycle of garments through encouraging design processes that use more of the materials and less of the waste. Instead of being considered a disposable, clothing is a resource that can be continually renewed by repair, repurposing, and upcycling [4]. Upcycling is a creative and sustainable approach to reuse discarded textiles into higher-value products while not breaking them down to a raw fibre [5]. This approach has the twin advantage of reducing waste and encouraging innovation and creative expression. Fashion education has a powerful pedagogical tool for inculcating the values of material stewardship as well as critical engagement with sustainability in emergent designers [6].

One of the most significant concerns in the fashion industry is the amount of textile waste produced worldwide, estimated at more than 92 million tons annually [7]. Much of this waste is in landfills or incinerated, adding to environmental degradation and greenhouse gas emissions. Uniforms form a special subset of the textile discards by their symbolic, functional, and standardised character. Institutional uniforms (from schools, hospitals, police, corporations, etc), however, are often produced in volume, replaced regularly, and disposed of systematically [8]. Their rigid aesthetic codes and limited post-use applications usually consign them to waste streams despite the durability and quality of their fabrics.

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Therefore, Upcycling uniforms provides an opportunity to divert textiles away from waste and to play with narrative-led design. Worn uniforms have histories of labor, identity and institutional culture embedded in them, and are rich materials for re-contextualization into garments that speak stories of transformation, dignity and renewal [9]. This narrative dimension lifts upcycling beyond functionality and transforms design into cultural commentary and advocacy for sustainable practices.

Educating the next generation of designers is critical in the shift towards sustainability in the fashion industry. Traditional curricula in fashion studies have sometimes been more focused on aesthetics, technical skills and responsiveness to trends than on environmental and social impact [10]. However, if we make circular design principles into pedagogy, we provide students with the tools to critically analyse consequences of material choices and systems of production. Experiential learning approaches- where students deal directly with scrapped textiles- have created a better understanding and personal commitment to sustainable practice than a purely theoretical approach [11].

Project-based learning is beneficial for sustainability education in design. By having the discarded uniforms as the only material resource, students are challenged to move out of their comfort zones, and to face the constraints of working with pre-existing garments [12]. These limitations assist to be the creative catalysts to foster innovation through deconstruction, repair and material manipulation. Such methods are in line with the "slow fashion" principles that favour craftsmanship, durability and intentionality over mass production and consumption [5]. Repair culture has historically been part of clothing use, through practices such as darning, patching, and visible mending. However, in the age of fast fashion, repair has all too often been stigmatized as a sign of poverty, rather than being known as a sustainable and creative act [13].

Visible mending and exploring with the surface, such as pleating, applique and dyeing, can make flaws a point of interest and infuse garments with new layers of meaning [14]. These methods emphasise beauty and feeling of care that lies in repair, which accords with sustainability discourses that conceptualise clothing as repositories of memory and identity [5]. For students, exposure to such practice promotes a greater understanding of craftsmanship, pulls them from the industrial uniformity and towards personalized and story-rich design.

Beyond environmental benefits, circular fashion solves the pressing social and ethical issues within the global textile supply chain. Conventional garment production is associated with exploited labour conditions,

underpayment and unsafe working conditions, particularly in developing countries [4]. If we shift our focus to reuse, upcycling and repair, then we will see less demand for new production which takes pressure off labour and natural resources. It also enables consumers and designers to be responsible for the lifecycle of garments and promotes a culture of accountability and care [15].

The pedagogical initiative "From Waste to Wearable: Upcycling Uniforms for Circular Fashion" answers directly to the need to introduce circularity in fashion education. By devising a three-week elective course that would focus invariance on the re-use of old uniforms, the initiative put the students in the crossroads between sustainable, creativity and social responsibility. The program was organized in three phases (awareness, skills building, reflection), which ensured that students were intellectually and practically engaged with the problems of circular design.

2. Methodology

2.1 Context and Rationale

This case study presents a pedagogical initiative "From Waste to Wearable: Upcycling Uniforms for Circular Fashion" that was conducted as an elective design course in the World University of Design. The course was organized as a three-week modular course, which was conducted from 8th November 2024 to 29th November 2024 as a target group for fashion design students in the third year. With a total of 21 participants, the course focused on the institutional transformation of the fashion education system towards more sustainable practices using hands-on projects (upcycling) with discarded institutional uniforms.

The ultimate aim was to stimulate a better knowledge of circularity in the fashion industry, textile waste minimisation and ethical material management through experiential learning. By working through examples of repurposed garments - in this case damaged uniforms - the course focused on the narrative potential of worn textiles and challenged the linear 'take-make-dispose' approach common in the fashion industry.

2.2 Pedagogical Approach

The course used a project-based, interdisciplinary approach combining theoretical discourse with practical application. It started with a foundation session where the students were introduced to the principles of sustainable fashion through a curated set of video presentations, case studies and discussions on global challenges of textile waste. Key concepts such as slow fashion, circular design, repair culture and material storytelling were explored to develop awareness and context.

A central theme was created: "Designing with reclaimed clothing, not virgin materials." This directive acted as a guiding principle throughout the project and encouraged students to reconsider the boundaries of design and embrace constraints as creative catalysts.

2.3 Course Structure

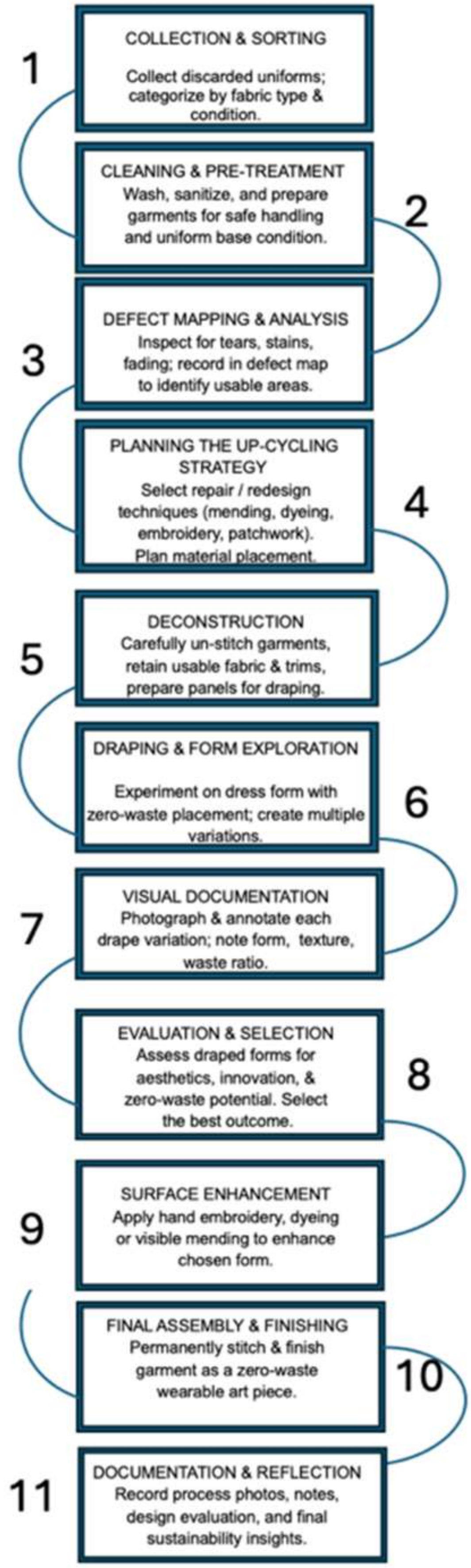
The three-week module was carefully structured into thematic phases to provide students with both conceptual grounding and practical design experience.

Week 1: Awareness and Inspiration opened the eyes of the students to the bigger picture of sustainability in fashion. The sessions started with lectures and discussions on what sustainability means and the urgency of sustainability in the industry. Students worked with visual content, including screenings of documentaries and select work by designers such as Gabriela Hearst, Stella McCartney and Tanya Taylor, whose practices focus on responsible design and circularity. These screenings were followed by group conversations about textile waste and the systems of uniform production, to encourage students to think critically about the life of garments. Towards the end of the week, students were given something they had never seen before: pre-collected discarded uniforms - such as school, college, hospital and police uniforms - that would serve as their primary material for exploration and creative experimentation.

Figure 1 - Stained discarded uniforms

Figure 2 - The ideation process to explore surface and form

Process by Bhavika Sharma



Week 2: Skill Development and Design Exploration (16-22 November) took the focus off awareness and began to get more hands-on. Through workshops, students were introduced to a range of techniques including deconstruction, patchwork, visible mending, dyeing, applique and structural manipulation. These methods were taught, not only as repair tools but as creative ways to prolong the functional and aesthetic life of garments. With these skills, students began sketching and prototyping design, finding inspiration in the history of the material, its texture and form. This stage encouraged them to balance the principles of sustainability with their own creativity and reimagining the discarded uniforms into pieces that had a new purpose and value.

Week 3: Finalization and Reflection (23-29 November) was the culmination of the module. Students completed their wearable pieces, combining the technical and conceptual knowledge they had been learning over the past weeks. The work in progress was openly shared during peer critique sessions which offered chances for constructive feedback and dialogue between participants. To conclude, individual reflective interviews were carried out with all 21 students. These conversations enabled them to express their own experiences, insights, and developing understandings of sustainability in fashion supporting the focus of the module on critical reflection alongside design practice.

Figure 3 - Creative outcomes

Garment Outcomes by Bhavika Sharma, Gauri Rauthan, Shradha

2.3 Data Collection and Analysis

In order to assess the effect of the course, qualitative data was gathered using open-ended reflective questions delivered to all 21 students after the final presentation. These questions were aimed to capture changes in mindset, design philosophy, and engagement with sustainability. Eight students actively participated in the upcycling project and completed full prototypes; the rest twenty-one participated in discussions and partially completed work but no garments. Responses were analysed thematically and key ideas relating to material consciousness, aesthetic appreciation of handwork, and emotional connection to reworked textiles were identified. Significantly, the eight students who completed the project offered more detailed reflections, suggesting deeper engagement with the course's key goals.

3. Results and Discussion

Student Engagement and Perception

Of twenty one students, eight decided to go all out on the upcycling challenge, by making wearable garments out of discarded uniforms. The remaining thirteen showed interest in the concept, but opted-out because of time constraints or hesitancy to work with non-traditional materials. This divergence speaks to the resistance to change at the beginning, as well as the transformative potential of experiential learning. Students that completed the project said that there was a great shift in their understanding of fashion design. One participant stated:

"The brief of the project was powerful. It pushed me to consider more than just aesthetics and the lifecycle of clothing, and the specific way that I work with discarded uniforms. It leads to a new perspective on sustainability through storytelling." This sentiment was echoed in several responses to suggest that the project did a good job moving students from passive awareness to active participation in sustainable design [16].

Design Intent and Message

Participants conveyed a powerful narrative intent with their designs. A common message was that waste isn't the end - it's a beginning. As one student articulated:

"Through this design I want to communicate that waste is not the end, it's a beginning." Every discarded uniform tells a story and by re-making it into a meaningful drape, the new design tells a story of renewal, dignity and responsibility: both to the planet and the people behind the fabric.

This emphasising of storytelling, dignity and renewal, are signs of a deepening emotional and ethical engagement with the material. Students began to view uniforms not as simple things to be left behind, but as objects with social, cultural and labor histories [17].

3.1 Awareness and Learning Outcomes

While some students had previous knowledge of repair and upcycling, the project gave students a more in-depth, hands-on knowledge. As one student noted:

"Yes, I was familiar with the concept, but this project gave me a deeper, hands-on understanding."

The tactile nature of deconstructing, mending and reconstructing garments enabled students to internalise the complexity of textile lifecycles and the importance of craftsmanship [18]. Many highlighted the beauty and depth of handwork, noting that handmade elements added "a layer of human touch, care, and intention that industrial production often lacks."

Application of Techniques

All eight participating students used handmade techniques in their design projects, showing both creativity and an interest in the work of sustainable practices. Rather than allowing the processes to be machine-based, they experimented with tactile, manual interventions that emphasized the importance of craftsmanship in fashion.

A number of specific uses of these techniques were noted throughout the projects. Some students made use of visible mending on seams and patches, creating intentional design features out of what had been flaws. Others played around with applique, layering contrasting uniform fabrics to add depth and interest to the fabric. Reinforcement stitching was common because it's not only the life of the garments which was extended but it was also used to highlight durability as an aesthetic choice. Additionally, structural manipulations, such as pleating and folding, were implemented to create volume, which changed the silhouette and form of the original garments in inventive ways. Finally, dyeing methods were employed to unify color palettes or create textured effects, all to allow for cohesion while simultaneously reinventing the materials.

Collectively, these handmade interventions made the finished designs more visually attractive and also carried a deeper conceptual message. They strengthened the argument that repair itself can be a design and changed the views of clothing longevity and encouraged students to find value in what could otherwise be scrapped [19].

Definition of Sustainable Fashion

When asked to define sustainable fashion, students constantly stressed intentionality, the reduction of waste and reuse for the future. One response summed up the point:
"Sustainable fashion is about designing with intention, minimizing waste, respecting labor, extending the life of garments, and designing for future reuse. It's a mindset that blends responsibility with creativity to reduce harm and increase positive impact over time."

This mind-set shifts from sustainability being a trend to the sustainability being a way of thinking is a critical result of the course.

3.2 Future Intentions and Advocacy

The majority of students articulated desire to continue with working within sustainable and circular design systems. As one participant stated:

"Absolutely. This project created a greater need to work within sustainable and circular design systems." Many affirmed their willingness to advocate for repair and upcycling among peers and consumers. One student declared:

"Yes, I will. Repair and upcycling are great acts of care - for our clothes, our environment and the people who make it. "I believe in spreading the message that sustainability commences in our wardrobes and that everyone can be a part of the solution, one garment at a time."

3.3 Perceived Impact and Innovation

Students saw the project as innovative, not only in a technological sense but conceptually. One reflected:
"Definitely. Innovation isn't necessarily just about tech, it is also about re-examining what already exists. Turning discarded uniforms into expressive, wearable drapes is emotionally as well as structurally innovative. It redefines fashion by combining utility, history and sustainability."

They realized these kinds of projects might be in conflict with throwaway culture, and get folks to think of clothing as worthwhile as opposed to disposable. It was through such initiatives that they felt broader dialogues about consumption, identity and ethics could begin in reworked materials [20].

4. Conclusion

The "From Waste to Wearable" initiative was able to quite successfully demonstrate the transformative ability of experiential, project-based pedagogy in the embedding of sustainability into fashion education. By working with discarded uniforms themselves, students were able to move beyond abstract conversations to gain first-hand experiences of the challenges and creative opportunities of circular design. The project not only worked on technical skills in repair, deconstruction and material manipulation but built an appreciation of the narratives and histories embedded in garments.

The results underlined that students transformed their view of sustainability from a superficial trend to a deep rooted mindset of responsibility and creativity. Importantly, they acknowledged repair and upcycling as forms of innovation that reposition fashion as a place of care, intentionality and prolonged value. While not all the participants went through prototypes, reflective accounts indicated significant changes in design philosophy, an awareness of materials and a willingness to be advocates for circular practices. Ultimately, this case study is about the power of targeted, immersive interventions in inspiring future designers to embrace sustainable ways as well as being advocates for a systemic change. Integrating such modules in design curricula is essential to equip the next generation for tackling the problem of textile waste to promote cultural and industrial transitions towards a circular fashion.

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Groundnut Shell Extract for Cotton: Assessing Antibacterial Action Against Staphylococcus Aureus

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Abstract:

The search for effective and sustainable antimicrobial finishes has brought attention to agricultural by-products as valuable sources of bioactive compounds. This study examined the antibacterial performance of groundnut shell extracts applied to cotton fabric, focusing on their activity against Staphylococcus aureus, a common skin pathogen. Extracts were prepared through hydrous, ethanolic, and methanolic methods in concentrations ranging from 20% to 60%. The agar diffusion test revealed that the 60% aqueous extract showed the most pronounced inhibition zone of 10 mm. Incorporating citric acid as a crosslinking agent further improved both antimicrobial potency and wash durability. Fabrics treated with the optimized extract retained significant antibacterial activity for up to eight wash cycles. These findings highlight the potential of groundnut shell extracts as a natural, eco-friendly alternative for imparting antimicrobial properties to textiles.

Keywords: *citric acid, cotton fabric, groundnut shells, laundering durability, Natural antimicrobials, Staphylococcus aureus*

Citation: Meena Batham, Shikha Singh, Sonia Chaudhary, "Groundnut Shell Extract for Cotton: Assessing Antibacterial Action Against Staphylococcus Aureus ", *Journal of the Textile Association*, **86/4** (Nov-Dec'25), 406-410, https://doi.org/10.63665/jta.v86i4.9

Article Received :29-10-2025, Revised: 17-11-2025, Accepted: 21-11-2025

1. Introduction

Textile surfaces often serve as breeding grounds for a wide range of microorganisms. These microbes don't just linger harmlessly they can cause stubborn odors, trigger skin irritation, and sometimes even lead to infections. Among them, Staphylococcus aureus stands out as one of the most common and concerning bacteria. It thrives on human skin and is a well-known culprit behind many healthcare-associated infections . While synthetic antimicrobial agents are frequently used to tackle such contamination, there is growing awareness about their environmental impact and the need for safer, more sustainable alternatives. This has sparked increasing interest in plant-based treatments that combine effectiveness with eco-friendliness 3].

One promising and often overlooked resource is the groundnut (peanut) shell, typically discarded as agricultural waste. These shells are surprisingly rich in bioactive compounds such as flavonoids and polyphenols, which have shown considerable antimicrobial properties — . Flavonoids, for instance, are a diverse group of plant metabolites characterized by their basic C6-C3-C6 skeleton, consisting of two aromatic rings connected by a three-carbon bridge. Polyphenols, on the other hand, are known for their multiple phenolic hydroxyl groups attached to aromatic rings, a structural feature that contributes to their antioxidant and antibacterial effects . By repurposing this material, we not only help reduce environmental waste but also create added value within the food production chain.

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Beyond their antimicrobial potential, peanut shells offer a striking example of how everyday waste can be transformed into something useful. Instead of piling up in landfills or being burned practices that often lead to soil degradation and air pollution they can be harnessed as a renewable raw material for functional textiles [6, 7]. This not only benefits human health by limiting microbial growth but also supports broader sustainability goals, giving industries a way to align with circular economy principles where waste becomes a resource rather than a burden [8, 9].

Moreover, the use of peanut shells resonates strongly with consumer preferences that are shifting toward natural and eco-conscious products. People today are more aware of how the choices they make whether it's the clothes they wear or the detergents they use affect both their own well-being and the environment [10, 11]. Introducing textile treatments derived from agricultural by-products provides a story of innovation that connects science, sustainability, and daily life [12, 13]. It's not only about antimicrobial efficiency; it's also about reimagining waste streams and showing that solutions to complex challenges can sometimes be found in the simplest, most familiar materials [14].

In this study, we set out to explore whether extracts derived from groundnut shells could serve as a natural antibacterial finish for cotton fabrics. Additionally, we investigated whether incorporating citric acid as a binding agent could enhance the durability of the antibacterial effect, especially after multiple wash cycles. Through this approach, the research aims to contribute to safer, more sustainable textile treatments that are kinder to both people and the environment.

2. Materials and Methods

2.1 Preparation of Extracts

Groundnut shells were washed thoroughly, sun-dried, and ground into a fine powder. For hydrous extraction, the powder was blended with distilled water at concentrations of 20%, 40%, and 60%. For solvent extractions, ethanol and methanol were used in the same concentrations. Mixtures were stirred and left to extract bioactive compounds, then filtered for further use.

2.2 Fabric Pre-treatment

Plain-woven cotton fabric was desized by soaking in 0.5% sulfuric acid solution at approximately 65 °C for 20 minutes to remove sizing agents. The fabric was then rinsed, neutralized with a dilute soda ash solution, cleansed again, and Oven-dried.

2.3 Implementation of Extracts

The prepared extracts were applied to cotton samples using two methods:

- Exhaustion Method: Samples were immersed in the extract solution at 40 °C for 30 minutes.
- Pad-Dry-Cure Method: The fabric was soaked, squeezed to remove excess liquid, dried at 80 °C, and cured at 140 °C for 3 minutes to fix the finish.

2.4 Antibacterial Assessment

The antibacterial activity was assessed using the agar diffusion method. Wells were created in nutrient agar plates inoculated with Staphylococcus aureus. Extract solutions were added to the wells, and plates were incubated at 37 °C for 24 hours. The inhibition zones were measured in millimetres.

2.5 Effect of Citric Acid

To improve binding and wash fastness, citric acid was mixed into the most effective extract at concentrations of 2%, 4%, 6%, 8%, 10%, and 12%. Treated samples were tested for antimicrobial performance using the same method.

2.6 Wash Durability

Fabric samples were subjected to up to ten wash cycles in a launder meter. After each cycle, antibacterial activity was reassessed to gauge the durability of the finish.

3. Results and Discussion

3.1 Antibacterial Activity of Extracts

The evaluation of the different extraction methods revealed a clear trend in how the type of solvent and concentration affected antibacterial performance. Overall, the aqueous extracts showed the strongest inhibitory effect against Staphylococcus aureus. Notably, the 60% methanol-based extract produced the largest inhibition zone, measuring 9 mm, which suggests that methanol was able to draw out a higher amount or broader variety of active compounds compared to the other solvents. ethanoic extracts also demonstrated some activity, especially at higher concentrations, where the inhibition zone reached 5.7 mm. Ethanol extracts were consistently less effective, with the highest reading at 5.7 mm even at the most concentrated level. This pattern highlights the role of solvent polarity in extracting antimicrobial constituents. As the concentration increased, the diameter of the inhibition zones also grew, confirming that higher extract loads contributed to stronger antibacterial action. These results indicate that both extraction method and concentration must be carefully considered to optimize performance.

Table 1: Extraction Techniques and Concentration Levels for Groundnut Shells

S. No.		Herbal-derived Concentration extract	Microbial Growth Suppression Zone (Mean Size, mm)
1	Ethanol	20%	1.25
2	Ethanol	40%	4.5
3	Ethanol	60%	5.7
4	Methanol	20%	1.75
5	Methanol	40%	5.1
6	Methanol	60%	9
7	Water	20%	0
8	Water	40%	0
9	Water	60%	0

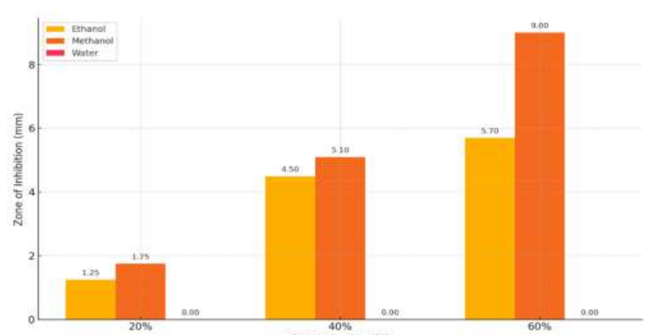

Figure 1: Antimicrobial Effect of different concentrations of extract (Methanol, ethanol and Water) on S. aureus

3.2 Effect of Citric Acid Addition

When citric acid was added to the extracts, there was a noticeable improvement in antibacterial efficacy. As shown in the results, the inhibition zones expanded steadily as the percentage of citric acid increased. For example, at 2% citric acid, the inhibition measured just over 2 mm, while at 10% and 12% it rose to 8.2 mm. This demonstrates that citric acid played a key role not only in fixing the extract onto the cotton fabric but also in enhancing the uniformity and possibly the stability of the antimicrobial compounds. Interestingly, after 10% citric acid, there was no further significant increase, suggesting that a threshold concentration had been reached. This plateau implies that while citric acid is beneficial, exceeding a certain amount does not necessarily yield additional gains. The findings reinforce the importance of optimizing the concentration of binding agents when developing antimicrobial finishes.

Table 2: Impact of Citric Acid Concentrations on Antibacterial Zone Size

S. No.	Sample Plates: Herbal Component and Citric Acid Level (%)	Microbial Growth Suppression Zone (Mean Size, mm)
1	2%	2
2	4%	3.5
3	6%	5
4	8%	6.5
5	10%	8.2
6	12%	8.2

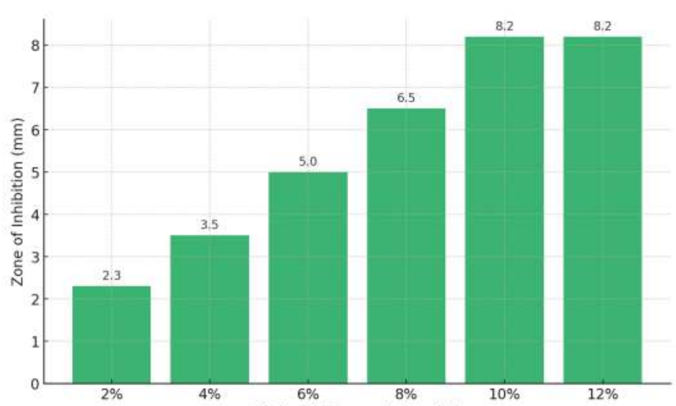

Figure 2: Effect of Citric Acid Concentration on Zone of Inhibition

3.3 Wash Durability

In everyday life, textiles go through countless wash cycles, and this simple act of laundering often becomes the biggest challenge for maintaining antimicrobial performance. Each wash not only removes dirt but can also strip away the very compounds that make fabrics functional, weakening their protective effect over time. Researchers have consistently shown that natural extracts alone tend to fade quickly in performance, but when cross linkers such as citric acid are added, the treatment lasts longer because stronger, more permanent bonds are formed with the cotton fibers. This means fewer active agents are washed away, allowing fabrics to retain their protective qualities through multiple laundering cycles [15, 16]. For consumers, this translates into a more reliable and sustainable product one that balances eco-friendly treatments with the practical realities of daily use.

The wash durability test provided insight into how well the treatments could withstand repeated laundering, which is critical for any textile application [17]. Fabrics treated with the extract alone began losing their antibacterial effectiveness after the third wash and showed no inhibition from the sixth wash onward. In contrast, the samples treated with the extract combined with citric acid retained strong antibacterial properties up to the fifth wash and still exhibited moderate activity through the eighth wash cycle. This extended durability can be attributed to the crosslinking effect of citric acid, which likely created stronger bonds between the active compounds and the cotton fibers, reducing leaching during washing. By the ninth and tenth cycles, however, all samples eventually lost their inhibitory effect. These results emphasize that while natural treatments can be effective, their performance over time depends heavily on the presence of cross linkers that help maintain their activity.

*Table 3: Antimicrobial Effect of Groundnut Extract on Cotton Fabric:
Pre- and Post-Washing (Zone Size in mm)*

Sr. No.	Washing Stage and Corresponding Zone of Inhibition (mm)	Methanol-Based Extraction of Groundnut Shell	Methanolic Groundnut Shell Extract Combined with Citric Acid
1	Before Washing	++	++
2	1	++	++
3	2	++	++
4	3	+	++
5	4	+	++
6	5	+	++
7	6	-	+
8	7	-	+
9	8	-	+
10	9	-	-
11	10	-	-

4. Conclusion

Due to the growing concern over antibiotic-resistant bacteria, plant-derived antimicrobial compounds have gained attention as alternative strategies for controlling microbial contamination on textiles. The potential of phenols and flavonoids in imparting anti-microbial functionality to the textiles is being researched through application of various plant extracts [18]. In this study, woven cotton fabric was treated with groundnut shell extract to assess its antibacterial potential against Staphylococcus aureus. The extract was prepared using both aqueous and solvent (Methanol/Ethanol) Extraction Techniques. Application onto the fabric was carried out through fabric treatment approaches: Exhaustion and Pad-Dry-Cure Methods.

The results showed that the 60% aqueous extract produced the largest inhibition zone, measuring 10 mm, indicating a strong antibacterial effect. Additionally, incorporating 12% citric acid as a crosslinking agent further enhanced the efficacy and helped the finish adhere more effectively to the cotton substrate. The treated samples were evaluated using the agar diffusion method, and the presence of clear inhibition zones confirmed the antimicrobial activity of the finish.

Wash durability testing revealed that fabrics treated with the extract alone retained activity up to the fifth wash, while those treated with the extract combined with citric acid maintained measurable antibacterial effects until the eighth wash cycle. Based on these findings, it can be concluded that cotton fabric treated with groundnut shell extract and citric acid exhibits effective antibacterial properties against Staphylococcus aureus, offering a promising, natural approach to developing functional textiles.

5. Limitations of the Study

Although the results of this study are encouraging, there are a few limitations that should be acknowledged. The antibacterial testing was carried out using only one method the agar diffusion technique which gives a good initial indication of activity but doesn't quantify the exact level of bacterial reduction. Also, the fabric was tested against just one type of bacteria (Staphylococcus aureus), so it's hard to say how the treatment would perform against other common microbes. Another point is that the washing tests were done under lab conditions, which may not fully reflect everyday use, where factors like detergent type, water quality, and temperature vary. These aspects could be explored further in future studies to get a more complete picture of the extract's real-world effectiveness.

6. Acknowledgments

We thank the Department of Fabric and Apparel Science, University of Delhi, for providing laboratory support and guidance.

7. Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Journal of the
TEXTILE Association

ISSN 0368-4636

Natural Bio-finishing of Cotton Material using Panchagavya for Textile Applications

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Abstract:

Purpose: *The development of an eco-friendly finished cotton material utilizing Panchagavya, a traditional Ayurvedic formulation using five co-products, namely Cow dung, Cow urine, Cow milk, Cow Curd, and Ghee. The aim is to explore a sustainable alternative to conventional chemical-based textile finishes by using Panchagavya as a natural antimicrobial agent.*

Design/Methodology/Approach: *The cotton fabric was pre-treated naturally by involving cow dung and cow urine. This step involves removing impurities and dust to create a higher fabric affinity for the final finish. Following the pretreatment, the fabric was treated with Panchagavya solution using the dip-dry cure method and cured at room temperature. The antibacterial property of the treated material was assessed against Gram-positive and Gram-negative bacteria, specifically Staphylococcus aureus (S.aureus) and Escherichia coli (E.coli). Fourier Transform Infrared Spectroscopy (FTIR) was used to analyze the chemical alterations in the cotton fiber.*

Findings: *The findings revealed significant antibacterial activity in both bacteria. The results for Panchagavya appeared to show considerable antibacterial activity. FTIR analysis showed the presence of functional groups and suggests the successful deposition and interaction of Panchagavya on the cotton material.*

Originality: *The study integrates a novel approach to sustainable antimicrobial development by using natural pre-treatment and finishing methods, by traditional Ayurvedic knowledge.*

Conclusion: *Panchagavya can serve as a sustainable and effective antibacterial finishing agent for textiles. The bio-based finishing agents highlight the possibility of incorporating traditional knowledge with modern textile processing.*

Keywords: Antimicrobial, Bio-finishing, FTIR, Natural finishing method, Panchagavya

Citation: Nandana. R, S. Grace Annapoorani, "Natural Bio-finishing of Cotton Material using Panchagavya for Textile Applications", *Journal of the Textile Association*, **86/4** (Nov-Dec'25), 411-416, https://doi.org/10.63665/jta.v86i4.10

Article History : Article Received :11-08-2025, Revised: 11-10-2025, Accepted: 15-10-2025

1. Introduction

Panchagavya was a traditional Indian formulation that exemplifies integrating natural resources into medicine, agriculture, and more recently, innovative cotton material science. It was derived from five cow-based ingredients- cow dung, cow urine, milk, curd, and ghee [1]. Cow dung was rich in beneficial microbes and served as an organic manure and a source of energy for biogas. It also demonstrated antibacterial and antifungal properties. Cow urine was found to be non-toxic and contained minerals, enzymes, and hormones. It was known for its diuretic, nephron protective, and antimicrobial effects. Curd was a probiotic-rich product that aided the digestive and immune systems. It also helped in blood purification and lowering cholesterol. Milk from Indian cow breeds was considered A2 type, which was rich in nutrients and associated with health benefits and also found to have antibacterial and anti-cancer properties. Ghee contained essential fatty acids and vitamins (A, D, E, K) and was used in Ayurveda to enhance memory, treat skin and gastrointestinal diseases, and promote wound healing [2]. It embodies the cultural and ecological reverence for cows in Indian traditions. Collectively known as 'Gavya', these ingredients are blended in various ratios, such as 16:10:8:2:1 or 1:1:1:1:1, depending on the intended application [3]. Enhanced formulation of Panchagavya, incorporating jaggery, coconut water, and ripe bananas, was designed to optimize its efficacy, particularly in agriculture and medicinal applications [4]. Panchagavya's historical significance was deeply rooted in Ayurvedic traditions, where it has been extensively documented in ancient texts like the Charak Samhita and Sushrut Samhita. These texts attribute diverse health benefits to Panchagavya, including curing skin disorders, infections, and gastrointestinal issues, and promoting wound healing [5]. Additionally, it was believed to enhance immunity, improve physical and mental vitality, and extend lifespan. For instance, Panchagavya plays a vital role in Ayurvedic formulations like Sanjeevani Vati, where cow urine serves as a processing medium [6]. These ancient practices highlight the multifaceted applications of Panchagavya, particularly its antimicrobial and therapeutic properties, which now being explored in modern innovations. In agriculture, Panchagavya has been a cornerstone for sustainable farming, where it functions as a biofertilizer and biopesticide. Its unique composition delivers essential nutrients, growth-promoting hormones, and beneficial microorganisms, fostering soil fertility and plant health. Moreover, it aids in converting organic nutrients

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into bioavailable forms for plants, thus supporting integrated nutrient and pest management systems. Panchagavya underscores the symbiotic relationship between humans and cattle in traditional Indian agriculture, where cow-derived products not only sustain but also enrich ecosystems. Modern scientific studies validate the antimicrobial properties of Panchagavya, especially when fermented at controlled temperatures like 37°C for 20 days. Such formulations exhibit significant antibacterial activity against various pathogens, including Escherichia coli, Staphylococcus aureus, Pseudomonas aeruginosa, and Bacillus subtilis [7]. Furthermore, Panchagavya shows notable antifungal properties against stains like Candida butyri and Aspergillus niger. These activities are influenced by its pH, which becomes more acidic during fermentations, and its microbial diversity, which contributes to its pharmacological potential [8]. Interestingly, Panchagavya, derived from indigenous cow breeds such as Gir and Sahiwal, has demonstrated superior antimicrobial efficacy [9]. The integration of Panchagavya into textile production represents a significant step toward sustainable antimicrobial solutions. Protective clothing designed to mitigate pathogen transmission must meet specific criteria, including strong antimicrobial efficacy, durability across multiple washes, biocompatibility, and environmental friendliness [10]. Studies indicate its potential to effectively reduce the viability of pathogens while maintaining eco-friendly characteristics [11]. Beyond Panchagavya, advancements in antimicrobial textiles include the use of natural dyes, bacterial pigments, and nano-emulsions [12]. For example, prodigiosin pigments derived from Serratia plymuthica and curcumin-based nano-emulsions have demonstrated antimicrobial activity when incorporated into cotton materials [13]. Zwitterionic polyamine finishes, applied using a water-based pad-dry-cure process, enhance resistance to bacterial adhesion while avoiding harmful chemical residues [14]. These innovations align with the principles of sustainability and complement Panchagavya's eco-friendly profile. The growing interest in natural antimicrobial treatments reflects a global shift toward reducing the environmental impact of synthetic materials [15]. Panchagavya, with its biodegradable and non-toxic nature, offers a sustainable alternative to synthetic antimicrobial agents. Unlike conventional treatments, which may release harmful chemicals into the environment, Panchagavya-based textiles align with circular economy principles. This approach minimises waste and leverages renewable resources, contributing to ecological preservation [16]. Adopting Panchagavya in antimicrobial textiles could revolutionise sectors such as healthcare, hygiene, and biodefense. Its compatibility with natural dyes and other eco-friendly antimicrobial agents opens new approaches for innovations in sustainable protective clothing. By combining traditional knowledge with modern technology, Panchagavya-based textiles promise to address pressing challenges in health and sustainable environmental [17, 18]. Panchagavya [19] is positioned as a cultural significance for its antimicrobial properties and environmental sustainability as a transformative agent in protective textiles. Its integration into cotton materials science reflected a balance between tradition and innovation, addressing the growing demand for sustainable, effective, and ethically aligned antimicrobial treatments.

2. Materials and Methods

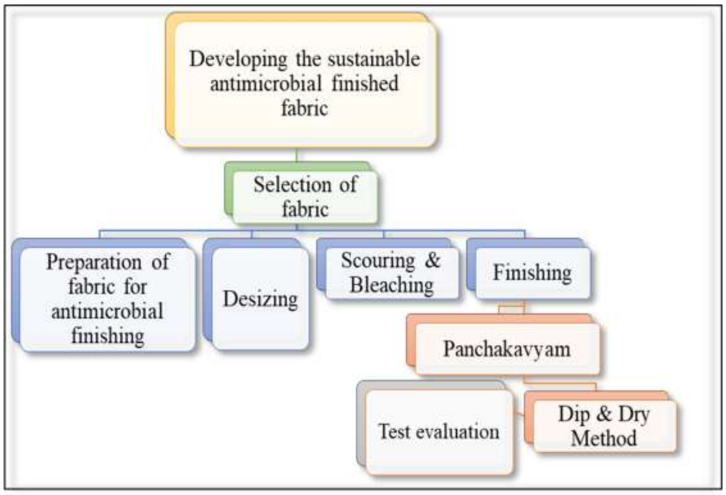

Figure 1: Work flow of the study

2.1 Selection of material

Cotton's adaptability and broad use are demonstrated by the choice and use of the material in a plain weave (60s count) structure. Cotton was preferred because of its inherent softness, breathability, and durability, which made it appropriate for a variety of applications. The balanced structure of the plain weave increases the material's strength and longevity, which makes it perfect for a variety of textile items.

2.2 Preparation of material

2.2.1 Desizing

The cotton material was boiled in a 1:2 ratios in sea salt water for one hour. Then, the cotton material was dipped in the salt water for 12 hours and washed in water, and spread in the sunlight to dry. The cotton material undergoes a process to remove impurities, gums, sizing, and oils to make it more absorbent. Detergents were not involved in this process as it contains hazardous chemicals [20].

2.2.2 Scouring and Bleaching

Now, the dried cotton material was stretched over the grass in the sunlight, and the process was continued for two to three days. Water was sprayed continuously on the cotton material for short intervals. Sun is a natural bleach but the impact of its combination of grass and water in bleaching cotton. The cotton material was soaked in cow urine [21] and cow dung. It was kept immersed in the solution for 12 hours. Afterwards, the cotton fabric was left to dry in the sun for four to five hours. The process is continued until the cotton material reaches the desired level of softness and whiteness. The work was repeated for 3-5 days.

2.2.3 Finishing of cotton material using Panchagavya

The source of Panchagavya was collected from SRE Panchagavya, Tiruchengode, Namakkal (dt). The bleached cotton material was coated using Panchagavya. The dip and dry cure technique was used for coating the cotton material. The cotton material was immersed in the Panchagavya solution for 12 hours. Then the cotton material was allowed for the shade drying.

2.3 Fourier-transform infrared spectroscopy (FTIR)

JASCO model was used to evaluate the FTIR to identify the free functional groups present in the Panchagavya of liquid and treated material of their unique chemical bonds using an infrared spectrometer. The sample was analysed in ATR (Attenuated Total Reflectance) mode a wavelength range of 500–4000 cm-1.

2.4 Field Emission Scanning Electron Microscopy (FESEM)

FESEM is a high-resolution imaging technique that uses a focused electron beam to study a material's surface at the nano- and micro-scale. It provides detailed information on a sample's particle size, shape, and distribution, making it an essential tool for materials science and nanotechnology.

2.5 Antibacterial activity

The agar disc diffusion method was employed to investigate the antibacterial activity of the sample. Nutrient broth medium was utilized to subculture the bacteria and incubated at 37°C for 24 hours. Subsequently, 70µl cultures of E. coli and S. aureus were taken and spread on Mueller Hinton agar plates (39g of Mueller Hinton agar was dissolved in 1000 ml of distilled water and sterilized under autoclave at 121°C for 15 minutes) using a sterile cotton swab to ensure uniform microbial growth on the plates. The cloth was subsequently positioned in the designated area alongside the negative control (DMSO) and the positive control (Antibiotic disc-Norfloxacin-Nx 10mcg). The plates underwent incubation for 24 hours at a temperature of 37°C, and the diameter of the inhibition zone was measured and recorded in millimetres [22, 23].

3. Results and Discussion

3.1 FTIR

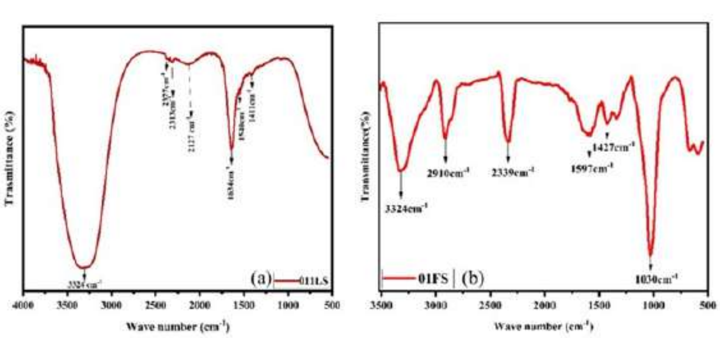

Figure 2: (a) FTIR graph for the liquid and (b) FTIR graph of the coated fabric

The above figure 2, (a&b) displays the FTIR spectrum for 011LS FTIR (liquid Panchagavya) and 01FS (coated material), it shows the peaks at 3324cm-1, 2377cm-1, 2313cm-1, 2127cm-1, 1634cm-1, 1540cm-1, 1411cm-1, indicating the presence of hydroxyl groups (O-H stretching), carbonyl compounds (such as carboxylic acids), amide groups (N-H and C=O stretching), and unsaturated compounds of alkenes or alkynes (C=C or C≡C), suggesting a complex composition of bioactive components [24, 25]. These include amino acids and the possibility of aromatic or phenolic compounds [26, 27]. For the sample 01FS (coated material), the FTIR spectrum shows the peaks at 3324cm-1, 2910cm-1, 2339cm-1, 1597cm-1, 1427cm-1, 1030cm-1, these peaks represent the presence of hydroxyl groups (O-H stretching), aliphatic C-H stretching, carbonyl compounds (C=O stretching), and other functional groups like phenolic or aromatic compounds and C-O stretching [28]. The FTIR spectrum shows evidence of organic materials' interaction with the cotton material. Phenolic and aromatic groups contribute to antioxidant and antimicrobial properties, while carboxyl and amide groups improve the binding affinity of bioactive molecules with the cotton fibers, thereby increasing wash durability of the finish.

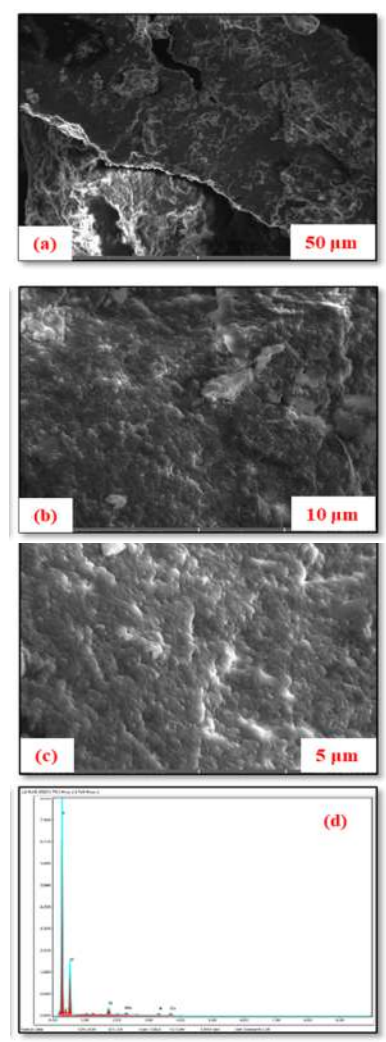

Figure 3: (a, b, c & d) FESEM and EDX images of Panchagavya

3.2 FESEM

The surface morphology of the Panchagavya material was examined using FESEM, which revealed a highly clustered nanosheet architecture. These nanosheets form a uniform, interconnected network, which can enhance surface area, mechanical adhesion, and functional properties such as antimicrobial activity or dye uptake. The corresponding EDX spectrum confirmed the presence of carbon (C), oxygen (O), silicon (Si), molybdenum (Mo), potassium (K), and calcium (Ca). The presence of these metals is attributed to the traditional Panchagavya formulation: Mo and K originate from mineral-rich herbal extracts, Ca is contributed by plant ash or natural additives, and Si may arise from silicate compounds in plant or soil sources. Elemental mapping demonstrated a uniform distribution of all elements over the textile fibers, indicating effective deposition and incorporation of metal ions within the nanosheet network. This uniform elemental distribution, combined with the nanosheet morphology, is expected to improve the functional performance of the textile, including enhanced durability, surface reactivity, and potential bioactivity.

3.3 Antibacterial activity

The table 1 and 2 shows, the antibacterial activity of two samples, 011LS (Liquid Sample) and 01FS (Treated material), against E. coli and S. aureus at concentrations of 20 µl, 40 µl, and 60 µl, as indicated by the zone of inhibition (in mm). For E. coli, sample 01FS exhibited higher antimicrobial activity at all concentrations compared to 011LS, with the largest zone of inhibition (13 ± 0.3 mm) observed at 20 µl. However, for both samples, the zone of inhibition gradually decreased as the concentration increased. In contrast, for S. aureus, sample 011LS was more effective than 01FS across all concentrations, with the highest inhibition zone (12 ± 0.2 mm) at 20 µl for 011LS. Similarly, the effectiveness of both samples against S. aureus diminished with increasing concentrations. Overall, sample 01FS was more effective against E. coli, whereas 011LS demonstrated better inhibition against S. aureus. The superscript letters (a, b, c) in the data indicate statistically significant differences in the zones of inhibition at different concentrations for each sample. These results suggest that both samples exhibit antimicrobial properties, but their efficacy varies with the organism and concentration.

4. Conclusion

The study focuses on the efficacy of Panchagavya as an eco-friendly, natural antimicrobial finishing agent for cotton materials. The use of a sustainable pre-treatment method, which involves cow dung and cow urine, prepares the material for enhanced interaction with the bioactive compounds present in Panchagavya. The FTIR spectral analysis reveals the presence of functional groups, including hydroxyl, carbonyl, amide, and aromatic compounds, in both

Table 1: Antibacterial activity of Panchagavya of 011LS

Name of Organisms	Concentration (µl)	Zone of inhibition (mm)	Df	F
		011LS		
E.coli	20	$11{\pm}0.2^{a}$	(2,8)	19.400^{***}
	40	$10{\pm}0.1^{b}$		
	60	$9{\pm}0.1^{b}$		
S.aureus	20	$12{\pm}0.2^{a}$	(2,8)	18.600^{***}
	40	$11{\pm}0.2^{b}$		
	60	$10{\pm}0.3^{b}$		

*Table -1; DF- Degree of Freedom; F – Frequency; ***- Highly significant, P>0.05 Significant*

Table 2: Antibacterial activity of Panchagavya of 01FS

Name of Organisms	Concentration (µl)	Zone of inhibition (mm)	Df	F
		01FS		
E.coli	20	$13{\pm}0.3^{a}$	(2,8)	16^{***}
	40	$11{\pm}0.4^{b}$		
	60	$10{\pm}0.2^{b}$		
S.aureus	20	$10{\pm}0.3^{a}$	(2,8)	9.364^{***}
	40	$9{\pm}0.3^{b}$		
	60	$8{\pm}0.3^{c}$		

*Table -2; DF- Standard deviation; F – Frequency; ***- Highly significant, P>0.05 Significant* the liquid (011LS) and the treated material (01FS). This indicates successful chemical interaction and deposition of organic constituents onto the cotton material. The antibacterial analysis demonstrated that the treated material (01FS) exhibited greater inhibition against E. coli, while the liquid sample (011LS) was more effective against S. aureus. In both cases, in increasing the concentration the activity decreases, which shows that lower volumes may be more effective for microbial inhibition. Furthermore, FESEM analysis revealed a clustered nanosheet morphology forming a uniform and interconnected network, while EDX and elemental mapping confirmed the presence and homogeneous distribution of bioactive elements such as C, O, Si, Mo, K, and Ca. This nanosheet architecture, along with the even elemental deposition, is expected to enhance the surface reactivity, durability, and functional properties of the finished textile. The findings confirm that Panchagavya is applicable as a sustainable alternative to chemical-based textile finishes for its antibacterial properties. The study integrates the traditional Ayurvedic finishing with the modern textile processing, which contributes to the development of eco-friendly alternatives and functional textile materials.

Acknowledgement

The research work was financially supported by the Tamil Nadu Chief Minister Research Fellowship (CMRF).

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Journal of the TEXTILE Association

ISSN 0368-4636

Sustainable Bio-Based Flame-Retardant Finishes for Cotton, Bamboo, and Cellulosic Textiles

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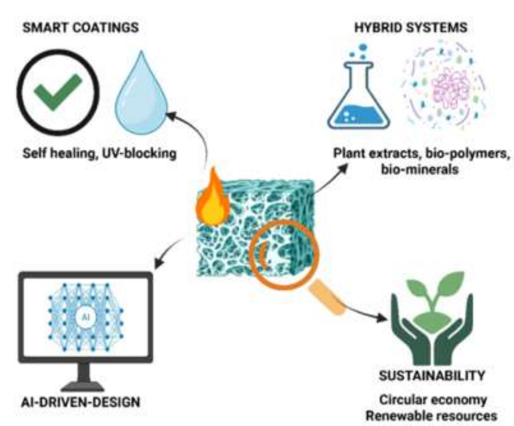
Abstract:

Home textiles constitute a unique fire hazard given that bedding, curtains, and upholstery are made of cellulosic materials (cotton, bamboo, and regenerated cellulosic blends) that are highly flammable. Conventional flame-retardant (FR) treatments use halogenated and other predictable harmful substances - antimony oxides and formaldehyde releasing agents - that are toxic, bio accumulative, and non-biodegradable. Because of increasing regulations, bio-based FR systems incorporating renewable, non-toxic, and biodegradable materials are emerging to respond to consumer preference for safer materials. This review focuses on developments concerning biopolymer and plant-derived FR coatings and natural extracts (banana pseudo-stem sap and spinach leaf substances) coupled with chitosan, alginate, phytic acid, proteins, and other nano-bio hybrids. Coating techniques, mechanisms of flame-retardation, surface chemistry, film integrity, and performance on cotton, bamboo, and cellulose blends are principal parameters of interest. The review discusses the FR bio-system limitations of processing, lack of wash, smoke, and scalable durability. The review also discusses the synergy of bio-hybrids, green cross-linkers, and circular design approaches to develop more sustainable FR finishes. This article will contribute towards the development of safe, effective, and sustainable flame-retardant technologies to serve next-generation domestic textiles.

Graphical abstract:



Keywords: *Bio-polymer, cellulosic materials, Flame retardant, Natural extracts, Sustainable*

Citation: Nathiya M, Kottappatty Manickampillai Pachiyappan, Ambedkar Gandamalla, "Sustainable Bio-Based Flame-Retardant Finishes for Cotton, Bamboo, and Cellulosic Textiles", *Journal of the Textile Association*, **86/4** (Nov-Dec'25), 417-424, https://doi.org/10.63665/jta.v86i4.8

Article History : Received : 09-11-2025, Revised: 04-12-2025, Accepted: 08-12-2025

1. Introduction

Cellulose is a natural polymer and the most plentiful polymer on the planet. Cellulose fiber is the chief component of many useful products like textiles, filters, and composites. Textiles utilize fibers from plants such as cotton, bamboo, flax, jute, and various grasses [1]. Primarily composed of cellulose, fibers also contain varying amounts of lignin, hemicelluloses, pectin, waxes, and inorganic salts, all of which determine the fibers' characteristics. Crystalline cellulose constitutes the major part of a fiber's tensile strength, while successive lignin removal by pre-treatment processes (delignification) increases the fiber purity [2]. The flammability of a polymer is a function of its composition, internal structure, and external treatments. The flammability of cellulose fibers is often countered during manufacture by incorporating fire retardants or applying flame-resistant coatings. Fire protection in home textiles is a regulatory concern worldwide because of the fire hazard textiles pose when used in bedding, upholstery, and curtains. In the United States, textile flammability is regulated by the CPSC regulations (16 CFR Parts 1630, 1631, 1633, and 1610) alongside California's TB 117-2013 and NFPA 701. In the UK, flammability hazard is regulated by the Furniture and Furnishings (Fire) (Safety) Regulations. Children's sleepwear and bedding, in the US and the EU, require third-party FR certification [3].

Last year, safety standards on labelling, testing, and fire safety were updated to ensure traceability and safety. Conventional fire retardants like bromine, chlorine, halogenated phosphonates, some phosphonamides, and phosphonates help reduce flammability but are persistent, toxic, bio-accumulative, and release harmful gases like dioxins and formaldehyde upon combustion [4]. Use of PFAS in fire coatings is criticized due to their persistence, toxicity, and health risks, including endocrine disruption, as they contaminate air, soil, and water during textile use. Regulations like the EU's REACH and California's Proposition 65 control PFAS and halogenated compounds. Manufacturers are developing PFAS and halogen-free alternatives to reduce toxicity and support the circular economy. Sustainable bio-based fire retardants made from plant and animal waste are emerging as non-toxic, biodegradable options [5].

Naturally occurring flame retardants (FR) are animal-based

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(e.g., chitosan, proteins, DNA) or plant-based (e.g., cellulose, starch, tannins, phytic acid, lignin, extracts, oils). They form char when heated, restrict oxygen, and release gases that suppress flammable vapours. Combining biodegradable bio-FR polysaccharides with minerals or phosphorus enhances flame resistance without sacrificing safety or biodegradability [6]. The textile industry prefers sustainable fibres; cotton is popular for softness and breathability but needs much water and pesticides. Alternatives like organic cotton, bamboo, and regenerated cellulose (Lyocell, Excel) are increasingly used. Bamboo is highly sustainable, renewable, and needs minimal input but requires more processing chemicals, necessitating greener closed loops [7]. Regenerated cellulose fibres from wood pulp via solvent recycling reduce chemical waste. Biodegradable Lyocell and Excel fibres support balance with their high tensile strength, processed innovatively and naturally sourced [8]. Banana pseudostem is a top lignocellulosic bio-resource, with over 120 million tonnes annually, mostly agricultural waste. Other residues like coconut coir, pineapple leaf fibres, and sisal are also available, renewable, low-cost raw materials ideal for bio-textile and bio-coating use. Their availability, biodegradability, and low processing needs make them suitable for sustainable industrial materials. The hybrid polymer-mineral constructions show improved char yield, lower smoke toxicity, and reduced heat release compared to bio-FR coatings with single polymer barriers, due to synergistic protection mechanisms. The shift to hybrid flame retardants with biopolymers and minerals for household textiles is driven by concerns over traditional treatments' environmental and safety risks [7, 12 & 14]. The use of cellulose-based fibre textiles is a step in the direction of the use of safer and environmentally friendly materials. Such textiles accommodate comfortability and functionality in home textiles while fulfilling regulatory requirements. This review addresses the sustainable flame-retardant coatings for cotton, bamboo, and regenerated cellulose fibres while tracking the design, chemistry, flame-retardant response mechanisms, and potential future bio-based innovations relating to fire safety [9]. Major global regulatory frameworks like REACH, Oeko-Tex Standard 100, ISO 15025 and ASTM D6413 were considered to ensure their relevance across international markets

2. Current Problems in Flame-Retardant (FR) Treatments

2.1 Toxicity and the Environmental Impact of FR Treatments

Brominated and chlorinated compounds cause cancer, reproductive, hormonal, and neuro damage, especially in children who are exposed through flame-retardant treated clothes and bedding. Toxic chlorinated phosphate esters LCEP, TCPP, and TDCPP are used in furniture, textiles, paints, and coatings, posing risks. Brominated HBCD is used in polystyrene and textiles, classified as a persistent organic pollutant. These chemicals release POPs into the environment during production and breakdown. Safer alternatives include non-halogenated, biodegradable flame retardants, which are essential for safety and environmental compliance health [10].

2.2. Wash Durability and Weak Bonding with Cellulose

Cellulose fibres like cotton and viscose are common in textiles and are highly flammable. Achieving flame retardancy and wash durability is challenging due to their flammability, moisture retention, and the toxicity of covalently bonded flame retardants. Active ingredients often wash out or are lost with moisture because of weak bonds. While green cross-linkers, bio-binders, and low-temp processes improve durability, many issues remain to be solved issues [11].

2.3. High Processing Temperatures and Fabric Property Loss

FR systems need high temperatures for durable bonds, forming a char layer that prevents combustion by limiting heat, oxygen, and releasing gases that suppress flames. Char formation requires temperatures over 150–180 °C, causing yellowing and stiffness. Developing FR treatments that form strong char bonds at lower temperatures is crucial to preserving fabric aesthetics and durability textile [12].

2.4. Regulatory and End-of-Life Disposal Challenges

Challenges with disposal and regulation remain as many flame-retardant (FR) compounds are banned or phased out globally. New formulations reduce toxicity but face disposal and lifecycle issues. Manufacturing CO_2 emissions and energy demands are costly. Non-biodegradable FR textiles pose disposal problems: landfills risk leaching, incineration is costly and energy-intensive, and biodegradable parts produce methane. Sustainable strategies should prioritise closed systems, recyclability, and environmental reduction biodegradability [13].

2.5. Lack of Mechanistic Compatibility in Multi-Fibre Blends

In modern textiles, blending fibres balances attributes like malleability, strength, and moisture retention, as seen in cotton/polyester and bamboo/Excel blends. Uneven flame-retarding properties pose challenges: cellulosic fibres char and diffuse bonds, while polyester is hydrophobic and burns differently; it reflows when burning. Polyester/cotton blends show inconsistent FR char coverage, causing localised burning. Balancing FR can be achieved through gas-phase treatments and surface coatings, such as silicone, nano-clay, or layer-by-layer applications [14]. A schematic overview of these interrelated challenges is illustrated in Figure 1, and Table 1 summarizing the chemical, environmental, and structural barriers that motivate the transition toward bio-based and multifunctional FR system.

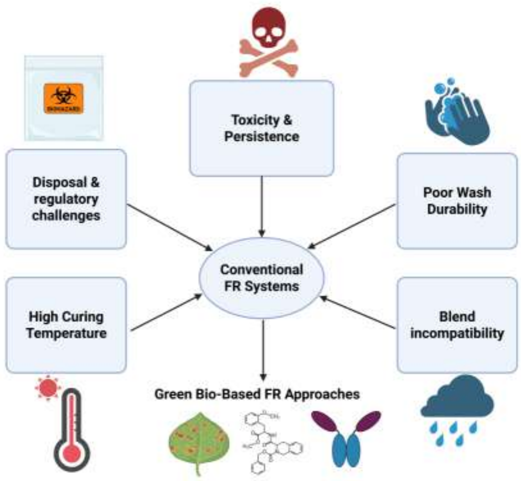

Figure 1: Key challenges and environmental impacts of conventional flame-retardant textile treatments

Table 1: Summary of key challenges associated with conventional flame-retardant (FR) treatments for textile applications

Problem Area	Representative Compounds / Examples	Mechanism / Issue	Environmental or Health Impact	Research Need / Solution Direction
Toxicity and persistence	Halogenated FRs (TCEP, TCPP, TDCPP, HBCD)	Release toxic gases (HCL, dioxins) and bio-accumulate	Carcinogenicity, endocrine disruption, neurotoxicity	Replace with biodegradable, halogen-free FRs (phosphorus-, nitrogen-, or bio-based) [5]
Wash durability	Phosphorus or nitrogen-based ionic coatings on cotton	Weak ionic bonding, easily leached during laundering	Short lifespan, water contamination	Develop covalent grafting, green cross linkers (citric acid, genipin) [31]
High processing temperature	Durable phosphorus/nitrogen FR finishes	Require =160 °C curing, causing fabric stiffening or discoloration	Property degradation and energy use	Low-temperature curing or enzymatic fixation [12]
Disposal & regulatory challenges	FR-treated synthetic fabrics, PFAS-based coatings	Leaching during landfill or incineration	Persistent organic pollutants, CO_2 & CH_4 emission	Circular FR systems, recyclable or biodegradable coatings[13]
Multi-fibre blend incompatibility	Cotton/polyester blends	Incomplete FR coverage, "scaffolding effect"	Partial combustion, molten polyester fuelling fire	Hybrid FR systems or layer-by-layer coatings tailored to fibre chemistry [14]

3. Cellulose Fibres in Home Textiles

3.1. Cotton – advantage and high fire load

Cotton is a natural textile that's moisture-absorbing, soft, and comfortable. Its cellulose structure aids dyeing and finishing, especially in garments, bedding, and towels. However, the high cellulose and porous structure make cotton easy to ignite, quickly consuming oxygen and acting as a high fire load. Its rapid burn rate can escalate fire spread, heat, and smoke, posing safety hazards. The lightweight, fluffy fabric also allows oxygen to sustain fires combustion [15].

3.2. Bamboo – antimicrobial & structural differences (lignin, silica)

Bamboo fibres are eco-friendly alternatives to cotton, valued for their natural antimicrobial properties. However, this is only partly due to bioactive compounds, which are affected by processing. Bamboo's structure differs from cotton because it contains lignin and silica in addition to cellulose. Lignin provides strength and UV resistance, while silica adds sheen and changes thermal stability. These features influence bamboo's mechanical and thermal properties, making it less uniform but more resistant to microbes and environmental conditions degradation [16].

3.3. Regenerated cellulosic (Lyocell/Excel) – thermal behaviour and process ability

Lyocell and Excel are regenerated cellulose fibres that combine synthetic and natural materials. They remain pure and stable during dissolving and regeneration. Lyocell, produced through solvent-spinning with NMMO, provides excellent moisture management, high wet tensile strength, and a smooth surface. Increased crystallinity and a dense structure improve thermal stability. Their thermal behaviour is similar to natural cellulose, but their uniformity ensures consistent performance. These fibres can be treated to be flame-retardant or blended. High packing density and low thermal conductivity offer good insulation, enhancing textiles both mechanically and functionally [17]. Industry estimates show the global Home Textile Market will grow at about 5.5% CAGR from 2024 to 2029, fueled by rising demand for eco-friendly textiles and online retail expansion. This growth highlights the importance of developing durable bio-based coatings and flame-retardant finishes.

3.4. Blends - synergy and challenges in FR applications

In home textiles, blending cellulose fibres with other materials like cotton-polyester and bamboo-viscose enhances comfort, strength, and fire safety. However, heat degradation complicates creating effective flame-retardant blends, as pure cellulose finishes or additives may not meet performance standards. Complex formulations must balance chemical compatibility, comfort, breathability, aesthetics, airflow, and processing ease. Combining natural flame-retardant textiles with regenerated cellulosic materials enables innovative, safer designs, with fibre composition and structure influencing flammability and flame resistance mechanisms. (Figure 2) [18].

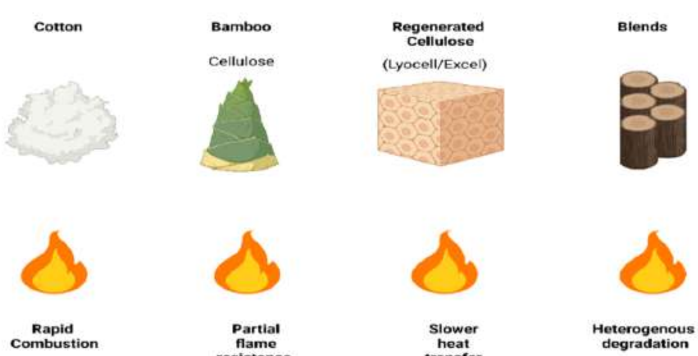

Figure 2: Structural and compositional differences among cellulose-based home textile fibres

4. Bio-Based Flame-Retardant Systems

Textile flame retardant (FR) systems are environmentally friendly coatings that are bio based and made from renewable resources such as plants and minerals. These systems help in reducing the toxicity and environmental impact of the textile flame retarding systems. These systems promote char formation and use synergistic mechanisms for the flame spread to be slowed. The following sections deal with the bio-based FR systems for cotton, bamboo, and cellulose blends [19]. Bio-based FRs rich in phosphorus–nitrogen–mineral units change PET's thermal degradation from volatile fuel evolution to char formation. This creates a cross-linked protective layer that reduces dripping and heat release, enhancing flame resistance in PET blends.

4.1. Natural Plant Extracts (Banana Pseudo Stem Sap, Spinach, and Other Botanicals)

Banana pseudo-stem and spinach extracts serve as eco-friendly flame-retardant precursors. They boost thermal stability and char formation through mineral salts, acids, and phosphorus compounds. Spinach's magnesium, sodium, silicate, phosphate, and nitrate ions increase LOI, reduce burning rate, and promote intumescent char, helping generate a self-extinguishing carbon dome and gases. During pyrolysis, banana extract aids dehydration and carbonisation via sodium, potassium, and phosphorus ions. Other extracts like coconut shell filtrate or pumpkin pulp improve smoke suppression, char yield, and effectiveness when combined. These renewable, biodegradable treatments enhance non-toxic textile processing. Table 2 shows bio-based FR systems and their effectiveness [20].

4.2. Biopolymers - Chitosan and Its Derivatives

Chitosan, a natural cationic polysaccharide from deacetylated chitin, is a versatile bio-based flame retardant. Its high nitrogen, film-forming ability, and affinity for cellulose make it a carbon source and reactive binder for inorganic additives. It aids polymeric char formation and stabilisation, limiting oxygen diffusion and heat transfer. Chitosan, combined with flame retardant additives like ammonium polyphosphate, silica nanoparticles, and melamine polyphosphate, significantly reduces heat release and smoke. Layered assembly with phosphorylated chitin or alginate enhances self-extinguishing properties and fabric LOI. Derivatives such as carboxymethyl and cross-linked chitosan improve dispersion and durability of flame-retardant coatings. Additionally, chitosan offers antimicrobial properties and boosts flame retardant effectiveness of sustainable materials textiles [21]. Plant extracts are eco-friendly but face shelf-life challenges. Aqueous extracts (e.g., banana pseudostem, spinach) have shorter stability due to microbial growth and oxidation, while concentrated or freeze-dried forms last longer and are easier to use in pad-dry-cure processes. Stability improves with pH and moisture control.

4.3. Phosphorus biomass, Phytic acid, DNA, Phosphorylated Polysaccharides

Phytic acid in cereals and legumes is a non-toxic flame retardant with 28% phosphorus, chelating toxic metals and promoting charcoal formation; combined with nitrogen and silicon compounds, it helps create intumescent coatings. Grafted phosphorus acid on cotton or blends, along with flame retardant phosphates, improves textile flame resistance while maintaining softness and breathability. It, with chitosan or silica nanoparticles, provides antibacterial, hydrophobic, and flame-retardant features. DNA, combined with polyphosphates and nitrogen, acts as a flame retardant by releasing acids that promote dehydration, forming a protective carbon scaffold, reducing heat and ignition. Phosphorylated cellulose nanofibers with M-Xene and polydopamine offer durable flame-retardant coatings for polyurethane foams. These materials demonstrate how phosphorus-rich compounds serve structural and sustainable roles in biomolecules [22].

4.4. Nano Bio-Hybrids and Inorganic Additives (Bio-SiO_2, TiO_2, Eggshell, and Clays)

Inorganic nanoparticles with bio-polymers form nano bio-hybrid systems. Chitosan–phytic acid on cotton with eggshell microparticles ($CaCO_3$) boosts flame retardancy by dehydrating to CaO and CO_2. Organic matrices improve adhesion and char. Chitosan phosphate coatings with TiO_2 reduce smoke and heat via photocatalytic self-cleaning. Silica (SiO_2) and montmorillonite inhibit volatiles, strengthen char, and enhance insulation while remaining breathable. Using bio-binders and waste minerals supports eco-friendly circular economy principles [23].

4.5. Synergistic Systems (Plant Extract + Chitosan + Phosphate/Mineral)

Recent findings show that hybrid systems with plant extracts, biopolymers, and additives outperform individual components in FR performance. During pyrolysis, chitosan sustains the carbon structure, while phosphates catalyse dehydration and radical scavenging. Mineral compositions like silica, clays, and $CaCO_3$ enhance barrier and heat reflection. Bio-based coatings show higher LOI, better wash resistance, lower smoke density, and are soft and flexible. These materials are likely used in commercial home environments textiles [24]. Low-temperature curing facilitates ion-crosslinking and hydrogen bonds between the bio-polymer matrix and cellulose surface without thermal degradation. This lowers energy use and boosts durability by preventing micro-cracking, stiffness, and loss of adhesion common in high-temperature curing.

Table 2: Comparative Summary of Representative Bio-Based Flame-Retardant Systems for Cellulosic and Blended Home Textiles

System Type	Representative Materials	Active Mechanism	Reported Effects / LOI (%)	Advantages	Limitations
Plant Extracts	Banana pseudo stem, spinach, pumpkin, coconut	Mineral-assisted char formation, intumescence	LOI ˜ 25–28	Renewable, non-toxic, low-cost	Limited wash durability [7]
Biopolymers	Chitosan, carboxymethyl chitosan	Char formation, radical quenching	LOI ˜ 28–30	Multifunctional, antimicrobial	Sensitive to pH and processing [16]
Phosphorus Biomolecules	Phytic acid, DNA, phosphorylated cellulose	Acid-catalyzed dehydration, intumescence	LOI ˜ 30–33	Strong synergism, multifunctional	Water solubility issues [8]
Nano Bio-Hybrids	Chitosan–TiO_2, eggshell–PA, SiO_2–chitosan	Barrier and insulation effects	LOI ˜ 31–34	High thermal stability, smoke suppression	Fabric stiffness, dispersion challenges [22]
Synergistic Systems	Chitosan + phytic acid + plant extract	Combined condensed & gas phase	LOI ˜ 33–36	Enhanced durability, eco-compatible	Process optimization required [30]

5. Mechanistic Insight

Understanding bio-based flame retardants (FR) mechanisms is crucial for designing durable treatments for cotton, bamboo, and regenerated-cellulosic blends. Most action occurs in condensed phases, forming chars, and in gas phases, quenching radicals. Effectiveness improves through synergistic interactions of organic polymers with phosphorus, nitrogen compounds, and inorganic fillers [25].

5.1 Char Formation Promoted by Phosphorus:

Phosphorus-rich bio-sources such as phytic acid catalyze cellulose dehydration on heating, forming polyphosphoric acid which assists char formation. The chars are stable, and the heat and oxygen blockage they provide slow the fibre decomposition. The condensed-phase action is the major phosphorus-based FR mechanism improving thermal stability and flame retardancy in cellulosic materials [26].

5.2 Intumescence Promoted by Nitrogen:

Chitosan and similar nitrogenous polymers improve flame retardancy via intumescence and gas effects. During decomposition, they release ammonia and water vapour that dilute flammable vapours, promoting a swollen, insulating char. This bio-intumescent system enhances char stability and flame resistance by harmonising phosphorus and nitrogen, similar to halogen-free classic intumescent coatings [27].

5.3 Barrier Effect of Silica and Titania:

Inorganic additives like SiO_2, TiO_2, and bio-silica enhance physical barriers and heat sinks, boosting thermal stability. Nano-silica and titania in polymers strengthen the char layer and block oxygen, reducing fragmentation and combustion. They also improve UV resistance and durability, making the coatings multifunctional flame-retardants for home textiles [28].

5.4 Synergistic Bio-Polymer and Mineral Systems:

Next-generation bio-based flame-retardant coatings use synergistic effects from phosphorus acids, polymers like chitosan or plant polysaccharides, and inorganic fillers such as silica and titania. These stabilise char, reduce heat and smoke, and enhance durability. The combined systems outperform individual effects, boosting flame-retardant quality performance. (Figure 3) [29]. Bio-polymer/mineral FRs create a dense char–mineral barrier that blocks oxygen and reduces aromatic volatiles. Phosphorus and nitrogen species catalyze the transformation of combustible gases into inert products like CO_2, H_2O, and N_2, greatly reducing toxic smoke. This combined action improves fire safety without adding harmful compounds.

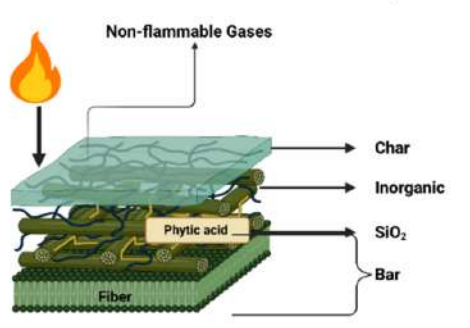

Figure 3: Synergistic flame-retardant mechanism of bio-based coatings on cellulose fibres

5.5 Schematic Mechanism Description:

A publication-quality illustration should depict a fiber cross-section with a bio-FR layer, chitosan/plant extract, phytic acid, and SiO_2/TiO_2, all color-coded and annotated. Labels and arrows should show heat flow, gas release, and char formation, demonstrating how the char triad reduces heat transfer, delays ignition, and suppresses smoke while maintaining fibre integrity. [30]. Bio-based FR systems have a lower ecological impact than halogenated ones, thanks to their renewable sources, fewer persistent pollutants, and limited bioaccumulation. Effluents from coating and washing are less eutrophic, mainly due to natural polymers' biodegradability. Recycling studies show FR-treated cellulosic textiles maintain strength after repulping, allowing partial reuse in cellulose recovery. At end-of-life, bio-FR fabrics are landfill-friendly, forming more char and leaching fewer toxins than halogenated systems, supporting circular design.

6. Challenges and Technological Gaps

Challenges in commercialising bio-based flame-retardant coatings on textiles include wash durability and weak fiber bonding, which are affected by physical bonding mechanisms like hydrogen bonds that wash off. Cross-linking with citric or tannic acids may improve durability but can soften fabrics, reducing wash fastness. Achieving durable adhesion while maintaining textile qualities is difficult, as heavy coatings compromise breathability and clarity. Uniform coatings are essential for scaling, but extreme curing temperatures can damage sensitive fibers like Lyocell. Low-temp methods or plasma activation could help but need more research. Multi-fibre blends pose additional challenges: cellulose bonds with phosphorus- or nitrogen-based FRs, while synthetic fibers like polyester are hydrophobic, melting, and causing uneven coatings or degradation. Although sustainability prospects are promising, issues such as wash durability, mechanical strength, multi-fiber use, low-temp processing, and regulations remain [31]. Overcoming these requires multidisciplinary innovations to bring lab results to market-ready, sustainable home textiles.

7. Strategies to Overcome Challenges

To overcome bio-based flame-retardant coating limitations, interdisciplinary methods like green chemistry, hybrid materials, and innovative processes are crucial. Using bio-crosslinkers such as citric, tartaric acids, tannic acid, and genipin enhances bonding of bio-FRS to cellulose, improving char formation, wash resistance, fabric feel, and biodegradability. Bio-intumescent systems with phosphorus/nitrogen bio-polymers and inorganic fillers like phytic acid, chitosan, nano-SiO_2, and Tio_2 boost flame retardancy via dehydration, char creation, and heat barriers across fiber blends. Surface modifications through plasma or enzymes improve bonding and uniformity. Process innovations like pad-dry-cure, layer-by-layer, and UV spraying allow scaling with less fiber damage. Waste-to-resource strategies from agricultural waste and plant extracts support sustainability. Life cycle and safety assessments ensure bio-FRs is breathable, durable, and safe. Overall, integrating green chemistry, hybrid systems, surface treatments, and scalable methods produces effective flame-retardant textiles [32].

8. Future Perspectives

Bio-based flame-retardant textile coatings are becoming multifunctional, addressing fire safety, environmental standards, and comfort. They can self-heal, block UV, and suppress smoke using responsive polymers, nanoparticles, or plant antioxidants, enhancing durability. Hybrids with bio-FRs, extracts, biopolymers, minerals, and proteins aim to improve protection via char formation and gas-phase quenching as new compounds emerge [33]. Development will move from trial-and-error to predictive methods, guided by regulations, sustainability, lifecycle assessments, and circular economy principles using renewable, recyclable resources. Scalable methods like coating and spray deposition allow mass production and sustainability via agricultural and industrial by-products. Success depends on collaboration among researchers, manufacturers, and regulators. Bio-FRs will use intelligent systems, hybrid approaches, AI, and eco-technologies to create safe, high-performance, sustainable flame-retardant textiles aligned with fire safety and environmental goals [34].

9. Conclusion

Bio-based flame-retardant (FR) coatings offer a sustainable alternative for textiles like cotton and bamboo, using natural extracts, chitosan, biopolymers, phytic acid, and hybrid formulations to enhance heat stability and flame retardancy while reducing ecological and health risks. These systems address char formation, radical quenching, and physical barriers, improving fibre protection. Challenges include maintaining fabric feel and adherence, which is addressed through green cross-linkers, surface activation, and nano-fillers. Hybrid systems with plant extracts, biopolymers, and minerals provide improved safety. Future directions involve AI, smart coatings, low energy use, and stakeholder collaboration. Bio-FRs improve fire safety and environmental health, with ongoing efforts to enhance efficiency, replace toxic treatments, and develop safe, high-performance solutions. Major barriers include low-temperature curing and wash durability. New eco-friendly and multifunctional biopolymer systems are needed for fully recyclable, flame-retardant textiles.

Acknowledgement

The authors gratefully acknowledge the management of PSG College of Arts and Science (PSG CAS) and the Department of Costume Design and Fashion, PSG CAS (Autonomous), Coimbatore, India, for their continuous support and encouragement.

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Journal of the TEXTILE Association

ISSN 0368-4636

Strategies for Achieving Sustainable Development in the Indian Textile Industry

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Abstract:

India is renowned for its textile materials which have been attracting global attention through its traditional costumes and attires. However, the country lacks internationally compatible technology, leading to a shift towards pollution prevention measures. The textile industry is exploring environmentally friendly substitutes for traditional chemical methods in wet-processing textiles, such as enzyme treatment and biodegradable polymers. These substances are abundant, renewable, and compatible with living organisms, providing functional characteristics in cellulosic textiles like antibacterial, UV-protection, and flame-proof qualities. However, further research and development are needed to improve manufacturing and implementation of applications in textile finishing processes. This paper reviews the significance of implementing sustainable practices in the traditional Indian textile value chains. The use of plant and herbal extracts, essential oils, and natural colors are not only cost-effective, but also non-toxic, renewable, and sustainable, resulting in little environmental impact.

Keywords: *effluent, Enzymes, health hazards, pollution, sustainability*

Citation: Saatish Lavate, Aadhar Mandot, Aravin Prince Periyasamy, "Strategies for Achieving Sustainable Development in the Indian Textile Industry", *Journal of the Textile Association*, **86/4** (Nov-Dec'25), 425-431, https://doi.org/10.63665/jta.v86i4.6

Article History : Received : 13-10-2025, Revised: 17-11-2025, Accepted: 21-11-2025

1. Introduction

To ensure their survival, every individual necessitates clothing, it is important for fundamental existence and should never be disregarded. The textile sector, as the largest employer globally, must meet the increasing demands of the public for superior product quality, variety, durability, and other technological requirements. Nevertheless, the global interest in natural dyes has been rekindled due to the harmful and detrimental impact of synthetic colors on all living organisms. However, even natural dyes are seldom environmentally friendly, as they need the use of certain mordants. Mordants, such as chromium, are utilized to permanently bind color onto cloth [1, 2]. They possess a significant level of toxicity and can greatly affect the quality of effluent.

Textile mills discharge vast quantities of dangerous toxic waste.The effluent comprises sulphur, naphthol, vat dyes, nitrates, acetic acid, soaps, chromium compounds, heavy metals, and auxiliary chemicals [3]. It frequently exhibits elevated temperature and pH levels, resulting in turbidity, unpleasant odour, and hindering the penetration of sunlight necessary for photosynthesis. The reduction of dissolved oxygen in water is a significant concern, as it impedes the natural purifying process of water. The discharge also obstructs the pores in the soil, resulting in reduced production and compacted soil texture. The effluent causes corrosion in sewage lines, impacts the quality of drinking water, and escalates maintenance expenses. Water impurities have a detrimental impact on textile processing, resulting in the appearance of yellow hues in white fabric and a lack of vibrancy in colors. Textile wastewater is a significant contributor to both environmental deterioration and human health issues. Approximately 40% of colorants used worldwide include organically bonded chlorine, which is a known carcinogen [4]. The presence of organic substances in textile wastewater is a significant issue in water treatment, since they tend to react with disinfectants, particularly chlorine. Chemicals can undergo evaporation and may also be absorbed via skin, leading to allergic responses and possible injury to children, even those who are still in the womb. The use of dyestuff is causing environmental concerns, prompting the need for legislation to improve health, safety, and environmental well-being. Consumers are increasingly prioritizing eco-friendly products, with a growing demand for sustainable clothing [3, 5 & 6]. Factors such as renewability, ecological footprint, and chemical usage in growth or processing determine a material's eco-friendliness. Textile companies that adopt eco-friendly techniques, such as wastewater reuse and recycling, can not only increase revenues but also contribute to environmental preservation. This trend towards eco-friendliness is a significant shift in consumer preferences, highlighting the need for sustainable textile production.

India's textile industry pollutes water more than usual. Wet finishing in textile baths releases wastewater into the environment. Many textile dyes and chemicals are non-biodegradable [7]. Industrial effluents pollute Bhavani and Noyal rivers in Tamil Nadu. Total dissolved solids (TDS)

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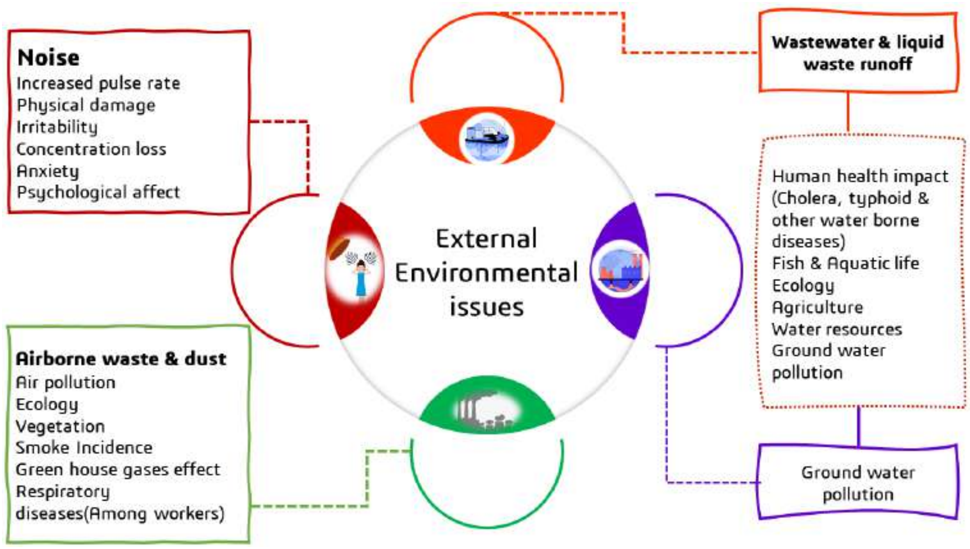

Figure - External Environmental Issues and their impacts

suspended solids (SS), biological oxygen demand (BOD), chemical oxygen demand (COD), chlorides, sulphates, and phenols exceeding acceptable limits endanger aquatic organisms and cause aesthetic and functional problems [4]. Cholera, typhoid, hepatitis, and gastroenteritis are common waterborne infections. Temperature, alkalinity, odor, and dye-related hues are common in textile effluents. Fish are affected by water pollutants and the toxic substances in water reduce biodiversity [8, 9]. Water turbidity blocks light, hindering plant development. In India, agricultural runoffs, sewage, and industrial effluents pollute water. WHO guidelines classify 70% of India's surface water as extremely contaminated [10].

Air pollution and Textile Industry

Textile industry contaminates air with solvent vapors such as ammonia and formaldehyde. Use of coal or natural gas for energy, emitting harmful gases that negatively affect nearby residents' health. Cotton dust from spinning can cause serious respiratory infections. WHO limits are 150 micrograms per cubic meter, yet major cities average over 360 micrograms. Increased public awareness of air pollution has resulted in stricter environmental regulations [11]. Dust from various materials, such as fiber, coal, ash, saw, and grain, can cause inhalation and air pollution. Inhaling cotton dust during textile processes can lead to health issues like asthma. While larger textile industries use extraction equipment, smaller sectors still lack such methods. To control dust and maintain safe concentrations, methods must be developed [12]. Apart from that, textile industry also generates toxic waste from textile processes, including fiber preparation, dying, printing, bleaching, and cleaning, can be found in effluent. [13–16].

2. Pollution from various Textile supply chain

The risk of dust explosions in the textile sector is regarded to be minimal or insignificant due to the inadequate understanding of the explosive characteristics of textile fibers (a). These fibers have only recently been recognized as hazardous materials in the technical requirements for protecting against explosions in industrial processes. Wet processing of textiles is a major source of water-based pollution, with air pollution from chemicals and lint being minor [4, 17]. Water quality data from a few textile factories in India reveals that the wastewater produced during the manufacturing process is highly polluted and potentially harmful (b & c). The data in makes it clear that the wastewater produced during the textile manufacturing process is extremely polluted and potentially harmful. Synthetic fibers are sized with water-soluble sizes, making them easy to scour or wash in a hot water cycle. Cotton and other natural fibers are sized with starch and other non-water-soluble materials, which are highly biodegradable and target waste treatment bacteria. Scouring is a chemical process used to eliminate dirt and debris from fibers, yarn, or fabric. Impurities include synthetic or natural lubricants, dirt, water-soluble sizes, antistatic agents, and fugitive tints. In a scouring bath, natural oils are saponified by alkali, while non-saponifiable impurities are emulsified and suspended by surfactants. Bleaching is a chemical process used to remove dyes and other distasteful substances from fibers, yarns, and fabrics, making them ready for further processing like dying or printing. Common bleaching agents include sodium hypochlorite, sodium chlorite, sulphur dioxide gas, and hydrogen peroxide [4].

Auxiliary used in sizing mixture include Adhesives and binders: Natural gum, (locust bean gum, gelatin, soya protein casein, acrylates, PVA, CMC). All these materials can be found in desizing operations waste streams if they were originally present in the size mixture but were later removed during wet processing. Sizing agents are responsible for up to 80% of the total COD load in wastewater, and most of these additives have very high BOD values. Almost none of these additives have ever been tested for toxicity [7, 18].

Table 1 - Wastewater generated from Indian Textile processing mills as against standards

Characteristics	Units	Standard	Cotton	Synthetic	Wool Scouring	Wool dyeing / Finishing
pH	-	5.5 – 9.0	8 – 12	7 – 9	3 – 10	5 -10
Alkalinity (as CaCO3)	mg/L	-	180-7300	550-630	80-100	240-300
Dissolved solids	mg/L	-	2100-7700	1060-1080	10000-13000	800-1000
Suspended Solids	mg/L	100-600	35-1750	50-150	5000-6000	500-700
BOD (5 days 20°C)	mg/L 5days	30-350	150-750	150-200	5000-8000	500-600
COD	mg/L day	250	200-2400	400-650	10000-20000	1700-2400
Phenols	mg/L		0.030-1.00	-	-	-
Oils & Grease	mg/L		4.5-30.00	-	2000-2500	400-500
Chlorides	mg/L		80-1500	100-200	200-350ppm	100-150ppm
Sulphates	mg/L		30-350	50-100	-	10-20ppm

Chemicals and dyes used in the process of dyeing fabric or printing can contribute to air pollution. These may have been caused by the dyes (e.g., salt, surfactant, levellers, lubricants, and alkalinity). Chemicals utilized in the dying, upkeep, and cleaning of machinery are also linked to environmental damage. Priority areas for pollution prevention include reducing the number of metals, salts, and colorants used in the dyeing process [6, 19]. It has been estimated that in a typical cotton finishing operation, the dyeing process accounts for 7% of the water used and 5% of the BOD. The finishing process produces airborne and ground-based pollutants, including fabric remnants, fiber dust, paper tubes, and chemical drums. Liquid waste includes used finishing products, tools, and equipments, as well as water used for cleaning. Vapors are released during drying and curing, and hazardous chemicals used in various processes can pose serious health risks to workers.

Fabrics can be colored using various synthetic dyes, including direct, basic, vat, sulfur, and reactive dyes. Exposure to formaldehyde has been linked to various health issues, including nasal and lung cancer, brain cancer, and leukemia. Long-term exposure can lead to respiratory difficulties and eczema. Chemical contact with skin and inhalation can also cause serious health effects. Respiratory sensitizers, such as reactive dyes, can cause asthma caused by occupational exposure to these chemicals. Reactive dyes can trigger allergic reactions, such as runny nose, watery eyes, wheezing, chest tightness, and shortness of breath. Other dyes, such as benzidine-based dyes, have been linked to an increase in cancer risk. It is important to keep a safe distance from corrosive chemicals, as they can cause severe burns and explosive reactions when mixed with other substances [20–23]. The adverse working conditions in the wet processing sector provide significant health risks to humans (Figure 2d), while the discharge of untreated effluents also poses health hazards to animals (Figure 2 e).

3. Change Industry to more sustainable

3.1 Sustainable approaches for textile dyeing

To improve sustainability, it is important to adopt a sensible strategy that incorporates utilising minimal amounts of water and energy in textile production, and also using environmentally friendly chemicals. figure 3 illustrates a classification of progress in sustainable processing [3]. Traditional padding techniques result in significant dye fluid consumption, which contributes to the generation of effluent

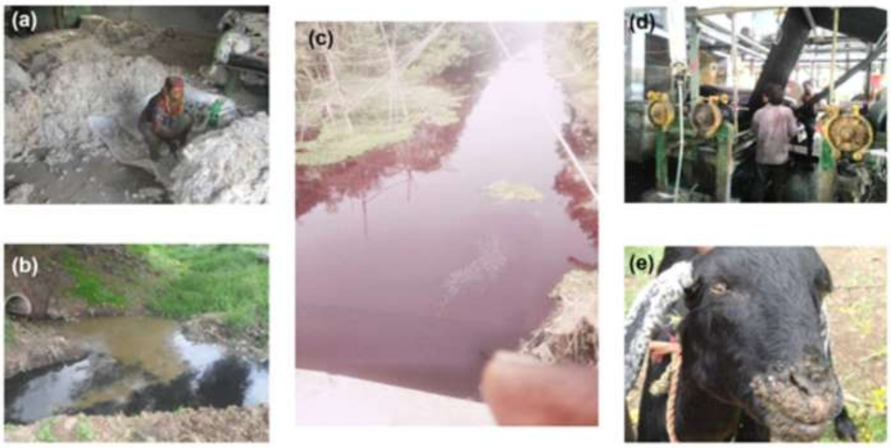

Figure 2 - Working condition of yarn spinning process (a), discharging untreated effluents in the river (b &c), working conditions of wet processing industry in Ichalkaranji (d) and animal health risks near textile manufacturing facilities (e)

and trash. In recent years, there has been a significant emphasis on decreasing the capacity of troughs via research. Benninger has designed U-shaped troughs with a minimal capacity of 10-14 L to reduce the amount of dyestuff and chemicals used. Additionally, these devices have roller adjustments to enhance the flexibility of fabric movement [3]. Alchemie Technology has created an innovative dye application technique that merges the advantages of inkjet printing with the durability of spray systems. The machine employs a set of autonomously regulated rollers to transport the material, while delivering dye at a rapid and accurate rate through 1,440 nozzles on either side of the cloth. The nozzles have a greater diameter compared to the nozzles used in inkjet printers, which prevents problems related to blockage and restrictions in chemistry. The Endeavour system is compatible with conventional dye chemistry and does not necessitate the use of special dyes. The machine is a dual-sided dyeing method, where the textile is flipped within the machine using rollers, and a second set of nozzles dyes the backside of the cloth. This procedure can only be run as a one-sided dyeing process, resulting in reduced energy and chemical use. The Endeavour method utilizes an optimal quantity of dye, hence minimizing water and energy requirements. The machine may be provided either as a standalone dye application unit or with the option of in-line fixing and softening. Additionally, it can be equipped with Alchemie's low water softening technology to further optimize water conservation [22].

Air dyeing process requires minimal amounts of water and energy, resulting in a reduction of 84% in its contribution to global warming. DyeCoo, a Dutch business, has pioneered the creation of the first textile dying machine that is readily accessible for commercial use and obviates the necessity for water and processing chemicals. This process enables the dissolution and deep penetration of dyes into fibers without the need for water or bonding agents. The carbon dioxide (CO_2) is purified and 95% of it is reintroduced into the system for further use. Membrane filtration is an innovative dyeing technique that minimizes water usage by generating a more concentrated waste stream and necessitating a smaller membrane surface for color elimination. The process of dyeing cellulose with direct dyes by exhaust dyeing method has the advantage of using a reduced amount of salt, eliminating the need for fixing alkali, and achieving the necessary level of wet fastness through certain post-treatments. These variables lead to a Dyeing process that is more sustainable and has a reduced environmental effect. The incorporation of these state-of-the-art technologies by the textile sector is essential in promoting a more environmentally friendly and ecologically aware future. Collaboration among governments, corporations, and consumers is vital to promote and implement these sustainable technologies and innovations, therefore guaranteeing a more environmentally friendly and eco-conscious textile sector for future generations [22].

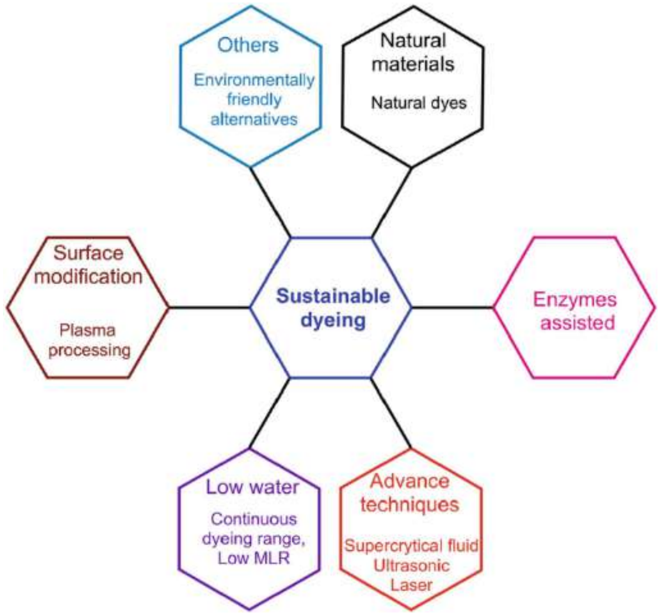

Figure 3 - Sustainable approaches in textile dyeing

Natural dyes

Extensive studies have been conducted on natural colors due to their potential to provide multifunctional features to cellulosic textiles, such as antibacterial, UV-protection, deodorizing, and insect-repellent effects. The use of natural colorants for dyeing has become increasingly popular in research and development activities as well as in the textile industry. This is mostly due to growing worries about the environment, the hazards of water contamination, and the need for sustainable raw materials, processes, and finished products. Pomegranate, madder, Gromwell, indigo, Eucalyptus leaves, turmeric, hard, and henna, which are natural dyes, have been effectively employed to simultaneously color and provide functional finishing to cellulosic textiles. Nevertheless, natural dyes have limitations in terms of their fastness qualities and resistance to washing. In order to address these problems, a range of treatment methods has been utilized, such as the application of metallic salt mordants, bio mordants, pre-chemical modifications, enzymatic treatment, plasma pre-activation, UV-radiation, and sonication. The objective of these techniques is to address these limitations and enhance the efficiency of cellulosic textiles [3, 24].

3.2 Use of Enzymes

Enzymes, such as cellulases, catalase, and laccase, are commonly used in the textile business. These enzymes are employed for starch removal, excess hydrogen peroxide breakdown, textile bleaching, and lignin degradation. The use of enzymes in the textile industry is now undergoing a significant surge due to their highly selective, efficient, non-toxic, and environmentally friendly characteristics. Cellulases are used for denim finishing, whereas lactases are used for decolorization of textile effluents and textile bleaching. Furthermore, the application of enzymes results in reduced processing times, preservation of energy and water resources, improved product quality, and the potential for integrating multiple processes. Cellulase is an essential component in the process of biopolishing in textile finishing. Its main function is to soften cotton fibers after they have been dyed on cloth. Bio stoning, an established finishing process that originated in 1989, is widely favored for its little response time. Non-cellulosic fibers like as polyester or nylon are utilized alongside denim for cellulosic treatment, enhancing the vibrancy of colours. Cellulase treatment safeguards denim from ripping and decolorization post-washing, rendering them pleasant to wear and suitable for the office [25].

Immobilized Enzymes with Nanoparticles

Recently, novel methods have been developed to enhance the productivity and efficiency of enzymes in the textile sector. These techniques involve immobilization and nanoparticle creation, which enhances the effectiveness at different phases of textile finishing. Enzymes are employed to enhance the speed and efficiency of reactions, whereas nanoparticles can be utilized to augment the reaction rate. Enzyme-nanoconjugates, when combined with other compounds, can enhance the efficiency of processes. An instance of nano-conjugates consisting of citric acid and Fe3O4 with protease has been formulated for the purpose of pretreating wool. This treatment has the effect of enhancing the wool's tensile strength and its ability to withstand alkaline conditions. Nanoparticles with immobilized enzymes have enhanced catalytic activity, making them suitable for augmenting production rates. The eco-friendly treatment of denim fabric involves the use of ZnO and TiO2 nanoparticles, in addition to citric acid/sodium. Advanced methodologies are now employed in the process of bioremediation for the treatment of wastewater. The process of denim polishing, once known as “stone washing”, has been substituted with bio stoning, an eco-friendlier and more economical alternative. Applying cellulase treatment to non-cellulosic fibers such as polyester or nylon can enhance color intensity and provide protection against ripping and color fading after washing. Several textile manufacturers have obtained patents for cellulase enzymes derived from promising species because of to their numerous benefits and extensive application in denim washing [25].

3.3 Use of Biomaterials as green, sustainable finishing agents

The recognition of cutting-edge, long-lasting, environmentally friendly, and economically advantageous cellulosic textile goods has experienced a substantial rise. Hence, researchers are keen on exploring green chemicals and devising ecofriendly techniques and new technologies to create novel and sustainable cellulose-based textiles with desirable functional characteristics. The use of biopolymers in the functional finishing of cellulosic textiles is gaining significant interest as an environmentally benign substitute for toxic and harmful textile chemicals. Biopolymers offer a way to modify and enhance the functionality of textile materials [26].

Chitosan

Chitosan, an amino polysaccharide biopolymer, has substantial potential uses in diverse industries such as biomedical, food, agriculture, cosmetics, textiles, and pharmaceuticals (Figure 4a). The material shows promise due to its non-toxicity, biocompatibility, biodegradability, and antibacterial properties. The antibacterial activity of chitosan is affected by several parameters such as the kind of deacetylation, molecular weight, and type of microbe, pH, and the addition of nonaqueous solvents. Chitosan possesses a wide range of antibacterial properties against bacteria and fungus because of the electrostatic interaction between positively charged amine groups and negatively charged residues on the cell surface. Elevating the positive-charge density of chitosan can enhance its antibacterial efficacy. Nanocomposites of modified chitosan can also provide functional and performance characteristics such as anti-crease and flameproof qualities. Nevertheless, the limited affinity of chitosan to cellulosic materials is a significant disadvantage. Several methodologies have been devised to enhance the fixation and functioning of chitosan [26].

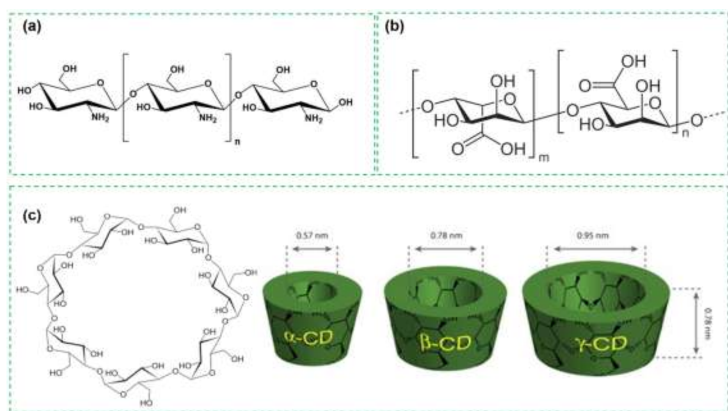

Figure 4 - Chemical structure of chitosan (a), Chemical structure of sodium alginate (b) and cyclodextrin and its various form

Sodium-ALG (SA)

Sodium alginate (SA) is a naturally occurring polysaccharide derived from seaweeds. It is composed of polyguluronate and poly-mannuromate polymers, as well as their copolymer (Figure 4 b). The compound has a range of molecular weights spanning from 32,000 to 400,000 g/mol and demonstrates low solubility in cold water. The viscosity of SA is directly proportional to its molecular weight and inversely proportional to the pH level, namely between 3 and 3.5. When cross-linked with divalent cations, this material exhibits good sol-gel forming properties, however monovalent cations or Mg2+ are not appropriate for this purpose. The industrial use of SA is linked to its composition of uranic acid. Possible uses of this technology includes treating wounds, releasing, and containing biocides, absorbing antimicrobial ions, and providing antimicrobial coatings. Additionally, it serves as a stabilizer in the process of synthesizing nanoparticles [26].

Cyclodextrin (CD)

Cyclodextrins (Cds), which are cyclic oligosaccharides formed by the breakdown of starch, include properties such as biocompatibility, biodegradability, environmental friendliness, and safety. As a result, they find use in many sectors including medicines, food, cosmetics, and textiles. Their classification includes three types: α-CD, β-CD, and γ-CD (Figure 4 c). β-CD is widely utilized for modifying cellulosic fabrics due to its limited solubility. Cyclodextrins (CDs) have the potential to create host-guest complexes with solid, liquid, and gas molecules. This property enhances several aspects such as solubility, stability, volatility, sublimation, control of active component release, and prevention of disorder. The strength of these complexes is contingent upon several parameters, including the size of the guest molecule, van der Waals contacts and the release of water, hydrogen bonding, charge-transfer interactions, and hydrophobic interactions. β-CDs have been extensively used in the functional treatment of cellulosic fabrics, such as fragrance and antibacterial finishes, medicinal textiles, and UV-protection finishes. Additionally, the immobilized CD cavity retains its ability to form inclusion complexes with other molecules [27].

3.4 Regulation and guidelines for Pollution Prevention

The Indian textile sector must implement pollution thresholds and stringent regulations to effectively manage and mitigate pollution. To do this, the industry should prioritize the reduction of water use and the improvement of chemical utilization in processing. Some recommendations consist of selecting the suitable fabric type and weight for process variables, regulating batch sizes, refraining from using spinning oils and non-biodegradable surfactants, employing transfer printing on synthetic materials, implementing pad batch dying, avoiding dyes that contain heavy metals, utilizing less harmful dye solvents and finishing chemicals, employing peroxide oxidation for vat dyes and sulfur dyes, and substituting sulfur- and chlorine-based alternatives with peroxide-based bleaches. It is advisable to limit the usage of strong chemicals in cosmetics, repurpose and recycle corrosive and other process chemicals, replace non-biodegradable spin finishes with biodegradable alternatives, and protect textiles with decomposable chemicals. In addition, it is imperative for enterprises to uphold appropriate water quality and temperature standards, minimize water consumption by utilizing less than 150 m^3 of water per metric ton of textiles manufactured, and repurpose the warm water from washing machines for residential heating purposes. Using environmentally sustainable manufacturing techniques and the mitigation of pollution, businesses may achieve positive outcomes for both their operations and the natural environment. In order to decrease the amount of volatile organic compound emissions to less than 1 kilogram of carbon per ton of fabric (or 20 mg/N.m^3), one can use techniques such as channeling the air collected from regions where solvents are used to a combustion system. The maximum permissible wastewater loads per metric ton of fabric manufactured should not surpass 150 cubic meters, with the optimal range being between 100 and 200 cubic meters. The implementation of these steps can enable the Indian textile sector to make a substantial contribution towards achieving a more sustainable and ecologically conscious future.

4. Conclusion

The textile industry is exploring eco-friendly alternatives to traditional chemical methods in wet processing. Enzymatic therapy is a promising technology for improving efficiency in biotechnological processes. Enzymes in textile wet processing have endless potential uses. Biodegradable polymers are abundant, renewable, and compatible with life, emerging as eco-friendly alternatives to harmful industrial chemicals and additives. These substances enhance functional traits in cellulosic textiles, including antibacterial, UV protection, and flame resistance. Further research is needed to enhance manufacturing and application in textile finishing processes for future potential. Plant and herbal extracts, essential oils, and natural colors are affordable, safe, renewable, and sustainable. However, their durability and fastness are limited. Investigations focus on improving longevity through crosslinking, β-CD grafting, microencapsulation, pre-modification of cellulosic substrates, and mordents for natural dyes. Improving extraction techniques and their practical use, considering economic and ecological factors, remains a major challenge. Using biological pathways like microbes, plant extracts, and biopolymers offers benefits for creating eco-friendly, biocompatible, non-toxic, and cost-effective solutions. Issues remain with size control, homogeneity, distribution, and stability. More investigation is needed to produce and attach biologically synthesized inorganic nanoparticles for durable functional cellulosic textiles.

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ISSN 0368-4636

Optimizing Fiber Blends: Impact on Handle and Mechanical Properties of Handloom Curtain Fabrics, Part –I

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Abstract:

This study examines the structural, mechanical, and tactile properties of woven polyester-based blended fabrics polyester-silk (PS), polyester-cotton (PC), and polyester-wool (PW) with varying blend ratios, specifically assessing their appropriateness for curtain applications. Structural analysis showed that PS blends, especially 65/35 and 80/20, are light and compact, while PC and PW blends are thicker and denser. Testing for abrasion resistance showed that adding more polyester makes the material much more durable. The PS and PC 80/20 blends had the highest resistance, lasting up to 32,000 cycles. Silk's smoothness made PS blends the best at resisting pilling, while PC blends were only moderately resistant, and PW blends were the least resistant. Mechanical tests showed that PC blends, especially 65/35 and 80/20, had the highest tensile and tear strengths, which made them the most durable. PW blends, on the other hand, had worse mechanical performance. The results show that the type of fiber and the blend ratio have a big effect on how well the fabric works. Polyester-rich PC blends have the best balance of properties for curtains that will last a long time and look good. These results offer significant direction for the selection and advancement of textiles in the home furnishing industry.

Keywords: *Abrasion Resistance, Fiber Blend Ratio, Pilling Resistance, Tearing & Tensile Strength*

Citation: Ushma Saini, Ramratan Guru, "Optimizing Fiber Blends: Impact on Handle and Mechanical Properties of Handloom Curtain Fabrics, Part –I", *Journal of the Textile Association*, **86/4** (Nov-Dec'25), 432-437, https://doi.org/10.63665/jta.v86i4.13

Article History : Received : 27-09-2025, Revised: 12-10-2025, Accepted: 16-10-2025

1. Introduction

Curtain fabrics contribute both practicality and aesthetic appeal to interior design. They improve decorative aesthetics, regulate light, maintain privacy, and provide thermal insulation, all of which have an impact on the atmosphere of a room. The performance, durability, and tactile qualities of the fabric are significantly influenced by the fiber composition selection. The fiber blend ratio is one of the most important factors influencing the properties of fabric [1]. Since it has a direct impact on drape, handle, tensile strength, and pilling resistance. Polyester's cost-effectiveness, durability, and resistance to wrinkles make it a popular synthetic fiber in the textile industry. However, the breathability, softness, and opulent texture that natural fibers provide are frequently absent from polyester-only textiles [2, 3]. Polyester is frequently mixed with natural fibers like cotton, wool, and silk to get around these restrictions. Silk improves luster and drapability, wool adds warmth and durability, and cotton increases comfort and breathability.

Curtain fabrics are important for both the look and the function of a room. They add style and privacy, keep the heat in, and keep the sun out. When choosing the right curtain materials, you need to think about a lot of different things, such as how long they will last, how easy they are to handle, how strong they are, and how well they resist wear and pilling [4, 5]. Polyester-based blended fabrics have gotten a lot of attention because they can combine the best qualities of both synthetic and natural fibers. Previous research has highlighted the substantial impact of fiber composition and blend ratio on fabric performance. Polyester is often mixed with natural fibers to make woven fabrics more useful [6, 7]. This is because polyester is strong, resistant to wear and tear, and stable in size. For instance, polyester-cotton (PC) blends have long been known for their perfect balance of strength and comfort, combining the durability of polyester with the softness and breathability of cotton. Because they are more comfortable and have better mechanical properties, these kinds of blends are commonly used in home textiles like curtains and upholstery [8-12]. People are also interested in polyester-silk (PS) blends because they combine the strength and durability of polyester with the smooth feel and luxurious look of silk. According to previously research work these blends exhibit excellent pilling resistance and a refined aesthetic, making them suitable for high-end curtain applications where appearance retention is crucial [13, 14]. Their mechanical properties are good enough, but they may not always be as good as those of PC blends, especially in high-stress situations. On the other hand, polyester-wool (PW) blends combine the warmth and bulkiness of wool with the strength of polyester. Yet, studies have shown that wool fibers, due to their softness and entangled structure, are prone to faster breakdown and inferior abrasion and pilling resistance compared to other blends [15, 16 & 24]. So, PW blends are usually only used for decorative or specialty textiles and not for tough household tasks. Even though there is more and more research on the mechanical and surface properties of polyester-based blends, there hasn't been much research that systematically compares these blends especially PS, PC, and PW at different ratios in the context of curtain fabrics. This study fills this gap by looking at the structural, abrasion, pilling, tensile, and tear strengths of nine woven polyester-based blends. In this research, we studied polyester blends with cotton, silk, and wool in handloom-

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made curtain fabric, focusing primarily on fiber blend ratios and their effects on tensile and handle properties. it will be more helpful for this research in future work related to curtain fabric and technical data knowledge related to these areas.

2. Material and Methods

2.1. Material

The as indicated in Table 1, nine fabric samples were made for this investigation using blended yarns with different blend ratios of polyester, cotton, wool, and silk (50/50, 65/35 and 80/20%). Table 2 gives the fiber parameters.

Table 1: Sample for handloom fabrics

S. No.	Types of Material
1	Polyester 50% + Cotton 50%
2	Polyester 65% + Cotton 35%
3	Polyester 80% + Cotton 20%
4	Polyester 50% + Silk 50%
5	Polyester 65% + Silk 35%
6	Polyester 80% + Silk 20%
7	Polyester 50% + Wool 50%
8	Polyester 65% + Wool 35%
9	Polyester 80% + Wool 20%

Table 2: Fiber's parameter

Fiber	Length (mm)	Fineness
Polyester	36	1.3 D
Cotton	32 (Avg. effective)	3.8 mic
Wool	30	3.5 mic
Silk	36	1.3 D

2.1.1. Preparation of yarns

The yarn denier was kept constant at 30 Ne to ensure equivalent fabric properties. During the yarn manufacturing process, pilot machines such as the carding machine, draw frame, simplex, and ring frame were used. All of these pilot machines were available at Sangam Pvt. Ltd., Bhilwara.

2.1.2. Preparation of fabric samples

Using different blended yarns, all of which were handloom-woven, nine handloom fabric samples with a Plain structure (as indicated in Table 1) were created. These fabrics were produced by local industries in the Varanasi area of India.

Figure 1: (a) Polyester/Silk (80:20), (b) Polyester/Silk (50:50), (c) Polyester/Silk (65:35)

Figure 2: (a) Polyester/ Wool (80:20), (b) Polyester/ Wool (50:50), (c) Polyester/ Wool (65:35)

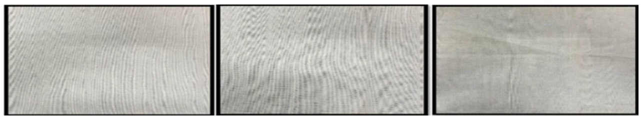

Figure 3: (a) Polyester/ Cotton (80:20), (b) Polyester/ Cotton (50:50), (c) Polyester/ Cotton (65:35)

2.2 Test Methods

The samples are conditioned for 24 hours before testing, and the woven curtain fabric will be subjected to typical atmospheric conditions of 65+/-2% RH and 27+/- 2 oC.

2.2.1. Thread Density and Fabric Mass (GSM)

Thread density, expressed as ends per inch (EPI) and picks per inch (PPI), quantifies the number of warp (EPI) and weft (PPI) threads in a woven fabric. This parameter influences fabric compactness, strength, and surface texture. Measurement followed IS: 1963-1981, ensuring consistency in woven fabric analysis. Higher thread density correlates with tighter weaves, enhancing durability and stability, while lower density improves breathability and lightness. Fabric mass, measured in grams per square meter (GSM), indicates weight per unit area, reflecting thickness and durability. Testing adhered to IS: 1964-01. High GSM is Heavier, robust fabrics for upholstery or outerwear, whereas Low GSM is Lightweight, breathable materials for linings or summer textiles. GSM is critical for quality control and application suitability [20, 25 & 26].

2.2.2. Pilling Resistance

External Pilling resistance (IS: 10971-1984) - Evaluates surface fuzz formation using IS: 10971-1984 (Innolab tester). Rated 1 (severe pilling) to 5 (none). High resistance is essential for apparel and furnishings to maintain aesthetics. Typically, samples that have been cleaned (either by washing or dry cleaning) are used to create specimens. This will assist in extending the cork liners' usable life. To guarantee that the crucial requirements of the standards are met, strict quality monitoring of the tubes and liners is necessary.

2.2.3. Abrasion Resistance

The abrasion resistance is determined by a Martindale (Amtlicher Anzeiger). Durability test on the EN 388(1994b) a test machine with an abrasive paper (ENGelsliesyandaetamon1982) (OAKEY Glass Quality Cabinet Paper Grade F2 Grit 100) is quite aggressive. Circular specimens of materials into the abrasion at pressure (9± 0.2) kPa. The abrasion resistance is quantified in cycles so as to introduced to trigger breakthrough [20, 22].

2.2.4. Tensile strength

The measures how much force the fabric can withstand when pulled lengthwise before breaking. This is especially important for curtains that undergo regular handling, such as opening and closing, or for heavier drapes that bear their own weight over time. A fabric with high tensile strength resists stretching and deformation, maintaining its shape and structure even with daily use. Tensile strength measures maximum load-bearing capacity before breakage, while elongation quantifies stretch percentage under tension. Evaluated via IS: 1969-1985 (strip method). Tensile strength (N/kgf) indicates durability, whereas Elongation (%) reflects flexibility. These metrics determine performance under mechanical stress.

2.2.5. Tearing Strength

Tear strength assesses resistance to tear propagation post-initial rupture, vital for heavy-duty applications. Measured in grams per IS: 6489-1990 (Elmendorf tester). Higher values: Enhanced tear resistance, whereas Lower values: Lightweight, less durable fabrics. On the other hand, determines how well the fabric resists ripping once a small cut or snag occurs. Curtains can accidentally get caught on sharp objects or experience stress at seams, so a high tear resistance prevents minor damage from turning into large, unsightly rips. Together, these properties ensure that curtain fabrics are not just visually appealing but also durable enough to withstand everyday wear and tear. By prioritizing both tensile and tear strength, manufacturers create curtains that balance beauty with long-lasting functionality - perfect for homes, offices, and high-traffic spaces.

3. Result & Discussions

The table 3, compares the structural properties of different polyester blends, focusing on yarn density, fabric mass, and thickness. In the PS (polyester-silk) series, thread density is higher, with PS 65/35 having 148 ends and 74 picks per inch. This results in a fabric mass of 98 GSM and a thickness of 0.48 mm, making it lightweight but compact. As the polyester proportion decreases, thread density also drops, like in PS 50/50 with 120 ends and 72 picks, showing a slight reduction in GSM to 95. The PS 80/20 blend, though lower in density, has a higher GSM (106) and thickness (0.51 mm). In the PC (polyester-cotton) series, thread density is constant at 50 ends, with 26 or 28 picks, leading to higher GSM (up to 191) and greater thickness (0.59 mm). Similarly, the PW (polyester-wool) blends follow the same structure as PC, with GSM ranging from 185 to 192, indicating durable, resilient fabrics.

3.1. Abrasion Resistance

The abrasion resistance of fabrics is an important factor that affects how long they last and how well they work for different purposes, especially in clothing and upholstery. This study measured the abrasion resistance of polyester/silk (PS), polyester/cotton (PC), and polyester/wool (PW) blended fabrics by counting how many cycles it took to see noticeable wear at different blend ratios. The findings indicate that PS and PC blends, especially with a higher polyester ratio (80/20), demonstrate enhanced abrasion resistance, achieving values of up to 32,000 cycles. That augmenting the polyester content in blended fabrics markedly improves their abrasion resistance, attributable to polyester's superior tensile strength and smooth surface. The 50/50 blend had the lowest value (18,000 cycles), which means that PW blends were less resistant to abrasion. The found that wool fibers break down more quickly when they are rubbed against each other over and over again because they are softer and less durable. The findings further demonstrate that cotton blends (PC) exhibit moderate abrasion resistance (25,000–32,000 cycles), In general, the study shows that the type of fiber and the blend ratio have a big effect on abrasion performance, with higher polyester content always making things last longer. These results corroborate prior studies, underscoring that fabric blends enhanced with polyester are optimal for applications necessitating superior wear resistance [17, 18, 20 & 22].

Table 4: Fabric handle property: Pilling and Abrasion resistance

S. No.	Sample Code	Pilling Grade	Abrasion resistance (No. of cycles)
1	PS 65/35	5	28,000
2	PS 50/50	4	26,000
3	PS 80/20	5	32,000
4	PC 65/35	4	27,000
5	PC 50/50	3.5	25,000
6	PC 80/20	4	32,000
7	PW 65/35	3.5	20,000
8	PW 50/50	3	18,000
9	PW 80/20	3.5	23,000

Table 3: Index property

Sr. No.	Sample Code	Thread Density		Fabric Mass (GSM) (Gram/Sq. Mtr.)	Thickness (mm)
		Ends/Inch	Picks/Inch		
1	PS 65/35	148	74	98	0.48
2	PS 50/50	120	72	95	0.46
3	PS 80/20	100	72	106	0.51
4	PC 65/35	50	26 (Per pick 2 thread)	187	0.58
5	PC 50/50	50	26 (Per pick 2 thread)	185	0.53
6	PC 80/20	50	28 (Per pick 2 thread)	191	0.59
7	PW 65/35	50	28 (Per pick 2 thread)	191	0.59
8	PW 50/50	50	28 (Per pick 2 thread)	185	0.57
9	PW 80/20	50	28 (Per pick 2 thread)	192	0.60

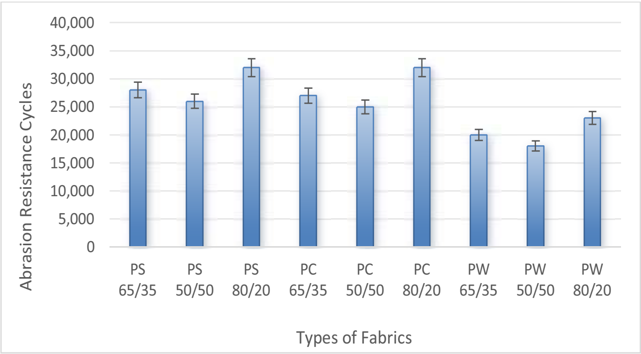

Figure 4: Abrasion resistance test PC, PS, PW Blend Ratio (80/20, 50/50, 65/35)

3.2. Pilling Resistance

The table 4 and figure 5, compares the pilling resistance of nine fabric samples with varying blend ratios and weave types. These handle properties are crucial for assessing aesthetic feel, comfort, and garment suitability.

The evaluation of pilling resistance in polyester-based blends: polyester-cotton (PC), polyester-silk (PS), and polyester-wool (PW), reveals distinct differences in performance, highlighting the impact of fiber composition on fabric durability and appearance. Pilling, the formation of fuzzy balls due to abrasion, directly affects a fabric's long-term aesthetic appeal. Polyester-silk (PS) blends consistently demonstrated superior resistance to pilling, with 65/35 and 80/20 PS blends achieving near-grade 5 ratings, indicating excellent performance. The smooth and fine nature of silk fibers makes PS blends less prone to tangle and pill formation. Even the 50/50 PS blend performed significantly better than both PC and PW blends, reinforcing silk's role in improving fabric resilience and aesthetic quality. Polyester-cotton (PC) blends showed moderate resistance, with scores ranging from 3.5 to 4. Cotton's natural structure is more susceptible to surface abrasion, though the fabric remains durable for everyday use. In contrast, polyester-wool (PW) blends exhibited the weakest pilling resistance, with the 50/50 blend scoring around grade 3 due to wool's bulkier, more entangled fibers [19, 23]. These findings highlight the importance of fiber selection in creating fabrics for applications where durability and appearance are crucial, such as curtains and upholstery.

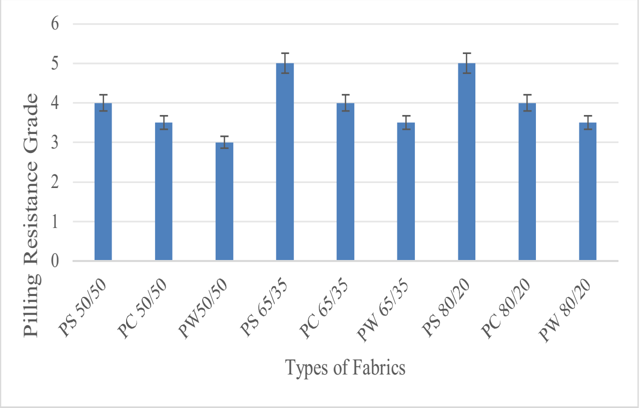

Figure 5: Pilling Resistance Test PC, PS, PW Blend Ratio (80/20, 50/50, 65/35)

3.3. Tearing Strength

The table 5, evaluates and compares the tensile strength, elongation, and tear strength of various woven fabric samples with different fiber blends and weave structures. These mechanical properties are essential for assessing durability, stretch ability, and resistance to mechanical damage, which influence both fabric performance and suitability for specific applications.

The tear strength analysis of polyester-based blended fabrics reveals significant differences in durability depending on fiber type and blend ratio. Tear strength is a critical property for textiles used in high-stress environments, like curtains and upholstery, as it determines how well a fabric resists tearing once damaged. The findings indicate that tear strength is consistently higher in the warp direction than in

Table 5: Mechanical Property

Sr. No.	Sample Code	Tensile Strength				Tear Strength	
		Warp wise		Weft wise			
		Breaking Force (Kg)	Elongation %	Breaking Force (Kg)	Elongation %	Warp-wise (gm)	Weft-wise (gm)
1	PS 65/35	72.3	19.9	59.7	17.6	2370	2176
2	PS 50/50	63.4	19.2	52.7	14.5	2240	2086
3	PS 80/20	80.4	22.1	69.5	15.2	2432	2230
4	PC 65/35	87.8	20.4	74.5	15.1	2500	2400
5	PC 50/50	74.8	17.1	61.5	13.7	2300	2100
6	PC 80/20	92.5	18.9	81.2	15.2	2600	2500
7	PW 65/35	62.4	18.7	51.5	13.7	2165	1954
8	PW 50/50	54.3	20.5	44.8	13.4	2000	1800
9	PW 80/20	72.8	19.3	66.2	13.8	2284	1987

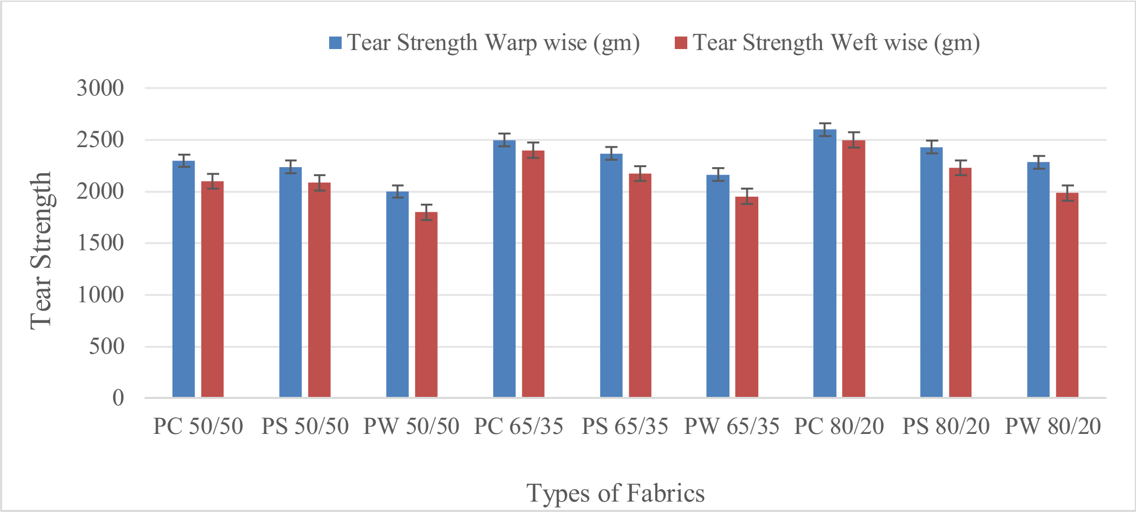

Figure 6: Tear Strength on PC, PS, PW Blend Ratio (80/20, 50/50, 65/35)

the weft, due to the structural advantages of tightly packed warp yarns, which enhance resistance to tearing forces. Among the fabric blends, polyester-cotton (PC) fabrics displayed the highest tear strength, particularly the 65/35 blend. This blend strikes an optimal balance, with polyester providing durability and cotton contributing firmness. Even the 80/20 PC blend showed strong performance, confirming that higher polyester content can further increase strength while maintaining cotton's structural support. Polyester-silk (PS) blends ranked second, offering moderate tear strength. While not as strong as PC fabrics, PS blends provide an ideal balance of durability and softness, making them suitable for applications where aesthetics and drape are important. In contrast, polyester-wool (PW) fabrics exhibited the weakest tear strength, especially in the weft direction. Wool's bulkier fibers offer warmth but less resistance to tearing. This makes PW blends less suitable for high-stress applications but more appropriate for use in specific niche markets.

3.4. Tensile Strength

The analysis of tensile strength in polyester-based blended fabrics reveals how fiber composition and blend ratios influence fabric durability and performance. Tensile strength is a crucial property, as it determines a fabric's ability to withstand stretching or pulling forces, making it particularly important for applications like upholstery and curtains that experience frequent handling. Consistently, fabrics exhibited higher tensile strength in the warp direction due to the greater tension applied to warp yarns during weaving, which are more tightly packed compared to the weft yarns.

Among the blends, polyester-cotton (PC) fabrics were the strongest, with the 65/35 ratio consistently showing the highest tensile strength in both directions. This blend combines polyester's toughness and cotton's firmness, resulting in a durable fabric ideal for high-stress applications like curtains. The 80/20 PC blend also performed well, reinforcing polyester's role in increasing fabric strength. Polyester-silk (PS) fabrics showed moderate tensile strength, with the 80/20 blend outperforming the 50/50 and 65/35 ratios. While silk adds softness and elegance, its contribution to tensile strength is not as significant as cotton. Lastly, polyester-wool (PW) fabrics demonstrated the weakest tensile strength, with wool's bulkier fibers offering less resistance to stress. These findings suggest that PC fabrics,

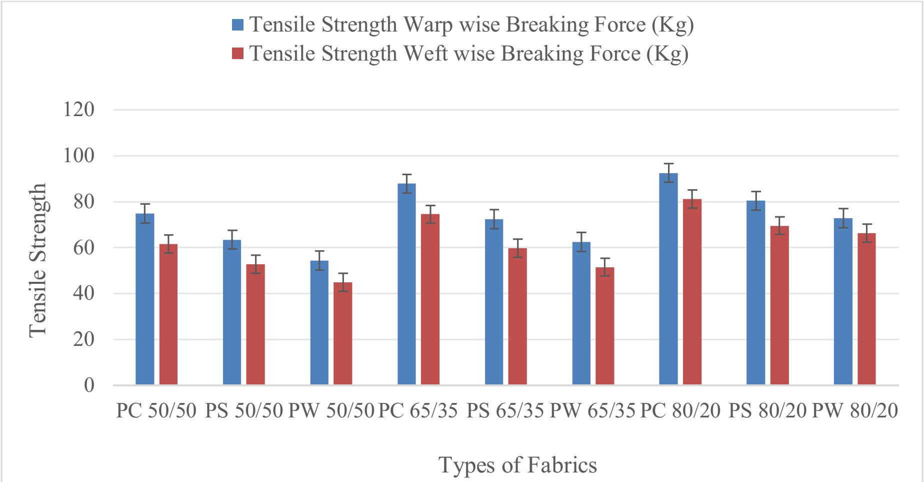

Figure 7: Tensile Strength on PC, PS, PW Blend Ratio (80/20, 50/50, 65/35)

especially at higher polyester content, are best for durability, while PS and PW blends are more suited for specialized uses.

4. Conclusions

The results show that the choice of fiber blends and their ratios have a big effect on how well curtain fabrics work. The study showed that polyester-silk (PS), polyester-cotton (PC), and polyester-wool (PW) blends were very different from each other in terms of their structure, abrasion, pilling, and mechanical properties. PC blends, especially those with a 65/35 or 80/20 ratio, always showed better durability in tests of tensile and tear strength. Because polyester is naturally tough and cotton has a supportive structure, this blend makes fabrics that are not only strong but also able to keep their shape even when they are stressed over and over again. This means that PC 65/35 and PC 80/20 blends are especially good for curtains, which need to be able to be handled and exposed to the elements without getting damaged over time. These blends also had a high resistance to abrasion, which made them even better for homes with a lot of foot traffic. PS blends were the best at resisting pilling because silk is smooth and fine. The 65/35 and 80/20 PS blends kept their great surface look even after a lot of use, which makes them perfect for situations where looks are important. But their mechanical strength is good enough, but not better than that of PC blends. PW blends had the right warmth and texture of wool, but they were the least durable, with lower tensile and tear strength and less resistance to abrasion and pilling. These fabrics might be better for decorative or specialized uses than for everyday curtains in tough places. In the finally the results strongly suggest that polyester-cotton blends, especially those with more polyester, are the best choice for curtain fabric because they are strong, last a long time, and keep their shape. PS blends are better for when you want a soft feel and better resistance to pilling, while PW blends are better for when you need something more specialized and less demanding. These insights can help both manufacturers and consumers choose the best fabrics for curtains, making sure they work well and last a long time in real life.

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Journal of the TEXTILE Association

ISSN 0368-4636

Nyctanthes Arbor-Tristis: Influence of Mordants on Colour Fastness in Artistic Rendering on Cotton & Silk

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Abstract:

Background: *This research addresses the need for sustainable practices in traditional arts by optimising the extraction of natural dye from Nyctanthes arbor-tristis (Parijat) and formulating it into a functional textile paint for Gond art.*

Methodology: *A concentrated aqueous extract was prepared at 90°C for 60 minutes and combined with tamarind seed powder as a natural binder to yield a viscous, paint-like medium. Cotton and silk fabrics were pre-mordanted with myrobalan (Terminalia chebula Retz) and alum, respectively, to enhance dye affinity.*

Results and Conclusion: *The resulting painted textiles demonstrated exceptional colour fastness, with an AATCC light fastness rating of 8 (outstanding) and wash and crocking resistance values of 4-5 (excellent). The optimized paint was effectively applied to create an elaborate traditional Gond motif, proving its viability for specific artistic application. The synergy between the optimized dye composition and mordant system ensured strong colour fixation and durability. This study expands a scientifically proven, eco-friendly alternative to synthetic paints, thereby enhancing the technical repertoire of Gond artists. It enables the creation of marketable, sustainable textile products, supporting cultural preservation while aligning with global demands for ethical and sustainable artisanal goods.*

Keywords: *Colour Fastness, Gond Art, Natural Dye, Nyctanthes arbor-tristis, Optimization, Sustainable Textiles*

Citation: Garima Malik, Sabina Sethi, "Nyctanthes Arbor-Tristis: Influence of Mordants on Colour Fastness in Artistic Rendering on Cotton & Silk", *Journal of the Textile Association*, **86/4** (Nov-Dec'25), 438-444, https://doi.org/10.63665/jta.v86i4.1

Article History : Received :09-10-2025, Revised: 17-11-2025, Accepted: 21-11-2025

1. Introduction

A major paradigm change is occurring in the worldwide textile industry as a result of growing customer demand for sustainable products and environmental consciousness. The transition away from synthetic colourants, whose manufacture and use are frequently linked to high energy consumption, water body pollution, and possible allergic reactions [1]. This has sparked an increased interest in natural colourants, which provide a biodegradable, renewable, and frequently non-toxic substitute for textile colouring [2].

1.1 Nyctanthes arbor-tristis L

India is leading the way in this revival of natural dyes owing to its rich biodiversity and long history of textile production. Nyctanthes arbor-tristis L., sometimes referred to as Night-flowering Jasmine, Parijata, or Harshinghar, has special place among Indian extensive flora [3]. This small tree is revered in Hindu mythology and traditional Ayurvedic medicine for its fragrant nighttime flowers, which are shed at dawn [4].

The flower has a distinctive shape, with lovely, vivid red corolla tubes contrasting with delicate white petals.

These corolla tubes are the primary component of a strong natural colourant that gives it its vibrant colour. It is full of bioactive substances including carotenoids, glycosides (particularly arbortristosides A and B), and tannins. The subtle dull yellow shade can be extracted from these dried flowers.

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1.2. Ancient heritage of natural paints in Gond art

Madhya Pradesh's Gond art is a well-known tribal art form that is distinguished by its elaborate motifs, vibrant colours, and legends drawn from myth and the natural world. Traditionally, the Gond artists developed natural colours and pigments to make artworks on walls and canvas. However, Gond art is presently produced with synthetic colours on paper and canvas, the artisan community is growing more interested in applying the Gond art onto fabrics to expand the range and marketability of their product [5]. According to the pilot study, present day artists face technical skill gaps in replicating the traditional recipes of applying these pigments to textile base. Therefore, this study aimed to overcome this research gap.

However, a transition to sustainable textiles requires pigments made especially for fabric, which provide high washability, durability, and retention. By methodically examining the optimization of colour extraction from Nyctanthes arbor-tristis for its particular application as a natural paint on cotton and silk fabric, this study attempted to bridge this gap. In addition, practical products using developed natural paints were constructed to enhance their market.

2. Materials and Methods

This research was designed to systematically develop and optimize a natural paint from Nyctanthes arbor-tristis L. (Harshinghar) flowers for application in Gond art on textile substrates. The experiments were conducted in Lady Irwin College Laboratory and Dyeing Laboratory at Weaver's Service Centre, Delhi, from June 2023 to February 2024. The methodology was executed in five phases.

Phase 1: Documentation of Challenges in Gond Art Practice and Formulation of Research Intervention

Phase 2: Substrate Selection and Pre-Treatment of Cotton and Silk Fabrics

Phase 3: Extraction Optimization and Formulation of Natural Dye-Based Printing Paste

Phase 4: Performance Evaluation of Painted Textile Samples

Phase 5: Prototyping and Product Development for Artistic Application

2.1 Phase 1: Documentation of Challenges in Gond Art Practice and Formulation of Research Intervention

A foundational diagnostic phase was conducted to identify the core challenges hindering the use of natural colours in traditional Gond painting practices. Semi-structured interviews and observation techniques helped in primary data collection from around forty artisans, selected using the snowball sampling method. Engagement with senior Gond artisans residing in Bhopal and Patangarh village, Madhya Pradesh, revealed that the primary obstacles were the difficulty in extracting consistent and stable colourants from natural sources and the subsequent variability in colour intensity and hue. This was critically attributed to the absence of standardized mordanting techniques in the traditional process. To address this, the study adopted a dual approach: first, documenting and evaluating traditional extraction methods through artisan insights, and second, introducing a scientific intervention through systematic mordanting to ensure colour fastness and reproducibility. In addition, the final phase focused on product development using Nyctanthes arbor-tristis (Harshinghar) flowers, along with Rubia tinctorum (madder roots), Acacia catechu (Kattha) and rusted iron and jaggery mixture to obtain various shades.

2.2 Phase 2: Substrate Selection and Pre-Treatment of Cotton and Silk Fabrics

- Fabric Selection: To evaluate the application and performance of the developed paint, a range of fabrics compatible with natural dyes and relevant to traditional crafts was selected. This included plain woven cotton in two different weights (Light and Medium GSM) to assess the effect of fabric construction, and tussar silk for a comparative analysis of colour development and shade on a protein fibre. The first sample, cotton A was a light weight khadi cotton fabric of sample size measuring, 25cm by 30 cm (width by length), having a GSM of 110 g/m^2 and the second sample, Cotton B was a medium weight Khadi cotton fabric with GSM of 196 g/m^2. The third sample was tussar silk fabric with GSM of 67 g/m2 having sample size of 25cm by 30 cm (width by length)
- **Scouring of Cotton fabrics:** The cotton fabrics were scoured using a solution of non-ionic soap (2 g/L) and a wetting agent (1 g/L) at 100°C for 45 minutes. This process effectively removed impurities, thereby ensuring better dye uptake.
- **Degumming of Silk Fabrics:** Silk fabrics were degummed using a solution of Lissapol (5 g/L) at 100°C for 45 minutes to remove sericin, which enhanced dye absorption.
- **Mordanting of cotton and silk fabrics:** Pre Mordanting: Cotton fabrics were mordanted with myrobalan powder (Terminalia chebula Retz) (20% o.w.f) in a water bath at 80°C for one hour, with a material-to-liquor ratio (MLR) of 1:40. Myrobalan (20 g/L or 20% o.w.f) was added to the water bath [6] [7]. The temperature of the water bath was raised to 80°C and to this bath, cotton fabric was added. Cotton fabric was immersed in the bath, and continuous stirring was carried out. After twenty minutes the mordanted fabric was taken out and drip dried in the sunlight. Special care was taken that no wooden or iron item came into contact with the fabric.

Tussar silk fabrics were mordanted using alum (10g/l or 10% o.w.f) at 40°C for 20 minutes, with an MLR of 1:40.

Simultaneous Mordanting: In addition to pre-mordanting, mordant was also added to the painting paste. Specifically, 6% alum of the total solution was added to the prepared thickener paste formulated with tamarind seed powder.

Figure 1: Dried flowers of Nyctanthes arbor-tristis used as raw material for natural dye extraction (Photograph by the authors)

2.3 Phase 3: Extraction and optimisation of Natural Dye-Based printing paste

- **Process of Preparation and Extraction Procedures**

  The plant materials were cleaned, dried, and ground into a fine powder (Figure 1). Harshinghar flowers (Nyctanthes arbor-tristis), collected at peak bloom in November, were used for each extraction batch. The flowers were first sun-dried for 24 hours to remove moisture and then manually cleaned using a mesh sieve to eliminate impurities. A two-stage grinding process, initial coarse grinding followed by fine grinding, which involved three rounds of grinding for 10 seconds each. It was employed to optimise colour strength. The extraction was performed by boiling the powdered material in water under controlled conditions to produce a concentrated dye solution.

  A neutral medium was used to extract the flowers of Harshringar. In particular, 500ml of water in a bath was mixed with 8g of manually ground Harshringar flowers. After being progressively brought to a boil, the mixture was kept at 80°C for an hour. Following boiling, evaporation was used to decrease the dye bath to 100 ml. A muslin cloth was used to sift the resultant solution, yielding a clear liquid that was then combined with a binder paste.

- **Formulation of Thickeners for Painting/Printing experiments**

  Initial experiments were undertaken with gum Arabic thickener; however, the results were not satisfactory as it made the brushes extremely sticky, creating a hindrance in the painting process. To overcome this challenge, tamarind seed powder was chosen after discussion with experts and traditional practitioners. In addition, TKP powder not only gave better colour yield matching to the traditional colour palette of Gond art, it was also economically viable.

  The extracted dyes were combined with thickener pastes formulated from tamarind seed powder. The dye to thickener ratio was optimized to attain the desired viscosity and colour intensity suitable for painting applications. A 5 % concentration of TKP was used to prepare a viscous paste [8]. One litre of water was heated and 50 g of tamarind seed powder was subsequently added to it. The mixture was then heated for a duration of 15 minutes. The mixture was continuously stirred to prevent lump formation and ensure uniformity in the thickener paste. Simultaneous mordanting was also done by addition of a mordant in the thickener paste to enhance the fastness properties. Alum was chosen as the Mordant. Specifically, 6 % alum of the total solution was added to the prepared thickener paste. The thickener paste and extracted dye were then combined in a predetermined proportion. A mixture of 200 ml of thickener paste with alum mordant and 100 ml of dye extract was prepared for application on fabric.

  This was followed by fixation in a steamer for an hour at high temperatures. The developed cotton and silk samples were washed under running water to remove the thickener paste.

2.4 Phase 4: Testing and Evaluation of Painted Textile Samples

To evaluate the durability of colours from natural sources on fabrics, standardized fastness tests were conducted under various conditions. The coloured samples, prepared after optimization and standardization were assessed for their resistance to: Washing (wash fastness), Light exposure (light fastness) and Friction (rub fastness).

The following sections outline the methodologies employed for each of these tests.

- Fabric Thickness, BS 2544:1954- This test specified the thickness of the selected textile fabrics. The fabric thickness was measured by calculating GSMs of the selected fabrics.

- Wash Fastness - The test standard ISO 105-A02 assessed the change in colour of painted fabrics after washing and 105-A03 evaluated staining on the adjacent fabric due to abrasion were followed [9]. It is either fastness to laundry or wash fastness

- Fastness to light- AATCC 16-2004 standard evaluated the colour fastness of painted cotton and silk samples to light exposure. The fabric specimens were exposed to a specified artificial light source under controlled conditions, and the degree of colour change was assessed. The test provided insights into how the dye will behave under prolonged exposure to light [9].

- Fastness to crocking- AATCC 8-2007 assessed the painted fabric's ability to resist rubbing off its colour onto adjacent surfaces. Both wet and dry rubbing tests were performed, and a grey scale for staining was used to measure the rating of colour transmitted [9].

3. Results and Discussion

3.1 Challenges in Contemporary Gond Art Practice and the Proposed Intervention

To address the technical limitations of natural colours on textiles, particularly poor wash fastness and lack of inherent substantivity, a series of scientific experiments was conducted to evaluate and enhance the performance of natural dyes used in Gond painting. The goal was not to replace traditional materials, but to test their viability on cotton and silk fabrics using low-impact, scalable methods that align with the community's eco-friendly ethos.

3.2 Pre-treatment of selected fabrics

- Scouring of Cotton Fabrics : Cotton fabrics were scoured in a 2 g/L detergent solution (1:50 MLR) at 60°C for 30 minutes to remove fats, oils, and sizing agents, ensuring uniform dye uptake.

- Degumming of Silk Fabrics : Silk was degummed in a 5 g/L soap solution (1:40 MLR) at 98°C for 60 minutes to remove sericin gum, improving dye penetration and surface smoothness.
- All fabrics were rinsed thoroughly and air-dried before mordanting.
- Mordanting of Cotton and silk: The recipes and choice of mordants and their application procedure undertaken during this study are based on years of expertise and traditional wisdom of practitioners in the field of natural dyeing and printing on textiles. The research protocol was developed under the guidance of technical experts working for more than a decade in Weaver's Service Centre of India.

  In order to mordant cotton, myrobalan was chosen for both cotton A and B as yellow shades gave their best fastness results with myrobalan over alum, found during the initial experimental phase. Mordanting was followed using the procedure mentioned in section 2.2. 20g/L finely crushed powder of myrobalan was taken in a 1:40 MLR water bath at 80o C for an hour. In case of silk the initial experiments depicted, alum to be a better mordant as it would not make the fabric patchy after application. 20g/l alum was taken at 1:40 MLR. The fabric was dipped in the mordant solution for 20 minutes at 40o C. The secondary data on the application of natural colours has been extensively explored in dyeing of cotton and silk fabrics. However, very limited research has been done for painting with natural dyes on textiles. Only direct references were given by Dr. Kumerson, where a comparison of different mordants with Nyctanthes arbor-tristis flowers on silk was done [10, 11]. The results showed that myrobalan mordanting on silk gave poor surface colour strength (K/s values), therefore, alum was selected for pre and simultaneous mordanting on silk.
- In addition, simultaneous Mordanting was followed to enhance the fastness of Gond painted samples, 6% alum powder was mixed directly into the thickener paste, enabling mordanting during application.

3.3 Extraction and optimisation of dye and printing paste

3.3.1. Optimization of Aqueous Dye Extraction from Nyctanthes arbor-tristis

- It was observed that Harshinghar flowers gave good results at 8gm/500 ml at a temperature ranging between 90oC to 100o C. The aqueous extraction of dried harshinghar flowers at 90o C was carried out for an hour. The liquor was reduced to 100 ml, which was mixed with the painting paste later. This concentration yielded the highest concentration of pigment as indicated by K/S values given below in Table 1. This concentration also displayed maximum colour shade matching to the original shade of yellow used in Gond painting made from natural colours.

3.3.2. ColourYyield and Mordant Influence on dye Performance

- Cotton A (L*=62.53) is lighter than Cotton B (L*=48.54) as indicated in the K/S value and also supports the visual inspection of shade. A lighter colour is indicated by a greater L* value. This difference is mostly due to the thread count and GSM of cotton fabrics. Cotton B, being heavier and denser, is showing a deeper dull yellow tone. Refer to Tables 1 and 2.
- The CIE Lab values for silk (L*=57.88, a*=8.48, b*=13.16) describe a light, moderately saturated colour with a noticeable red-green component (positive a*), resulting in a brownish-yellow hue (h°=57.17). This is less vibrant than the bright yellow achieved on Cotton A but aligns with the earthy colour palette often sought in natural dyeing. Refer to Tables 1 and 2.

Table 1: K/S Values of Mordanted and Painted Silk with Tamarind Seed Powder

Sample	Mordant	K/S Value	L	a	b	C	h
Cotton A	Myrobalan	8.168	62.53	4.1	39.13	39.35	83.98
Cotton B	Myrobalan	7.006	48.54	12.51	21.38	24.77	59.64
Silk	Alum	2.001	57.88	8.48	13.16	15.65	57.17

Null Hypothesis (H_0): There is no difference in the median K/S values between Cotton A, Cotton B, and Silk.

Alternative Hypothesis (H_1): At least one fabric has a different median K/S value than the others.

Selection of the Kruskal-Wallis Test: This test is used to determine whether the difference between three independent groups is statistically significant, where the groups are the three different fabrics, cotton A, B and Tussar silk. The dependent variable being compared is the K/s values of the three fabrics. The data was not normally distributed; therefore, this non-parametric test was undertaken for the study.

The tests were conducted only the K/s Values, that is, column 3 in table 1

R1 (K/S value of Cotton A) = 3

R2 (K/S value of Cotton B) = 2

R3 (K/S value of Silk) = 1

The H Statistic was calculated using this formula:

$$H = \frac{12}{N(N+1)}\left(\frac{R_1^2}{n_1} + \frac{R_2^2}{n_2} + \frac{R_3^2}{n_3}\right) - 3(N+1)$$

Where:
N = total number of observations (3)
n_1, n_2, n_3 = number of observations in each group (all are 1

in this tiny example)

R_1, R_2, R_3 = sum of ranks for each group

$$H = \frac{12}{3(3+1)}\left(\frac{3^2}{1}+\frac{2^2}{1}+\frac{1^2}{1}\right) - 3(3+1)$$

$$H = \frac{12}{12}(9+4+1) - 12$$

$$H = (1)(14) - 12$$

$$H = 2$$

The H statistic is compared to a critical value from the Chi-Square distribution (χ^2). With 2 degrees of freedom (number of groups - 1) and a significance level of 0.05, the critical value is 5.991.

The result obtained for H = 2.0, since, 2.0 < 5.991, Based on the analysis, where the H statistic (2.0) was found to be lower than the critical value of 5.991, the null hypothesis could not be rejected. So it can be concluded, that there is no statistically significant difference in the K/S values.

Table 2: Shade card of mordanted and painted cotton and silk with Tamarind seed powder thickener

Fabric	Mordant	Shade
Cotton A (110 g/m^2)	Myrobalan	
Cotton B (196 g/m^2)	Myrobalan	
Tussar Silk (36 g/m^2)	Alum	

3.4 Testing and Evaluation of Painted Textile Samples

3.4.1 Washfastness of Pre-Mordanted cotton and silk samples (ISO 105 A)

In order to assess the durability and compatibility of the optimized Nyctanthes arbor-tristis paint for Gond art applications, the fastness characteristics of the painted fabrics which included two cotton varieties (A and B) and Tussar silk were thoroughly assessed.

- Cotton A (Myrobalan) demonstrated excellent wash fastness. There is minimal fading and very little colour transfer to nearby textiles, as shown by the Colour Change (CC) grade of 4/5 and the Staining on Cotton (SC) value of 4.
- The wash fastness of Cotton B (Myrobalan) ranged from very good to outstanding. Good shade colour retention is indicated by a CC grade of 4, which is somewhat lower than Cotton A. With an overall rating of 5, Staining on Wool (SW) is remarkable as depicted in Table 3.
- Similar to Cotton A, Tussar Silk (Alum) demonstrated exceptional wash fastness. The high ratings (CC: 4, SC: 4/5, SW: 5) indicate the effectiveness of the alum mordant on silk and the absence of any colour fading or staining problem. Refer to Table 3.

Comparative analysis revealed that all three substrates had very good to exceptional wash fastness (ratings of 4 or above), demonstrating the durability of the painting and mordanting procedures. Cotton A's slightly higher CC grade implies that its composition or interaction with the mordant may provide better colour retention following washing.

Table 3: Wash fastness of Nyctanthes arbor-tristis painted cotton and silk with pre and simultaneous mordanting as per ISO 105 A

Sample	Mordant	CC	SC	SW
Cotton A	Myrobalan	4/5	4	5
Cotton B	Myrobalan	4	4	5
Tussar Silk	Alum	4	4/5	5

3.4.2 Crock fastness of Painted Fabrics (AATCC Test Method 8)

Dry Crocking: Each of the three samples had exceptional performance, receiving the highest possible rating of five for both Colour Change (CC) and Colour Staining (CS). This shows that no colour transfer takes place while rubbing dry, which is important when working with Gond art on Textiles. Refer to Table 4.

Wet Crocking : Cotton A and B both continued to perform really well. Cotton A received a very excellent score of four for CS and a flawless score of five for CC. For both CC and CS, Cotton B received an excellent 4/5.

Tussar Silk: Under wet conditions, it performed wonderfully, obtaining a perfect grade of 5 for both CC and CS. Refer to Table 4.

Table 4: Crock fastness assessment of painted cotton and silk samples with pre and simultaneous mordanting as per AATCC 8

		Dry		Wet	
Sample		CC	CS	CC	*CS*
Cotton A	Myrobalan	5	5	5	4
Cotton B	Myrobalan	4/5	4/5	5	4/5
Tussar Silk	Alum	5	5	5	5

3.4.3 Light Fastness of Painted Cotton Samples (AATCC 16-2004)

Comparatively, the crock fastness is consistently quite good. The cottons had very little to no discolouration, while the silk had full wet fastness. This demonstrates that even when wet, the paint coating is well foxed and barely abrades.

According to AATCC 16-2004, light fastness standard, the results obtained are discussed below. The Myrobalan cotton A and B: On a scale of 1 to 8, an exceptional light fastness grade of 8 was obtained for both the cotton samples. This indicates remarkable resistance to fading when exposed to light, which qualifies it for uses involving long term display as painting or curtain etc. Refer to Table 5.

Tussar Silk (Alum): The silk sample also displayed outstanding performance with an overall grade of 8.

Comparatively, Silk and Cotton samples showed remarkable light fastness. Given that many natural dyes fade fast; this is a very important finding. The colourant's grade of 8 indicates that it is exceptionally stable, which significantly increases the life and market value of artwork created with this paint. Refer to Table 5.

Table 5: Lightfastness assessment of painted cotton and silk samples with pre and simultaneous mordanting

Sample	Mordant	Lightfastness Rating
Cotton A	Myrobalan	8
Cotton B	Myrobalan	8
Tussar Silk	Alum	8

3.5 Phase 5: Prototyping and Product Development for Artistic Application

This study directly enhances artisan capabilities by providing a scientifically-backed, standardised protocol that mitigates the traditional challenges of colour inconsistency and poor fastness. By transitioning from synthetic paints on paper to durable natural dyes on textiles, artisans can now create high-value, sustainable products such as framed textile art, wearable art, and home furnishings.

Painting using natural paints and binder was developed to keep the essence of the art alive. Sustainability was a major factor, and eco-friendly production methods were maintained by using natural plant-based colours in the traditional colour scheme of the Gond art, which is red, yellow, black, brown, and green. One such painting was developed with a culturally significant motif, of the fondest animal among the Gond artist's community, that is the dear as illustrated in Figures 2,3,4. The motif had many other natural colours, including a yellow shade from the harshringhar flower. The painting has yellow shade extracted from Harshringhar in the background, along with other shades like madder red, katha for brown and rusted iron and jaggery mixture for black.

This not only expands their market opportunities but also strengthens the eco-cultural narrative of their work, aligning with global demand for artisanal, biodegradable, and ethically produced goods.

Figure 2, 3: Close-up views of the yellow hue derived from Nyctanthes arbor-tristis flower extract, applied as a background wash (Photograph by the authors)

Figure 4: Traditional Gond-style painting created using natural textile paints, including Nyctanthes arbor tristis flower extract

(Photograph by the authors, Artist: Purushottam Shyam from Madhya Pradesh)

4. Conclusion

This study successfully optimised the extraction and application of Nyctanthes arbor-tristis as a natural textile paint. The findings demonstrate that the mordanted Nyctanthes arbor-tristis paint exhibits outstanding overall fastness properties on all tested substrates, like cotton and silk. The combination of myrobalan for cotton and alum for silk effectively fixes the dye, resulting in excellent resistance to washing, rubbing, and light exposure. This high level of durability confirms the strong potential of this natural paint for creating sustainable and marketable Gond art textiles. The successful creation of a traditional natural dye painted prototype validates its practical application, offering Gond artisans a scientifically backed, eco-friendly medium to enhance their craft's viability and appeal in conscious consumer markets, ensuring both cultural preservation and environmental sustainability. Future studies could explore the application of Nyctanthes arbor-tristis dye on a wider range of natural and synthetic fabrics using a broader spectrum of eco-friendly mordants to further expand its commercial potential.

5. Acknowledgements

This work was enriched by the artistic mastery of Shri Purushottam Shyam Ji, who brought the natural dyes to life on fabric. We also acknowledge the support of Mr Singh and his team at the Weaver's Service Centre for their expert counsel.

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Quality
Textile Technology
Journal

Journal of the
TEXTILE Association

Journal of the TEXTILE Association

ISSN 0368-4636

Functionalizing of Fabrics by Utilizing Herbal Extracts

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Abstract:

Purpose - *Natural products from plants have always been important for human health, especially in the past ten years as research into herbal remedies has grown. The demand for antimicrobial fabrics is being driven by consumers' growing awareness of the negative effects on personal hygiene and the health risks associated with specific microorganisms. Natural fibres and fibre combinations are vulnerable to bacterial colonisation and microbial growth due to the surface characteristics of textiles. Numerous negative effects are caused by the growth of microbes on textiles, affecting both the wearer and the material itself. The purpose of the study is research of five different types of herbs about the phytochemical screening and antioxidant, finishing of fabrics with extractions can act as antibacterial textile for human welfare.*

Methodology- *This study evaluated the antibacterial efficacy of five plant leaves Dodonaea viscosa, Euphorbia hirta, Catharanthus roseus, Tribulus terrestris, and Limonia acidissima extracted using acetone, ethanol, petroleum ether, and methanol against human pathogenic bacteria. The methanol extract exhibited the most extensive zone of inhibition against Euphorbia hirta and Limonia acidissima, both measuring 22 mm. In order to do the "phytochemical analysis" of "Euphorbia hirta" leaves identified flavonoids, phenols, tannins, and alkaloids. The phytochemical examination of Limonia acidissima revealed the presence of phenols, tannins, terpenoids, and alkaloids. This experiment employed the agar-well diffusion method to evaluate antibiotic effectiveness.*

Findings - *The findings showed that the methanolic leaf extracts of Limonia acidissima and Euphorbia hirta are effective antibacterial agents and pharmacologically active. The current study examines the phytochemical analysis, antioxidant and antibacterial properties of five different types of herbs, as well as the effects of herb extraction on various types of fabric, in order to produce good antibacterial natural fabric for human everyday use.*

Keywords: *Antibacterial textile, Fabrics, Herbs, Healthcare textiles, Phytochemical*

Citation: V. Ramya, R. Prabha, S. M. Naseera, “Functionalizing of Fabrics by Utilizing Herbal Extracts”, *Journal of the Textile Association*, **86/4** (Nov-Dec’25), 445-452, https://doi.org/10.63665/jta.v86i4.7

Article History : Received :19-10-2025, Revised:03-11-2025, Accepted:07-11-2025

1. Introduction

Medicinal plants have been recognized as rich reservoirs of bioactive compounds with diverse pharmacological and industrial applications. In recent years, increasing environmental awareness has accelerated the shift toward sustainable and eco-friendly alternatives to synthetic chemicals, particularly in textile processing. Natural plant extracts are gaining importance as potential substitutes for synthetic dyes due to their biodegradability, non-toxicity, and additional functional properties such as antibacterial and antioxidant effects.

Dodonaea viscosa, a flowering woody shrub belonging to the Sapindaceae family, is widely distributed in tropical and subtropical regions. The plant has a long history of traditional use, originating in western America where it was first reported. It is known for its resilience to arid conditions, wind, saline aerosols, and sandy or rocky substrates [1]. Among Australian populations, D.viscosa has been traditionally used in the treatment of snake bites, wounds, haemorrhage, and bone fractures. In Indian traditional medicine, it is employed to manage headaches, indigestion, diarrhoea, wound healing, and snake bites, while its fractured stem is also used in bone fracture remedies [2, 3 & 4].

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Euphorbia hirta L., a member of the Euphorbiaceae family, is a common medicinal herb prevalent across tropical Asia, particularly in the Philippines. It is widely known as the “asthma herb” due to its extensive use in the treatment of respiratory ailments such as asthma [5–7]. The plant possesses a broad range of pharmacological properties, including antioxidant, anti-inflammatory, and anticancer activities [8].

Catharanthus roseus, commonly known as Madagascar periwinkle, derives its name from the island nation of Madagascar, where it was first identified. It is now widely cultivated as a perennial ornamental plant around the world. The species can reach 30–60 cm in height and has been traditionally used for diabetes management, as the plant's juice exhibits a dose-dependent hypoglycaemic effect in both diabetic and normoglycaemic rabbits [9].

Tribulus terrestris, an annual herb of the Zygophyllaceae family, is distributed mainly in subtropical and Mediterranean regions, including India, Pakistan, China, Mexico, Spain, and South America. Commonly known as “goat head,” it grows as a small prostrate shrub reaching a height of 10–60 cm, with either smooth or coarse hairs [10]. The plant has been traditionally employed to treat headaches, mastitis, flatulence, conjunctivitis, and chest fullness, and also functions as a mild laxative and general tonic [11].

Limonia acidissima L., belonging to the Rutaceae family, is commonly referred to as wood apple, curd fruit, or monkey fruit. Native to India, it is a medium-sized tree with considerable importance in both nutrition and traditional medicine [12]. Its fruit and leaves contain several bioactive compounds that contribute to its antioxidant and antimicrobial potential.

Given their rich phytochemical profiles and traditional medicinal significance, these selected plants Dodonaea viscosa, Euphorbia hirta, Catharanthus roseus, Tribulus terrestris, and Limonia acidissima were chosen for the present investigation. The study aims to analyse their phytochemical constituents and evaluate their antioxidant and antibacterial activities, with a specific focus on their application to fabrics. The integration of natural plant extracts into textile finishing provides a sustainable pathway for developing eco-friendly fabrics with functional properties, aligning with current environmental and industrial trends.

2. Materials and methods

2.1 Materials

The selected fabrics for this investigation are presented in Table 1 and Figure 1. The organisation VSM Weaves India (P.) Ltd., headquartered in Tamil Nadu, India, was chosen for supplying all fabrics. In the Madurai region of Tamil Nadu, located in South India, the flora employed in this study were gathered from several locations during the examination. The identification and validation of the plants were conducted by Dr. Sharief M. U, a scientist and head of office at Tamil Nadu Agricultural University in Coimbatore, Tamil Nadu. The selection of herbs considers their pharmacological and therapeutic effects as documented in the pertinent literature. The scientific nomenclature of the selected herbs is enumerated in Table 2, accessible online.

Table 1: Types of fabrics

Fabric	Yarn Count	GSM	Weave	Nomenclature
Cotton 100%	40's	169	Plain Weave	C
Linen 100%	40's	173		L
Linen (warp): cotton (weft) (50%:50%)	40's	178		S

Figure 1: Types of Fabric

Table 2: Taxonomy of herbs

Order	Species	Family Name	Common Names	Tamil Names
Sapindales	*Dodonaea viscosa* (L.) Jacq.	Sapindaceae	Hop Bush	Virali
Malpighiales Juss. ex Bercht. & J. Presl	*Euphorbia hirta* L.	Euphorbiaceae	Asthma Weed	Amman Paccharisi
Gentianales	*Catharanthus roseus* (L.) G.Don	Apocynaceae	Madagascar Periwinkle	Nithyakalyani
Zygophyllales	*Tribulus terrestris* L.	Zygophyllaceae	Puncture Vine	Nerunji
Sapindales	*Limonia acidissima* L.	Rutaceae	Wood Apple	Kapittam

2.2 Preparation of Extraction process

Each plant leaves placed on aluminium trays; the leaves were oven dried for 24 hours at 40°C to 50°C until the moisture disappeared. After being processed through a metal sieve and pounded into a powder, the dry materials were stored at room temperature. Acetone, ethanol, pet ether and methanol were the solvents utilized in the extraction process. Ten grams of leave powder were obtained, and 100 millilitres of each solvent were used to make the extract using a Soxhlet. After that, a membrane filter (0.45 µm) was used to filter the extract. After being concentrated in a rotary evaporator at 40°C under decreasing pressure and stored in a refrigerator between 2 and 8°C, the filtrate was employed in further study.

3. Qualitative phytochemical analysis of plants

For each, a separate qualitative phytochemical study of plant extracts was conducted. Qualitative analysis is used to identify five phytochemical compounds: alkaloids, flavonoids, terpenoids, phenols, and tannins.

4. Antibacterial activity

In order to establish the antibacterial activity of each plant that was associated with the species that was investigated, the well diffusion method was utilised. After inoculating cultures of Escherichia coli and Staphylococcus aureus into a sterile nutrient broth, the cultures were then incubated for a period of time ranging from twenty-four to forty-eight hours. Following that, the broth was employed in the process of cultivating the bacterium. All of the organisms that were being investigated were swabbed in a uniform manner across the surface of the agar at a concentration of 0.1% for each organism, which included Staphylococcus aureus and E. coli. Wells of a diameter of six millimetres were bored into the surface of each nutritional agar plate in order to guarantee that the environment would continue to be sterile. Following the distribution of roughly twenty microlitres of the herbal extract fraction into each well, the plates were then incubated at a temperature of 37 degrees Celsius for a period of twenty-four hours. It was necessary to repeat this operation as many times as necessary. In order to evaluate the capability of each polluted NA plate to impede the growth of bacteria, the zone of inhibition that surrounded the wells was utilised. The effectiveness of the plate was evaluated by the use of this method.

5. Method of finishing

5.1 Preparation of fabric

A five-by-five-inch square was cut from the selected fabric. Initially, the materials were pre-soaked in fresh water at 70°C for 20 minutes. Any leftover surface dirt and pollutants were carefully removed from the cleaned fabrics by washing them under running water. All of the ingredients were air dried and then very gently pressed. Fabrics were washed, then dried under the sun.

5.2 Finishing of fabric - Concentration of Extraction

The standard M: L ratio (1:20) was used to finished the selected fabrics on based on procedure. Using a padding mangle, under the standard finishing conditions of 20 g/l of plant powder, 28°C to 30°C, 80% wet pick up, and pH 7.0. The curing process was carried out after the finished fabrics were dried at standard oven temperature at 80°C for 10 minutes.

5.3 Antioxidant properties

Through the utilisation of this technology, an assessment of the radical scavenging activity of DPPH was carried out. In total, there were three millilitres of methanol, three millilitres of extract, and three millilitres of a radical solution containing 2, 2-diphenyl-1-picrylhydrazyl (DPPH) in methanol that had a concentration of 0.5 millimolar [13]. Each and every one of these constituents was included into the reaction mixture. Following an incubation time of forty-five minutes, a spectrophotometer was able to measure absorbance at a wavelength of five hundred seventeen nanometres with a high degree of precision. An approach known as the deoxyribose test was employed in order to ascertain whether or not an aqueous medium possesses the capability to scavenge hydroxyl radicals. In order to create the herbal extract, a potassium phosphate buffer with a concentration of 20 millimolar and a pH of 7.4 was utilised. The herbal extract was present in the reaction mixture at a concentration of 100 grammes per millilitre. 7.4 was the pH of the buffer at the time. After the addition of 100 mM of iron (III), 104 mM of ethane-1,2-diyldinitrilo) tetra acetic acid, 1 mM of hydrogen peroxide, and 2.8 mM of carbon monoxide, the combination was ultimately finished producing the desired results. Over the course of two hours, the mixture was kept in an incubator at a temperature of 37 degrees Celsius. TCA (2.8%) and TBA (0.5%) were added to 0.025M sodium hydroxide with 0.02% BHA after the mixture had been brought to a boil in a water bath at 95 degrees Celsius for fifteen minutes. The temperature of the water bath was maintained at 95 degrees Celsius. Following the preparation of the liquid to a boil, this step was carried out. After the reaction mixture had been refrigerated on ice for a predetermined amount of time, it was centrifuged for fifteen minutes at a speed of five thousand revolutions per minute. This process was repeated until the reaction mixture was completely chill. A measurement was carried out at a wavelength of 532 nm in order to achieve the goal of determining the absorbance of the supernatant.

6. Results and Discussion

6.1 Qualitative phytochemical analysis of herbs

The investigation indicated that the plant extracts contained the highest amount of phytoconstituents. Catharanthus roseus preparations included phenol, alkaloids, flavonoids, and terpenoids. Alkaloids, flavonoids, phenol, and tannin were found in Euphorbia hirta extracts. Alkaloids, terpenoids, phenol, and tannin were all detected in the extracts of Limonia acidissima. In Table-3 the presence and absence of phytochemical constituents were presented for each herb. In Fig. 3, the colour change indicating the presence or absence of phytoconstituents were presented for Dodonaea viscosa, Euphorbia hirta, Catharanthus roseus, Tribulus terrestris, and Limonia acidissima respectively.

Table 3: Qualitative phytochemical analysis of herbs

Herbs	Phytochemical Analysis				
	Alkaloids	Flavonoids	Terpenoids	Phenol	Tannin
Dodonaea viscosa	-	-	+	+	+
Euphorbia hirta	+	+	-	+	+
Catharanthus roseus	+	+	+	+	-
Tribulus terrestris	-	+	+	+	-
Limonia acidissima	+	-	+	+	+

Euphorbia hirta

Limonia acidissima

Figure 2: Qualitative phytochemical analysis of herbs

Euphorbia hirta leaf phytochemical screening and qualitative assessment were investigated [14]. Terpenoids, alkaloids, flavonoids, sponins, and carbohydrates were detected in ethanol extracts [15]. The procedure looked at the ethanolic and methanolic extracts of Euphorbia hirta leaves' chemical makeup. The study identified alkaloids, flavonoids, terpenoids, tannin, phenol, steroids, glycosides, and saponin. [16] Investigated the phytochemical components of Limonia acidissima using extracts of water, methanol, and petroleum ether. Alkaloids, flavonoids, terpenoids, lipids, proteins, carbohydrates, and tannin were all found in the phytochemical analysis. The researchers also revealed that all of the chemicals found were associated with antibacterial activity in the aforementioned studies.

6.2 Antibacterial screening of individual herbs

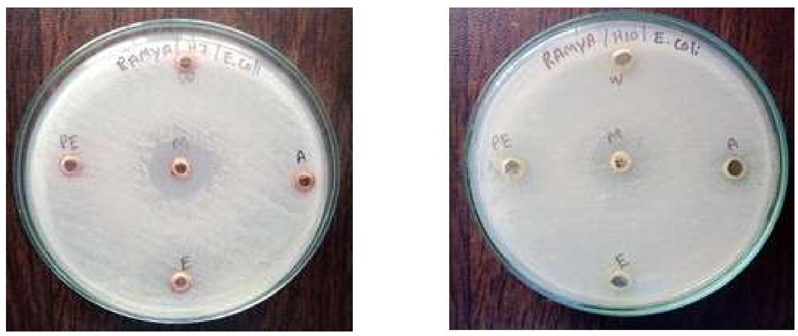
The methanol extract was shown to have the most potent inhibitory zones against both of the bacteria that were examined, which were Escherichia coli and Staphylococcus aureus. This was the case among the five different solvent extracts that were investigated. The extracts of Euphorbia hirta exhibited inhibitory zones that measured around 22mm and 21mm, whereas the extracts of Coleus aromaticus exhibited inhibitory zones that measured approximately 21mm and 22mm. In addition, extracts of Limonia acidissima demonstrated inhibitory zones against E. coli and S. aureus that were approximately 21mm and 22mm, respectively (see to Table 4 and 5 as well as Figures 3 and 4 for further information).

Table 4: Antibacterial screening of individual herbs (E. coli)

Herbs	Zone of Inhibition against *E. coli* (in mm)				
	Water	Acetone	Ethanol	Pet Ether	Methanol
Dodonaea viscosa	-	10	-	-	19
Euphorbia hirta	**-**	**-**	**07**	**-**	**22**
Catharanthus roseus	-	-	-	08	16
Tribulus terrestris	-	-	09	-	20
Limonia acidissima	**-**	**08**	**-**	**-**	**21**

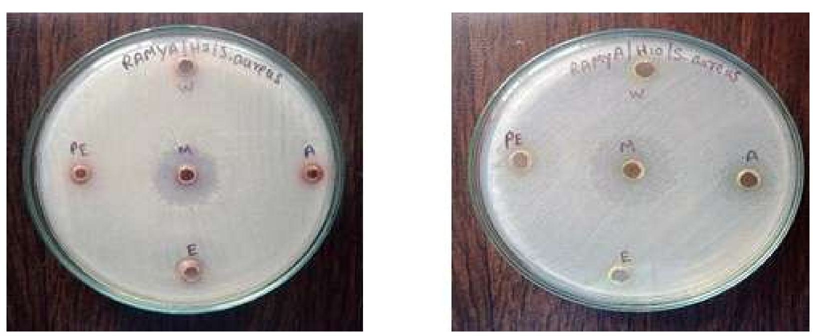
Table 5: Antibacterial screening of individual herbs (S. aureus)

Herbs	Zone of Inhibition against *S. aureus* (in mm)				
	Water	Acetone	Ethanol	Pet Ether	Methanol
Dodonaea viscosa	-	09	-	-	17
Euphorbia hirta	**-**	**-**	**-**	**-**	**21**
Catharanthus roseus	-	-	-	-	15
Tribulus terrestris	-	-	-	-	17
Limonia acidissima	**-**	**13**	-	-	**22**



H2 - *Euphorbia hirta* H5 - *Limonia acidissima*

Figure 3: Antibacterial screening of herbs against E. coli



H2 - *Euphorbia hirta* H5 - *Limonia acidissima*

Figure 4: Antibacterial screening of herbs against S. aureus

6.3 Antibacterial activity of herbal extract finished fabrics

Among the five herbal extracts finished fabric samples (Cotton-C, Linen-L and Linen Cotton-S) Euphorbia hirta and Limonia acidissima extract finished fabric samples showed good antibacterial inhibitory zones. Other herbal extract finished fabric samples also exhibited inhibitory zones but the size of the zones was found less than 30mm against both test bacteria.

The inhibitory zones found for each of the three completed fabric samples were shown in Table 6. After the samples were treated with Euphorbia hirta extract, sample C demonstrated an inhibitory zone against Staphylococcus aureus and Escherichia coli that was approximately 30 mm and 30 mm, respectively. Following treatment with Euphorbia hirta extract, L samples had an inhibitory zone measuring approximately 32 mm and 31 mm, whereas S samples demonstrated 30 mm and 31 mm of antibacterial activity against the same test microorganisms (Figs. 5 and 6). After being treated with Limonia acidissima extracts, C samples demonstrated an inhibitory zone against Staphylococcus aureus and Escherichia coli that measured around 30 and 31 mm, respectively. Regarding the test microorganisms, the L samples displayed an inhibitory zone measuring approximately 31 and 32 mm, whereas the S samples had antibacterial activity measuring 30 and 32 mm (Fig. 7 and Fig. 8).

Several plant extracts were utilized in the current study to complete cloth samples that showed strong antibacterial activity. Likewise, several studies have demonstrated the efficacious antimicrobial properties of various plant extract-finished textiles. In order to create an antibacterial finish for cotton fabric [17] examined the effects of leaf extracts from T. cordifolia, T. procumbers, and E.globulous. Following the

Table 6: Antibacterial activity of finished fabrics

Herbs	Zone of Inhibition (in mm)					
	Cotton		Linen		Linen+Cotton	
Dodonaea viscosa	***E. coli***	***S. aureus***	***E. coli***	***S. aureus***	***E. coli***	***S. aureus***
Euphorbia hirta	27	28	29	29	26	26
Catharanthus roseus	**30**	**30**	**32**	**31**	**30**	**31**
Tribulus terrestris	28	26	28	24	27	26
Dodonaea viscosa	29	30	30	30	33	31

pad-dry-cure method, the samples were treated with ethanol extracts at a concentration of 10%. This was done in order to prepare them for further analysis. Following an analysis of the data, it was concluded that the plant sources offered resistance against gram-positive as well as gram-negative bacteria. The microbiological development that took place in a typical kitchen environment at a temperature that was thought to be normal was determined through the use of dishcloths as the medium of investigation.[18]. The findings indicate that the fabric promotes the proliferation of bacteria, such as Klebsiella, Shigella, and Staphylococcus. Research has been done on the antibacterial qualities of plant extracts, including cyclodextrin, pomegranate peels, banana peels, and curry leaf were studied the aloe vera leaf gel extract's softness and antibacterial qualities on cotton fabric [19]. The gel was extracted using methanol, and the viscosity was added using Luteal Hit Plus, a wetting agent. The pad dry approach outperformed the coating method in terms of antibacterial activity. In order to investigate the antibacterial action of plant finishing on natural fibers including cotton, bamboo, and soya bean textiles performed research [20].

The chosen natural antibacterial agents include Terminalia chebula, Ocimum tenuiflorum (tulsi), Coleus aromaticus, Aloe barbadensis, Asteraceae, and Cymbopogon flexuosus (lemon grass oil). The antibacterial methanol extracts from various plant sources were directly applied to fabrics utilising the pad-dry-cure method. The findings indicated that textiles made from cotton and bamboo, when exchanged with Asteraceae, exhibited no antimicrobial properties. The fabric made from soybeans exhibited significant microbiological activity. It has been demonstrated by researchers that the application of lemon grass oil to cotton fabric resulted in the most potent antibacterial action against gram-positive as well as gram-negative bacteria. It makes no difference whether the germs are beneficial or harmful; this is always the case. Neem (Azadiracta indica), pomegranate (Punica granatum), and Curcuma longa rhizome leaves were the topics of the study, which evaluated the antibacterial properties of these natural ingredients. The study focused on the antibacterial properties of these natural ingredients. In terms of the overall amount, the methanolic extracts that were obtained from the rind of the pomegranate fruit, the leaves of the neem tree, and the turmeric each accounted for 38%, 42%, and 29% of the total, respectively. It was established through research that the exhaust approach was superior to the dip method when it came to the application of cotton materials. This was the case when comparing the two methods. As a result of the findings of a number of research investigations, it was shown that pomegranate possesses greater antibacterial properties in comparison to neem and turmeric. The antibacterial effects of natural extracts were shown to be more efficient against gram-negative bacteria than they were against gram-positive bacteria. This was discovered through research [21].

Figure 5: E. hirta (H2) extract finished fabrics for antibacterial effectiveness against E. coli

Figure 6: E. hirta (H2) extract finished fabrics for antibacterial effectiveness against S. aureus

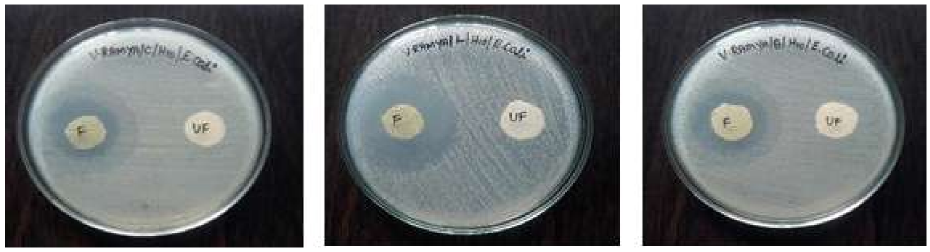


Figure 7: L. acidissima (H5) extract finished fabrics for antibacterial effectiveness against E. coli

Figure 8: L. acidissima (H5) extract finished fabrics for antibacterial effectiveness against S. aureus

6.4 Antioxidant properties of herbs

The antioxidant capability of the five herbal extracts was assessed using DPPH and hydroxyl scavenging activities in their methanol extracts, as shown in Tables 7&8. Maximum DPPH activity of 48 ± 0.10 was observed for Dodonaea viscosa. And maximum hydroxyl scavenging activity of 46 ± 0.03 and 45 ± 0.01 was observed for Euphorbia hirta, Catharanthus roseus.

Table 7: Diphenyl-1-Picrylhydrazyl (DPPH) assay

Herb	Inhibition (%)	
	Ascorbic acid (Control/Standard)	Herbal extract (Sample)
Dodonaea viscosa	50 ± 0.12	48 ± 0.10
Euphorbia hirta	48 ± 0.08	46 ± 0.12
Catharanthus roseus	48 ± 0.09	44 ± 0.09
Tribulus terrestris	48 ± 0.08	45 ± 0.08
Limonia acidissima	47 ± 0.09	43 ± 0.06

**Mean ± S.D of three triplicates*

Table 8: Hydroxyl radical scavenging activity

Herb	Inhibition (%)	
	Ascorbic acid (Control/Standard)	Herbal extract (Sample)
Dodonaea viscosa	44 ± 0.01	40 ± 0.04
Euphorbia hirta	48 ± 0.02	46 ± 0.03
Catharanthus roseus	49 ± 0.01	45 ± 0.01
Tribulus terrestris	46 ± 0.04	43 ± 0.02
Limonia acidissima	45 ± 0.05	43 ± 0.05

**Mean ± S.D of three triplicates*

The proportion of scavenging activity that was suppressed by the methanol extract fractions was nearly identical to the percentage of scavenging activity that was suppressed by the reference chemical ascorbic acid. This was determined by comparing the two percentages. There are a variety of plants that have been discovered to possess substantial antioxidant qualities. "Some examples of these plants include Euphorbia hirta and Limonia acidissima". The use of these plants in the treatment of diseases that are linked to the production of free radicals by the body is something that has the potential to be utilised. Additionally, the consumption of a significant quantity of this plant may, as a consequence, minimise the likelihood of contracting a variety of diseases that are brought on by free radicals. This conclusion is based on the fact that this plant contains antioxidants.

7. Conclusion

The study revealed that methanolic leaf extracts of Euphorbia hirta and Limonia acidissima showed notable antibacterial activity against both Gram-positive and Gram-negative bacteria. Phytochemical screening confirmed the presence of bioactive compounds such as flavonoids, phenols, tannins, alkaloids, and terpenoids, responsible for their antimicrobial potential. When applied as natural dyes, these extracts exhibited excellent compatibility and durable antibacterial effects, particularly on linen and linen–cotton blended fabrics. The antioxidant properties of the herbs further enhance their value by neutralizing free radicals and reducing oxidative stress. Overall, the findings demonstrate that these medicinal plant extracts can serve as effective, eco-friendly finishing agents for functional textiles, offering both aesthetic appeal and sustainable antimicrobial performance.

Conflict of interest
No potential conflict of interest

Funding Source
Authors report no financial support from any funding agency

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Metal Ion Complexation on Polyester Fabrics for EMI Shielding Applications

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Abstract:

Background: *Electromagnetic interference (EMI) is recognised as fourth form of pollution after air, noise and water pollution and this has prompted for the preparation of electromagnetic shielding fabrics. Textile materials being flexible can be used to cover on the material that radiates electromagnetic radiation. These fabrics have been deposited with different metals on textile substrates for producing EMI shielding effect.*

Methods: *Polyaniline (PANI) was deposited on polyester (PET) fabric by insitu polymerisation process with hydrochloric acid (HCl) as a dopant. Following polymerisation, The PANI coated fabric was immersed in acid dye to undergo dopant exchange process replacing chloride anions with acid dye anions improving the functionality, and modify its performance for EMI shielding applications. Subsequently, the fabric was immersed in metal salt solutions such as* $NiSO_4$, $K_2Cr_2O_7$, $FeSO_4$, $FeCl_3$, $CuSO_4$ *and* $CoCl_2$ *to undergo metal ion complexation.*

Results and Conclusion: *Resulting metal ion complexed fabrics showed EMI shielding efficiency increasing by 16 dBm (266%) compared to the chloride-doped PET/PANI fabric and by 10 dBm (97.83%) for Acid dyed fabric. The thickness and synergistic action of the metals caused the EMI Shielding Effectiveness (SE) of the treated fabric to rise up to 42 dBm with number of folds. Acid dye acts as a dopant replacing chloride ions with sulfonated anions, enhancing structural stability of PANI coated fabrics and improves their EMI SE. Metals build a surface on the fabric that can block or reduce electromagnetic waves boosting EMI SE. After washing, fabric's EMI SE remained durable.*

Keywords: *acid dye, dopant-exchange, EMI shielding, metal ion complex, polyaniline, polyester*

Citation: Rohan C. Meshram, Asfiya Q. Contractor, Amol G. Thite, Ravindra D. Kale, "Metal Ion Complexation on Polyester Fabrics for EMI Shielding Applications", *Journal of the Textile Association*, **86/4** (Nov-Dec'25), 453-460, https://doi.org/10.63665/jta.v86i4.03

Article History : Received :20-08-2025, Revised:04-12-2025, Accepted: 08-12-2025

1. Introduction

EMI shielding in electronic devices uses manufacturing techniques and materials to protect signals from external electromagnetic signals and prevent interference with surrounding instruments and electronic devices. EMI includes various unwanted radiated signals that can disrupt electronic equipment. A standard method to create effective EMI shields and reduce electromagnetic pollution is by coating fabrics with conducting polymers like PANI and Polypyrrole [1, 2, & 3]. In these composites, radical cations, or polarons, absorb electromagnetic radiation and scatter it as heat. Polarons in conducting polymers are dispersed across multiple energy bands [4], enabling them to absorb These conducting polymers are referred to as synthetic metals because they look similar to metals with energy levels.

Metal particles have been used to deposit on the surface of conducting polymer films, increasing their EMI shielding efficiency by several decibels. Metals have with finer energy structures and absorb electromagnetic radiation better than conducting polymers, so electroless methods are usually employed to coat PANI films with metals. [5, 6]. Metal nanoparticles are deposited from metal ion salt solutions onto the polymer through oxidation by redox chemistry. Through autocatalytic electroless deposition, nanoparticles can form continuous layers when the right reducing agents are used. Metal nanoparticle dispersion on polymer films is challenging. This problem is addressed by electrochemical nucleation, which requires precise control of the deposition potential through managing the redox states of PANI [8]. Because fabrics act as insulators, this can cause a problem. More metal crystals and random deposition are visible in thicker PANI layers [9], however washing and abrasion can damage the film's integrity. Thicker PANI layers can result in loosely bound dendritic structure, reducing the durability of EMI shielding fabrics.

By studying chemically coating cotton fabrics with silver nanoparticles and hydrophobic agents [9], explored a simple method to produce multifunctional fabrics with ultrahigh EMI shielding, antibacterial qualities, et al have studied is through the use of a straightforward electroless copper plating technique, this study produced a highly conductive, copper-plated fabric with super hydrophobicity, excellent EMI shielding, and electric heating performance all of which make it perfect for flexible circuits and wearable technology [10].

To overcome these problems, we proposed incorporating metals into textile fabrics using a method similar to traditional metal mordanting. This involved applying anionic acid dyes to PANI coated fabrics and then complexing them with metal ions. Metal salts like Ni (II), Cr (VI), Fe (II), Fe (III), Co (II), and Cu (II) were used for complexation.

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2. Materials and Methods

2.1 Materials

75 GSM plain weave fabric of PET was provided by Piyush Syndicate (Mumbai, India); Aniline (EMPARTA ACS 99%) and Ammonium Peroxodisulphate (APS) (Emplura 98%) by Merck Life Science Pvt Ltd. (Mumbai, India), CI Acid Blue 113 from DyStar India Pvt. Ltd., (Mumbai, India), Copper sulphate ($CuSO_4$) and Nickel Sulphate ($NiSO_4$) from Molychem (Mumbai, India), Hydrochloric acid (HCl), Ferric Chloride ($FeCl_3$), Ferrous Sulphate ($FeSO_4$), Cobalt Chloride ($CoCl_2$) and Potassium Dichromate ($K_2Cr_2O_7$) from S.D. Fine Chemicals Ltd (Mumbai, India). Non-ionic Soap, Celdet-R from Sarex Chemicals Ltd (Mumbai, India)

2.2 In-situ deposition of PANI on PET fabric

The PET fabric was treated with 20 % NaOH solution for 35 mins at 95°C, washed for 30 mins at 40°C [6] and dried. Aniline (0.1 M) was mixed with 1 M of aqueous HCl into which PET fabric was immersed. A solution of oxidizing agent, APS, was slowly added so that final reaction mixture becomes 0.1M in APS. Material to liquor ratio (MLR) was maintained at 1:40. Chemical polymerization by in-situ method was carried at room temperature (RT) for approximately 2 hrs. Then fabric was washed by using 2 gpl non-ionic soap at 50 °C for 30 mins and dried.

2.3 Functionalization of PET/PANI composite fabric with Acid Dye

The fabric was then treated with acid dye, Telon Navy AMF (CI Acid Blue 113) in 2% shade on the weight of fabric at 80 °C for 60 minutes, followed by washing and this fabric samples were mentioned as PANI/AD.

2.4 Metal ion complexation on acid dye-treated fabrics

The fabric was then immersed in different metal salt solutions (5%) $NiSO_4$, $K_2Cr_2O_7$, $FeSO_4$, $FeCl_3$, $CuSO_4$ $CoCl_2$ and for 18 hours overnight. The fabric samples were then washed and dried. They were represented as PANI/AD/(Ni/Cr/$FeCl_3$/$FeSO_4$/Cu/Co). The prepared metal salt solutions exhibited ionic strengths of 0.630 M ($CoCl_2$), 0.719 M ($FeSO_4$), 1.110 M ($FeCl_3$), 0.761 M ($NiSO_4$), 0.747 M ($CuSO_4$), and 0.510 M ($K_2Cr_2O_7$). Corresponding pH values for this metal salt solutions were acidic, in case of $FeCl_3$ and $K_2Cr_2O_7$ pH was between 1 to 3, while $CoCl_2$, $FeSO_4$, $NiSO_4$, and $CuSO_4$ ranged between 4 to 6. These metal ions were chosen as they can form coordinate with PANI and also undergo redox reactions that helps the fabric to improve its EMI shielding performance (1–10). Metal ions initially coordinate on the nitrogen sites of PANI and undergo redox reactions whereas PANI donates electrons to reduce the metal ions at the surface of fabric. The overall rate of this process is controlled by diffusion of metal-ion towards the polymer interface and the kinetics of electron transfer that enables their reduction.

3. Characterization

3.1 Fourier Transform Infrared Spectroscopy (FTIR)

FTIR of the samples were evaluated to confirm the functionalization of fabric samples PET/PANI fabric, and PET/PANI/AD composite fabric. Instrument used for analysis was SHIMADZU IR Spirit with a QATR-S ATR unit within the range 400–4000 cm^{-1} having 45 scans per sample.

3.2 Scanning Electron Microscopy (SEM) and Energy Dispersive Analysis of X-rays (EDAX)

Samples were analysed by SEM using JEOL JSM IT 200 LV, Japan. Before analysis, the samples were gold-sputter-coated by JEOL-550 Twin coater, Japan.

The SEM machine had an energy-dispersive X-ray (EDS) detector for elemental composition and mapping analysis for all treated and untreated samples using EDAX (EDAX, USA) with a mapping area of 30 mm^2.

3.3 Resistivity (Surface and Volume resistivity) & EMI Shielding Effectiveness (EMI SE)

Surface and volume resistivity of samples was measured by Keithley Instruments, Mumbai by ASTM D 257 method. The samples were cutted into 10 × 10 cm and placed between two electrodes and tested at 100V.

EMI SE was measured by Tektronix RSA503A at frequency of 2.4 GHz and recorded at six different places on the fabric and average was calculated. Difference between the initial and final values gave the resultant EMI SE.

3.4 Effect of Folding Fabric on EMI SE

The fabric was folded at the centre to form multiple layers like 1-fold corresponds to 2 layers, 2-fold to 4 layers, and 3-fold to 8 layers of fabrics and was measured for EMI SE at the frequency of 2.4 GHz. Five readings were taken for each sample and average was reported.

3.5 Static charge decay time

Samples of size 10 x 10 cm were conditioned in a standard atmosphere, and decay time was measured by ASTM D 4238 method on TREK 156A charged plate monitor. Each sample was flipped on its front and back side at five different places. By varying supply voltage from 1000 to 0 V and 1000 to 500 V full and half charge decay time were observed and noted.

3.6 Tensile Strength

The tensile strength testing instrument (Model H5KS, Tinius Olsen Inc., Horsham, PA, USA) was used to measure the breaking strength and elongation of composites following ASTM D 5035(1995) as standard test method. The samples used for testing had dimensions of 150 X 25 mm.

3.7 Washing Durability

For investigating washing durability, the metalized fabric samples were analysed using AATCC 61–2013e (2020) 2A standard test method.

4. Results and Discussion

4.1 FTIR Spectroscopy

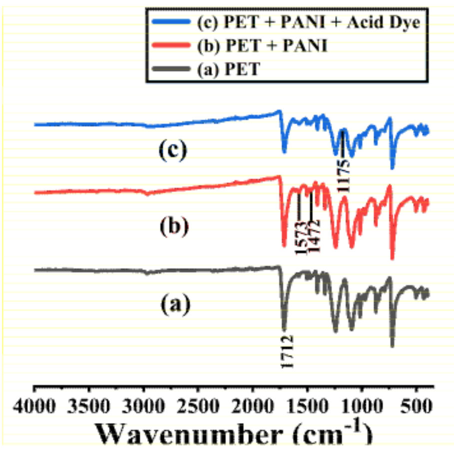


Figure 1: FTIR spectra of (a) PET, (b) PET/PANI, and (c)PET/PANI/AD

In FTIR spectra (fig.1), the peak observed at 1712 cm^{-1} correspond to carbonyl groups of ester. The peaks at 1472cm^{-1} and 1573cm^{-1} to N-B-N and N=Q=N groups in benzenoid and quinoid structures of PANI [11]. The peak at 1175cm^{-1} represented presence of sulphonic group [12]. This confirms PANI and Acid dye were present on the fabric.

In addition, the fingerprint region in those three samples (1400cm^{-1} to 700cm^{-1}) was very similar because the film of PANI on the PET fabric, the PET fabrics peaks were prominent [13]. The fingerprint region was dense with peaks from the azo, sulphonic acid, and nitro group of the dye in addition to other groups from PET and PANI chains.

4.2 Scanning Electron Microscopy (SEM) and Energy Dispersive Analysis of X-rays (EDAX)

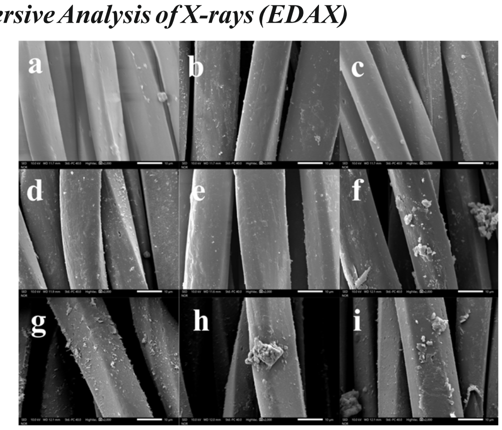


Figure 2: SEM photos of (a) PET, (b) PANI, (c) PANI/AD, (d) PANI/AD/Ni, (e) PANI/AD/Cr, (f) PANI/AD/FeSO$_4$, (g) PANI/AD/FeCl$_3$ (h) PANI/AD/Cu, (i) PANI/AD/Co

Surface morphology of the fabrics was observed using SEM analysis (Fig. 2). It showed smooth PET fabric pretreated with NaOH (Fig.2a). The coating of PANI increased the surface roughness of the fabric (Fig.2 b). Treatment with CI Acid Blue 113 seemed to decrease the roughness (Fig.2c). Acid dyes usually don't have affinity to PET, but when PET fabric is coated with PANI, the PANI provides positively charged nitrogen present in aromatic rings that help acid dye attach through electrostatic attraction and stacking layering of aromatic group of acid dye and aromatic backbone of PANI.

The fabric was rougher than previous samples after metal ion deposition (Figs. 2 d to i). Metals got incorporated via two mechanisms: metal ion complexation with the sulfonate groups of PANI acid dye treated fabrics which behaved as ligands and metal ion deposition through redox reactions forming nanoparticles that aggregated into larger particles as shown in schemes 1 and 2. Some metals exhibited higher particle deposition, while nickel and dichromate exhibited higher ligand complexation based on EMI SE results. Ferric ions showed the larger amounts of deposits other than any metal ion in EDAX spectra.

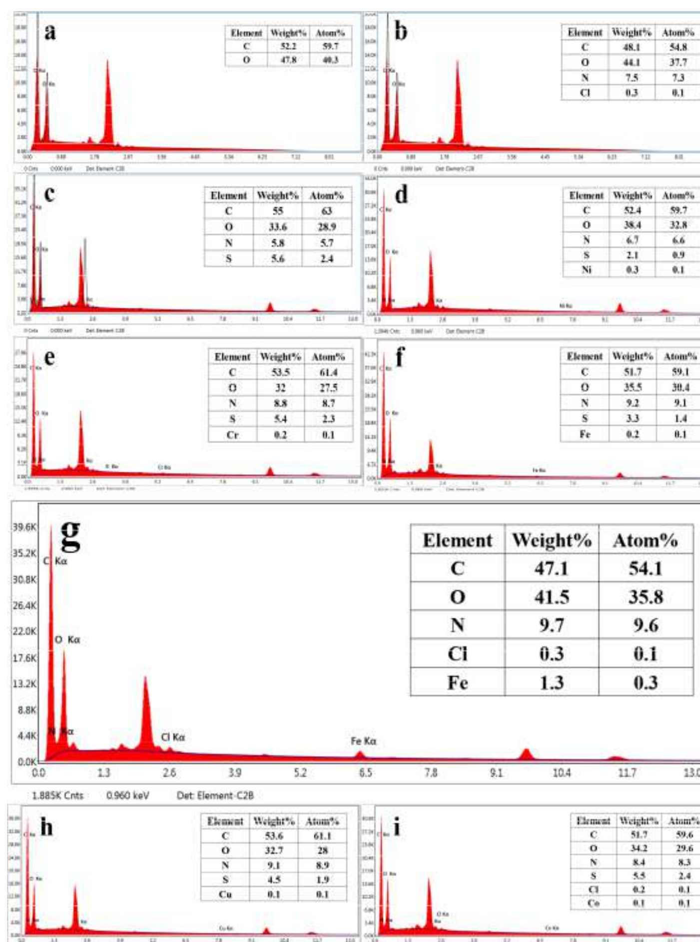


Figure 3: EDX spectra of (a) PET, (b) PANI, (c) PANI/AD, (d) PANI/AD/Ni, (e) PANI/AD/Cr, (f) PANI/AD/FeSO$_4$, (g) PANI/AD/FeCl$_3$ (h) PANI/AD/Cu, (i) PANI/AD/Co

After surface morphological analysis, Elemental analysis of samples was performed in (fig.3) and showed most composites were majorly composed of carbon and oxygen as the substrate material was PET. Nitrogen (N) existed because of PANI and was present in variable % in the metalized samples as it was difficult to obtain a reproducible layer of PANI on each sample. Similarly, S was present due to the presence of acid dye (Fig. 3c) and some metal salts are sulphates (Fig. 3 d, e, f, h, i). In case of (fig. 3 g) S is not visible as it could be due to $FeCl_3$ having maximum weight amongst all samples that is 1.3%. The weight of the metal ions varied between 0.1% and 0.4%, but was sufficient to increase the EMI SE. The ferric ion sample complexation had highest metal content by weight because of favourable interaction between dye and ferric ions that is borne out by use of ferric ions for electrocoagulation treatment of this dye [14, 15]. Chloride was also present in some samples because PANI was initially doped with chloride, and some metal salts also contained chlorides.

4.3 Resistivity (Surface and Volume resistivity) & EMI SE

Table 1: Surface resistivity and Volume resistivity of metalized PET/PANI composite fabrics

Fabric Sample	**Surface Resistivity Ω/square ×10^7**		**Volume Resistivity Ω.cm × 10^7**	
	Average	**Std Deviation**	**Average**	**Std Deviation**
PET	6.904 × 10^6	0.033	9.43×10^6	0.040
PANI	280.1	2.02	49.08	0.37
PANI/AD	647.3	5.31	75.72	0.64
PANI/AD/Ni	892.7	9.82	2.172	0.023
PANI/AD/Cr	0.34	0.0037	0.07582	0.00088
PANI/AD/$FeSO_4$	638.6	7.66	85.72	1.11
PANI/AD/$FeCl_3$	373.1	4.29	0.4832	0.01
PANI/AD/Cu	65.23	0.72	1.852	0.02
PANI/AD/Co	723.7	8.32	94.85	1.09

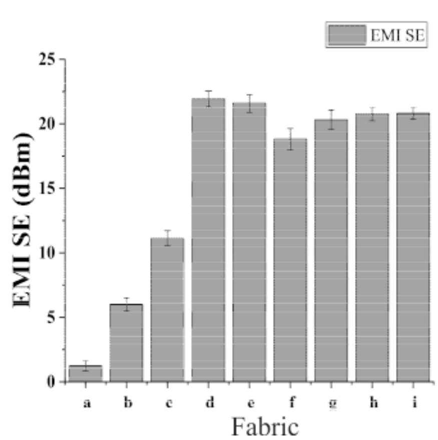


Figure 4: EMI SE of (a) PET, (b) PANI, (c) PANI/AD, (d) PANI/AD/Ni, (e) PANI/AD/Cr, (f) PANI/AD/FeSO4, (g) PANI/AD/FeCl3 (h) PANI/AD/Cu, (i) PANI/AD/Co

In conducting polymers, electromagnetic energy is absorbed by polarons and bipolarons and dissipated as heat.

Surface resistivity and volume resistivity are shown in (Table 1) and EMI SE data is shown in (fig.4).

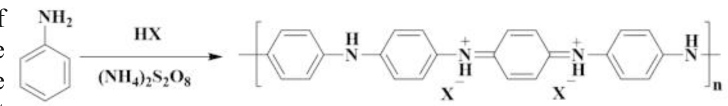
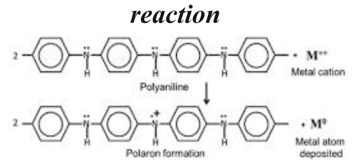


Figure 5: PANI synthesis from Aniline (HX represents Polaron (+/charge carrier) and corresponding acid radical)

The untreated PET fabric is highly insulating, but coating with chloride-doped PANI, as shown its synthesis from aniline as shown sin (fig.5) reduced its volume and surface resistivity till seven and six orders of magnitude, respectively, due to movement of polarons enhancing EMI SE. Chloride-doped PANI showed the lowest resistivity as small chloride ions allow easy polaron hopping along the polymer chain. After acid dye treatment, the resistivity increased to 647.3 x 10^7 Ω/square in case of surface resistivity, and 75.72 x 10^7 Ω.cm in case of volume resistivity when acid dye anions were replaced for chloride dopant. They are bulky in nature as they contain two azo groups and two sulfonic acid groups and one nitro group and so, the polarons were not able to move like chloride doped PANI. The dye and its interaction with PANI are exothermic due to stacking, and is supported by the fact that PANI is used for removal of dyes from water [16] which increased the EMI SE.

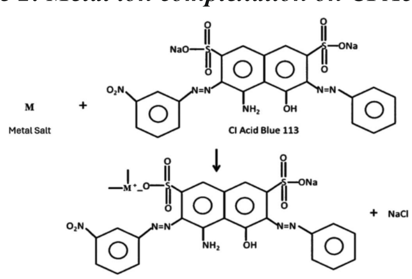
In PANI/AD samples, metal ion complexation at RT involved coordinate bonding between metal ions (Lewis acids) and ligands (Lewis bases) like sulfonate groups from the dye and nitrogen atoms of PANI. According to crystal field theory, these bonds are electrostatic, arising from ion–ion interactions (metal cations with sulfonate anions) or ion–dipole interactions (metal ions with nitro or amine groups) [17]. The attraction occurs through ion–ion interactions, where metal cations bind with negatively charged sulfonate groups, or ion–dipole interactions, where nitro and amine groups coordinate with the metal ion. In ion-dipole interactions, groups such as nitro and amine interact with central metal ion. In ion–dipole cases, the ligand region near the metal gains partial negative charge (δ–), while the distant region acquires partial positive charge (δ+). Ligand-field interaction was strongest with Ni and Cr ions, giving the highest EMI SE, with Ni also absorbing more radiation. Co^{2+}, Fe^{2+}/Fe^{3+}, and Cu^{2+}, undergo redox with PANI, forming metal atoms that aggregate into micron-sized particles (Scheme 1) [18]. These ligand interactions influence EMI SE through both metal atoms and polarons, but the effect is weaker with $NiSO_4$.

Scheme 1: Metal deposition on PANI utilizing a redox reaction



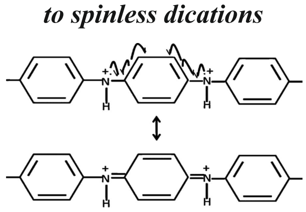
Ferrous ions show the weakest ligand interaction, likely due to lower electropositivity, giving lower EMI SE. EDAX data indicates ferric ions interact most, enabling maximum complexation. Cobalt, nickel, and ferric ions, being ferromagnetic, show higher EMI SE than ferrous ions. Copper is widely used in EMI shielding for its consistent attenuation of electric and magnetic waves [19], malleability, ductility, and easy soldering. Metal atom deposition on PANI by redox reaction increases polarons, reducing resistivity. Co^{2+} complexes show the lowest resistivity as Cl^- from $CoCl_2$ eases polaron movement. Ni^{2+} can accommodate six ligands (sulfonate, nitro, azo groups, from dye anions or nitrogen from PANI chain), with sulfonate interaction being strongest, giving both intra- and interchain coordination, which enhances conductivity and EMI dissipation. Thus, the Ni^{2+} ions exhibited both intrachain and interchain coordination [20] in PANI, increasing conductivity and thereby enabling the dissipation of electromagnetic radiation. In cobalt, resistivity was higher as polarons did not increase. For copper, polarons increased but resistivity rose due to one slow-moving sulphate ions for every two polarons thereby increasing resistivity. Being more noble, copper reduced more easily than Ferrous, so Fe treated samples showed higher resistivity. SEM-EDAX shows ferric ions incorporate into PET/PANI more than other metals through ion reduction and complexation. Ferric ions also bind dye sulfonate ligands, while reduction increases polaronic charges (Scheme 2). With three positive charges, ferric ions bridge PANI chains, allowing polaron movement across nodes, thus reducing resistivity to nearly half that of ferrous ions.

Scheme 2: Metal ion complexation on CI Acid Blue 113



$K_2Cr_2O_7$ is an oxidizing agent capable of oxidizing some of the PANI polarons to bipolarons [21]. Bipolarons are not as facile in charge conduction as polarons. Hence, the conductivity decreased. However, bipolarons are diradical dications that resonate to form spinless dications (see Scheme 3 below). Thus, the material is a good absorber of electric fields as it is charged and at the same time it blocks magnetic fields as it is spin-less. Therefore, the EMI SE is high.

Scheme 3: Resonance conversion of diradical dications to spinless dications



4.4 Effect of folding of the Fabrics on EMI SE

Here the PANI Acid Dye fabric complexed with metals complexed fabrics was folded in combination such as 1-fold, 2-fold and 3-fold with single metal, two different metal and three different metal coated fabric layers. This was done to evaluate thickness of the fabric and the synergies of metals with each other. In all fabric samples, it was found that EMI SE increased with increase in thickness [22] with the number of folding. However, increase in EMI SE differed as per the nature of the metal as each metal has different synergies for each other that affected the EMI SE. Nickel has got highest synergies than copper and cobalt as per observation after measuring for EMI SE [23] (Fig.6).

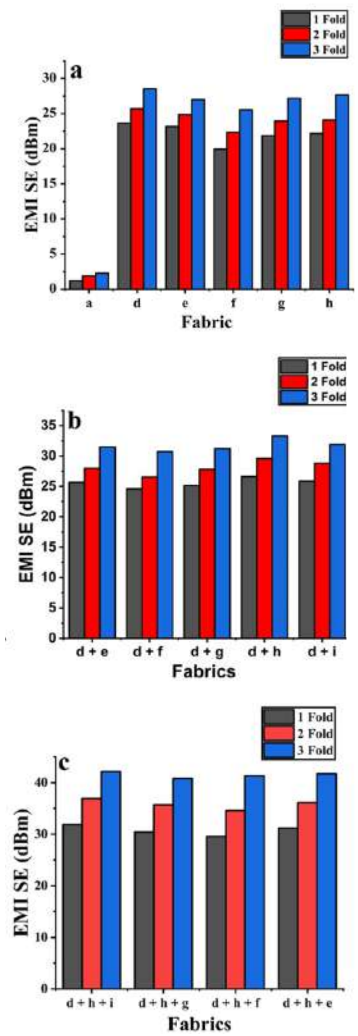


Figure 6: Data of EMI SE of Thickness and synergistic effect of Fabrics - a) Folding Effect for single metal b) two metals c) three metals (a) PET (d) PANI/AD/Ni, (e) PANI/AD/Cr, (f) PANI/AD/$FeSO_4$, (g) PANI/AD/$FeCl_3$, (h) PANI/AD/Cu, (i) PANI/AD/Co

4.5 Decay time

Decay time or the time taken for conduction of charge through the samples was measured for untreated PET and all the treated fabrics. The decay time for untreated PET was more than 100 seconds whereas in case of treated fabrics, it was less than one second as charge decay was immediate. This indicates that all the treated fabrics were highly conducting in nature. Also, after 5 washes the charge decay was less than one second showing its conductive nature.

Table 2: Static Decay charge time of the samples

Sample	Decay Time (sec)	
	Half Decay	Full Decay
Untreated PET	114	189
Treated Fabrics (PANI, PANI/AD, PANI/AD/Ni, PANI/AD/Cr, PANI/AD/$FeSO_4$, PANI/AD/$FeCl_3$, PANI/AD/Cu, PANI/AD/Co)	>1	>1
Treated Fabrics - After Washing (PANI, PANI/AD, PANI/AD/Ni, PANI/AD/Cr, PANI/AD/$FeSO_4$, PANI/AD/$FeCl_3$, PANI/AD/Cu, PANI/AD/Co)	>1	>1

4.6 Tensile Strength

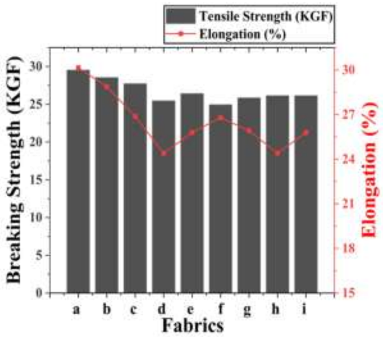
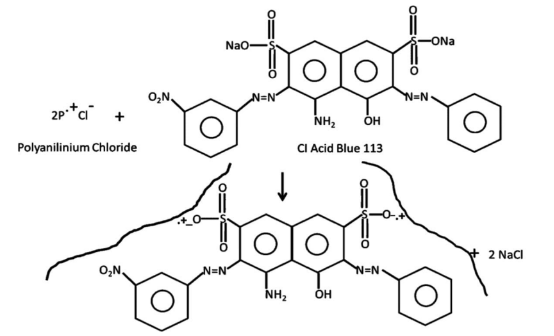


Figure 7: Tensile Strength and elongation at break of (a) PET, (b) PANI, (c) PANI/AD, (d) PANI/AD/Ni, (e) PANI/AD/Cr, (f) PANI/AD/$FeSO_4$, (g) PANI/AD/$FeCl_3$ (h) PANI/AD/Cu, (i) PANI/AD/Co

Fig.7 shows breaking strength and elongation (%) from the obtained data it can be said that each process carried out affects the amorphous regions of PET, reducing its crystallinity. Overall, the decrease in strength of the samples varied and was due to in-situ polymerization followed by metal ion complexation that was between 16-18%. The untreated PET fabric had the highest breaking strength and elongation. When a composite was prepared with PANI, tensile strength decreased as the solution used for polymerization was acidic affecting the PET chains adversely [24]. When sample was further treated with a solution of the sodium salt of acid dye, the Na ions combined with the chloride ions from PANI chloride, and the sulphonate groups of the dye were exposed for doping with PANI (see Scheme 4).

Scheme 4: Dopant exchange of chloride ions with CI Acid Blue 113 in PANI chains



A favourable interaction of dye with PANI took place because it is an aromatic molecule [16] and further swelling of PET fabric with the dye occurred. This reduced its strength more due to further breaking of bonds in PET fabrics. Crosslinking of chains, can embrittle the fabrics, was also possible as the dye has two sulfonic acid groups. After this, when fabric samples were kept for 18 hours at RT in acidic metal salt solutions resulting in additional bond-breaking.

4.7 Washing Durability

The effectiveness of any functionalization depends on its retention after repeated washing. To evaluate washing durability [25], the EMI SE of metal-complexed fabrics was measured after five washes. Readings were taken at five different points on each sample, and the average values are reported in Table 4. The % decrease in EMI SE ranged from 1.75% to 5.02%, indicating the coatings remained fairly durable after five washes.

Table 4: Average EMI SE of metal complexed samples which were washed five washes

S. No.	Fabric Sample	EMI SE before washing durability test, dBm	Average EMISE after five washes, dBm	% Decrease in EMISE
1.	PANI/AD/Ni	21.92	20.82	5.02
2.	PANI/AD/Cr	21.57	20.90	3.11
3.	PANI/AD/$FeSO_4$	18.80	18.47	1.75
4.	PANI/AD/$FeCl_3$	20.31	19.58	3.59
5.	PANI/AD/Cu	20.75	19.86	4.29
6.	PANI/AD/Co	20.81	20.11	3.36

5. Conclusion:

Metal particles were incorporated into PET/PANI fabrics to enhance EMI shielding. PANI was doped with HCl on PET fabric, followed by dopant exchange by CI Acid Blue 113, whose sulphonic acid groups enabled metal ion complexation. Metal ions from 5% aqueous salt solutions were added at RT for 18 hours, improving EMI SE up to 16 dBm, with Ni(II) showing best performance at 21.92 dBm. SEM-EDAX revealed two mechanisms: ligand interaction (e.g., nickel, dichromate) and redox reactions with PANI, depositing micron-sized metal particles. Fe(III) showed both complexation and reduction, with highest deposition. Acid dye metallization reduced tensile strength by 16–18%, though EMI SE was retained after five washes. Although EDAX was used for elemental analysis, more quantitative techniques like XRFS can provide more insight on composition and will be performed in future work. These fabrics demonstrate strong potential for smart textiles and everyday use as flexible EMI shielding materials to reduce radiation from sources like Wi-Fi and mobile phones. As all the three steps like coating of PANI, dyeing, and metal treatment are commonly used in textile mills, the process can be easily scaled up with the existent machinery. It also offers an economic advantage by avoiding expensive chemicals used in electroplating and reducing overall usage of metal.

Acknowledgments:

We are grateful that Rohan C. Meshram was granted a fellowship by the BARTI (Dr. Babasaheb Ambedkar Research and Training Institute), Pune, Maharashtra, India, for his Ph.D. research.

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ISSN 0368-4636

A Comparative Multi-Criteria Decision-Making Analysis of Sheep Wool-Epoxy Composites for Sustainable Applications

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Abstract:

Natural fiber composites have emerged as a viable substitute for conventional synthetic materials in light of the growing demand for sustainable resources worldwide. This study uses a sound decision-making framework to assess the acceptability of a novel sheep wool-epoxy composite in comparison to seven other natural fiber options. The Bharat Method and the ranking-based R-Method were used to evaluate the various mechanical, thermal, and physical qualities. Through the MCDM methodology, it was discovered that sheep wool plus epoxy resin consistently performed well in both methods, while sheep wool plus silicone rubber also demonstrated a respectable rank.

This work validates the substantial potential of underutilized sheep wool as a formidable reinforcement for sustainable composite applications and provides a methodical and quantitative approach to material selection in engineering design.

Keywords: *Bharat Method, Epoxy Resin, MCDM technique, Natural Fibers, R-Method, Sheep Wool Composites*

Citation: Mangesh Mohan, Ravindra Garmode, Vivek G. , Dattatraya K. "A Comparative Multi-Criteria Decision-Making Analysis of Sheep Wool-Epoxy Composites for Sustainable Applications", *Journal of the Textile Association*, **86/4** (Nov-Dec'25), 461-466, https://doi.org/10.63665/jta.v86i4.4

Article History : Received :02-11-2025, Revised:17-11-2025, Accepted: 21-12-2025

1. Introduction

The global construction industry is a huge energy and resource user, contributing significantly to both environmental emissions and overall energy usage [1]. The sector now urgently needs to embrace ecologically sustainable development techniques because of this significant impact [2]. The creation and application of eco-friendly materials that limit waste, lessen environmental footprints, and support global sustainability goals is a crucial tactic in this shift [3].

One of the most popular classes of sustainable materials is natural fiber composites (NFCs), which provide a good substitute for traditional synthetic composites made from non-renewable resources [4]. NFCs have many benefits, such as low density, biodegradability, renewability, and a greatly diminished environmental impact over the course of their existence [5]. However, obstacles to their broad use include increased susceptibility to moisture and issues with long-term durability, which call for careful material selection and design [6].

Sheep wool is still a relatively untapped resource with remarkable natural qualities among the wide variety of natural fibers. It is a very promising reinforcement material because it is non-toxic, naturally fire resistant, and provides good thermal and acoustic insulation [7 - 10]. The dairy sheep business produces a significant amount of waste wool each year, which presents a significant opportunity to valorize this byproduct in high-performance engineering applications [11].

The composite materials used in this study are made from sheep wool and epoxy resin, a combination that has shown a lot of promise. Their exceptional mechanical qualities, such as tensile strengths of up to 40 MPa at an ideal 50% fiber loading, are highlighted by recent study [12]. These composites' potential for applications needing both structural integrity and energy efficiency is further supported by their improved thermal insulation, which shows a 30% reduction in thermal conductivity when compared to neat epoxy [13, 14].

But selecting the best composite material among the variety of choices is a difficult undertaking. Every material has a different set of characteristics, frequently with competing performance standards (e.g., low density vs. high strength). Because of this complexity, an organized and quantitative evaluation method is required. By weighing several options against a variety of criteria in a cohesive framework, Multi-Criteria Decision-Making (MCDM) offers collection of methodical approaches intended to address such challenging selection issues [15, 16].

This paper has two primary objectives. Using a comprehensive set of eight performance criteria, it first assesses and rates eight distinct natural fiber composite choices, with a particular focus on the performance of sheep wool-epoxy. Secondly, the ranking-based R-approach will be used, and the potential impact of an objective weighting approach such as Bharat Method on the outcomes will be

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discussed. This research helps to the development of sustainable engineering solutions by suggesting a clear framework to select best composite materials.

2. Methodology

2.1 MCDM Technique

The selection of an optimal material from a pool of viable candidates is a critical decision-making challenge, especially when multiple, often conflicting, performance criteria are involved. The weight of the criterion has a major impact on the choice of any MCDM technique. As a result, it is crucial to give the criterion the right weight and to use proper weighting techniques [18]. To address this complexity with quantitative rigor and objectivity, this research considers two formal Multi-Criteria Decision-Making (MCDM) methodologies. This section details the procedural steps of the two distinct methods used, R-Method and the Bharat Method.

2.2 Data Preparation

The decision matrix X = [x_{ij}] was constructed, where each element x_{ij} refers to the performance value of the *i-th* alternative under the *j-th* criteria. The criteria include both beneficial (topmost value preferred) and non-beneficial (bottommost value preferred) parameters. The criteria weights (w_j) were assigned based on expert judgment and literature review, ensuring that the sum of all weights equals 1.

$$\sum_{j=1}^{n} w_j = 1$$

2.3 Bharat Method

The Bharat Method is a simplified, normalization-based MCDM technique developed to streamline the ranking process by integrating the effects of beneficial and non-beneficial criteria into a single performance index, termed the Bharat Index (BI).

Step 1 – Normalization of Criteria Values

Each element of the decision matrix is normalized to bring all criteria to a comparable scale using the following formula:

$$ij \begin{cases} \dfrac{x_{ij}}{x_j^{\max}} & if\ criterion\ is\ beneficial \\ \dfrac{x_j^{min}}{x_{ij}} & if\ criterion\ is\ non-beneficial \end{cases}$$

Where $x_j^{max}\ and\ x_j^{min}$ are the maximum and minimum values of jth criterion respectively.

Step 2 – Weighted Normalized Matrix

The normalized values are multiplied by the corresponding criterion weights.

$$v_{ij} = \omega_j \text{ x } r_{ij}$$

Step 3 – Calculation of Bharat Index (BI)

For each alternative, the overall Bharat Index is calculated as:

$$BI_i = \sum_{j=1}^{n} v_{ij}$$

Step 4 – Ranking of Alternatives

The Bharat Index (BIi) values of the options are used to rank them. The choice that is thought to be the most liked is the one with the highest BI value.

2.3 R-Method

The R-Method (Relative Reference Method) determines the relative performance of choices by comparing their closeness to the ideal and anti-ideal solutions. It combines normalization, weighting, and Euclidean distance computation to derive a relative closeness index for each alternative [17].

Step 1 – Normalization of Decision Matrix

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}$$

Step 2 – Weighted Normalized Matrix

$$v_{ij} = \omega_j \text{ x } r_{ij}$$

Step 3 – Determine Ideal and Anti-Ideal Solutions

The ideal (A^+) and anti-ideal (A^-) solutions are obtained as:

$$A^+ = \{\max(v_{ij}) | j \in J_b\}$$

$$A^- = \{\max(v_{ij}) | j \in J_b\}$$

Where J_b denotes the setoff beneficial criteria.

Step 4 – Compute Euclidean Distances

The separation measures of each alternative from the ideal and anti-ideal solutions are calculated as:

$$s_i^+ = \sqrt{\sum_{j=1}^{n} (v_{jj} - A_j^+)^2}$$

$$s_i^- = \sqrt{\sum_{j=1}^{n} (v_{jj} - A_j^-)^2}$$

Step 5 – Determine Relative Closeness (R-Score)

$$R_i = \frac{s_i^-}{s_i^+ \quad s_i^-}$$

Step 6 – Ranking of Alternatives

The ranking of alternatives according to their R_i values. A higher R-score indicates a more favourable alternative.

3. Problem Formulation: Alternatives and Criteria

To effectively use the chosen MCDM models, we need to create a clear problem structure. This involves defining the set of composite material options for evaluation and the specific performance criteria we will use to assess them. This section outlines the materials and metrics that form the basis of our comparative analysis.

3.1 Composite Alternatives

Eight distinct natural fiber (plant and animal) and composite materials were selected for this comparative study. These alternatives represent a range of fiber and matrix combinations, including the primary material of interest, Sheep Wool + Epoxy Resin. The alternatives are as follows: 1. Jute + Epoxy Resin 2. Banana Fiber + Polyurethane (PU) 3. Bamboo + Silicone Rubber 4. Sheep Wool + Epoxy Resin 5. Sheep Wool + Polyurethane (PU) 6. Sheep Wool + Silicone Rubber 7. Sheep Wool (Unreinforced) 8. Camel Hair (Unreinforced)

3.2 Evaluation Criteria and Decision Matrix

A set of eight criteria was used to evaluate the performance of the eight options. Important mechanical, thermal, and physical characteristics were examined using these criteria. Tensile strength (σ_t) Young's modulus (E), flexural strength (σ_f), impact strength (σ_i), density(ρ), elongation(δl), thermal stability(Δ), and thermal conductivity (α) are the chosen criteria.

The performance data for each alternative against these criteria are compiled into the decision matrix presented in Table 1.

4. Results and Discussion

This study presents the outcomes derived after applying the R-Method to the decision matrix defined in the previous section. The results are analysed to determine the most suitable composite material for sustainable applications, followed by a qualitative discussion of how an alternative objective weighting method could influence the selection process.

4.1 Ranking using the R-Method

Each alternative was given a rating depending on how well it performed for each criterion, and these ranks were weighted based on the qualities' predetermined importance in order to use the R-Method. Table 2 displays the final composite scores and the corresponding ranks.

Sheep Wool + Epoxy Resin was the top-ranked composite material according to the R-method study. Its exceptional tensile strength (275 MPa), strong flexural strength (65 MPa), and greatest heat stability (275°C) among all alternatives are the main reasons for its good rating. These characteristics demonstrate its rigidity, high load-bearing capability, and resistance to degradation at high temperatures. Its overall composite score was greatly

Table 1: Decision matrix of all composites and criteria

Composite Combination	σ_t (MPa)	E (GPa)	σ_f (MPa)	σ_i (J/m²)	Δ (°C)	α (W/mK)	ρ (g/cm³)	δl (%)
1. Jute + Epoxy Resin	225	4.5	75	55	225	0.25	1.2	1.5
2. Banana Fiber + Polyurethane (PU)	75	2	30	75	200	0.225	1.3	15
3. Bamboo + Silicone Rubber	125	7.5	65	75	225	0.3	1.4	7.5
4. Sheep Wool + Epoxy Resin	275	4	65	65	275	0.3	1.3	7.5
5. Sheep Wool + Polyurethane (PU)	75	1.5	30	50	200	0.2	1.2	30
6. Sheep Wool + Silicone Rubber	50	1	20	70	350	0.3	1.15	75
7. Sheep Wool	140	4	10	5	225	0.04	1.35	30
8. Camel Hair	100	3	10	5	230	0.03	1.35	30

Table 2: Final composite scores with R method

Composite Combination	σ_t (MPa)	E (GPa)	σ_f (MPa)	σ_i (J/m²)	Δ (°C)	α (W/mK)	ρ (g/cm³)	δl (%)	Comp. Score	Rank
1. Jute + Epoxy Resin	0.155	0.127	0.233	0.112	0112	0.102	0.155	0.086	0.132	5
2. Banana Fiber + Polyurethane (PU)	0.095	0.102	0.112	0.233	0.09	0.112	0.112	0.102	0.115	7
3. Bamboo + Silicone Rubber	0.112	0.233	0.155	0.233	0.112	0.095	0.086	0.095	0.134	3
4. Sheep Wool + Epoxy Resin	0.095	0.112	0.155	0.127	0.155	0.233	0.112	0.086	0.146	1
5. Sheep Wool + Polyurethane (PU)	0.095	0.09	0.112	0.095	0.09	0.127	0.155	0.155	0.112	8
6. Sheep Wool + Silicone Rubber	0.086	0.086	0.095	0.155	0.194	0.095	0.194	0.230	0.139	2
7. Sheep Wool	0.127	0.112	0.09	0.086	0.112	0.155	0.095	0.155	0.12	6
8. Camel Hair	0.102	0.095	0.09	0.086	0.127	0.233	0.095	0.155	0.133	4
Weight assigned to attributes	0.127	0.102	0.112	0.095	0.194	0.194	0.088	0.088		

improved by the weighted influence of mechanical and thermal factors, despite its moderate elongation and impact strength. In comparison to the other studied composites, this combination shows the best balance between mechanical performance and thermal resistance, making it the best material for structural and high-temperature applications.

4.2 Ranking using Bharat Method

While the R-Method provides a robust ranking based on a decision-maker's priorities, it is valuable to consider how an objective weighting method might alter the outcome. The Bharat Method offers such an alternative by deriving criteria weights directly from the data, thus removing subjective bias. A full quantitative application of this method is beyond the scope of the available data, but a qualitative discussion can provide significant insight. Table 3 shows normalised matrix for Bharat Method while Table 4 shows BM scores of all the alternatives.

The CRITIC method assigns higher weights to criteria that exhibit both high variance (contrast) among alternatives and low correlation (conflict) with other criteria. An examination of the decision matrix (Table 1) reveals that criteria such as Tensile Strength (ranging from 50 to 275 MPa), Elongation (1.5% to 75%), and Thermal Conductivity (0.03 to 0.3 W/mK) show significant variance. An objective method like CRITIC would likely assign these criteria substantial weights. This could potentially elevate a material like Alternative 4 (Sheep Wool + Epoxy Resin), which possesses the maximum Tensile Strength, in the final ranking. Similarly, Alternative 6 (Sheep Wool + Silicone Rubber), with its extreme value in Elongation, would also be favored. Conversely, criteria with lower variance, like Density, might get less weight. This could change the final ranking compared to the R-Method. This example shows that while the best materials would probably still be strong contenders, their exact order could vary based on how important their standout properties are.

4.3 Discussion and Synthesis of Findings

The R-Method analysis shows that sheep wool-based composites are very suitable for sustainable uses, with two different formulations taking the top spots. The performance of Alternative 4 (Sheep Wool + Epoxy Resin) stands out. It ranked first due to its excellent Tensile Strength (275 MPa) and high Thermal Stability (275 °C). This finding aligns with research that highlights the strong mechanical performance and improved thermal insulation of sheep wool-epoxy systems [6, 7]. These key strengths make it a strong choice for applications that need high structural integrity.

The second-ranked material, Alternative 6 (Sheep Wool + Silicone Rubber), shows a different yet just as impressive performance profile. Its second-place finish is attributable to its superior Thermal Stability (350 °C), lowest Density (1.15 g/cm³), and remarkable Elongation (75%). This highlights a critical trade-off in material selection: while Alternative 4 is the strongest, Alternative 6 offers an outstanding combination of thermal resilience, light weight, and flexibility, which the R-Method's scoring ultimately favored.

The strong performance of two distinct sheep wool composites in the top positions validates the viability of sheep wool as a high-performance reinforcement fiber. Furthermore, the consideration of an objective weighting scheme like Bharat Method suggests that these materials

Table 3: Normalised matrix for Bharat Method

Composite Combination	σ_t (MPa)	E (GPa)	σ_f (MPa)	σ_i (J/m²)	Δ (°C)	α (W/mK)	ρ (g/cm³)	δl (%)
1. Jute + Epoxy Resin	0.818	0.6	1	0.733	0.643	0.12	0.958	0.02
2. Banana Fiber + Polyurethane (PU)	0.273	0.267	0.4	1	0.571	0.133	0.885	0.2
3. Bamboo + Silicone Rubber	0.455	1	0.867	1	0.643	0.1	0.821	0.1
4. Sheep Wool + Epoxy Resin	1	0.533	0.867	0.867	0.786	0.1	0.885	0.1
5. Sheep Wool + Polyurethane (PU)	0.273	0.2	0.4	0.667	0.571	0.15	0.958	0.4
6. Sheep Wool + Silicone Rubber	0.182	0.133	0.267	0.933	1	0.1	1	1
7. Sheep Wool	0.509	0.533	0.133	0.067	0.643	0.75	0.852	0.4
8. Camel Hair	0.364	0.4	0.133	0.067	0.657	1	0.852	0.4

Table 4: Ranking of composites with Bharat Method

Composite Combination	Normalized Sum	BM score	Rank
1. Jute + Epoxy Resin	4.892	0.391	3
2. Banana Fiber + Polyurethane (PU)	3.729	0.298	7
3. Bamboo + Silicone Rubber	4.986	0.399	2
4. Sheep Wool + Epoxy Resin	5.138	0.411	1
5. Sheep Wool + Polyurethane (PU)	3.619	0.29	8
6. Sheep Wool + Silicone Rubber	4.615	0.369	4
7. Sheep Wool	3.887	0.311	5
8. Camel Hair	3.873	0.31	6

would remain top contenders regardless of the evaluation method, due to their exceptional and high-variance properties. This reinforces the central finding that sheep wool can be valorized to create sustainable composite materials that outperform other common natural fiber alternatives.

4.4 Visual Representation of Results

Table 5: Representation of combined ranking by Bharat Method and R-Method of all composites

Composite Combination	BM score	Rank	R Score	R Method Rank
1. Jute + Epoxy Resin	0.391	3	0.132	5
2. Banana Fiber + Polyurethane (PU)	0.298	7	0.115	7
3. Bamboo + Silicone Rubber	0.399	2	0.134	3
4. Sheep Wool + Epoxy Resin	0.411	1	0.146	1
5. Sheep Wool + P olyurethane (PU)	0.29	8	0.112	8
6. Sheep Wool + Silicone Rubber	0.369	4	0.139	2
7. Sheep Wool	0.311	5	0.12	6
8. Camel Hair	0.31	6	0.133	4

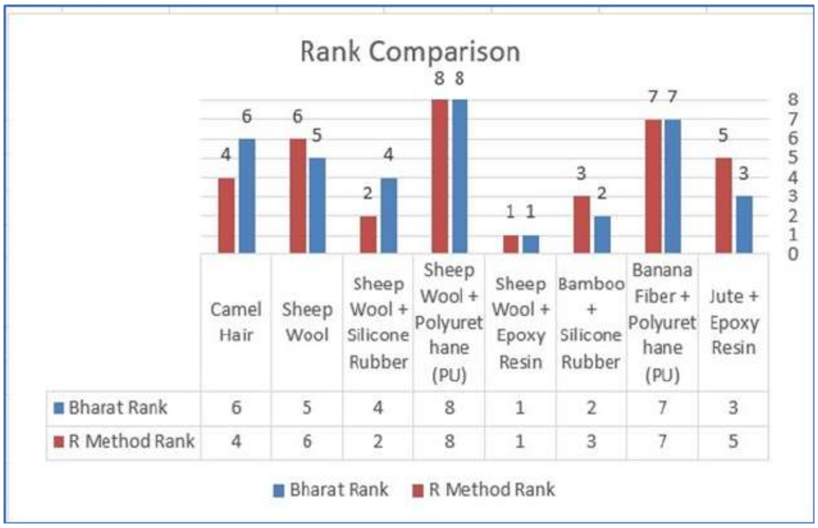

Figure 1: Rank comparison using histogram

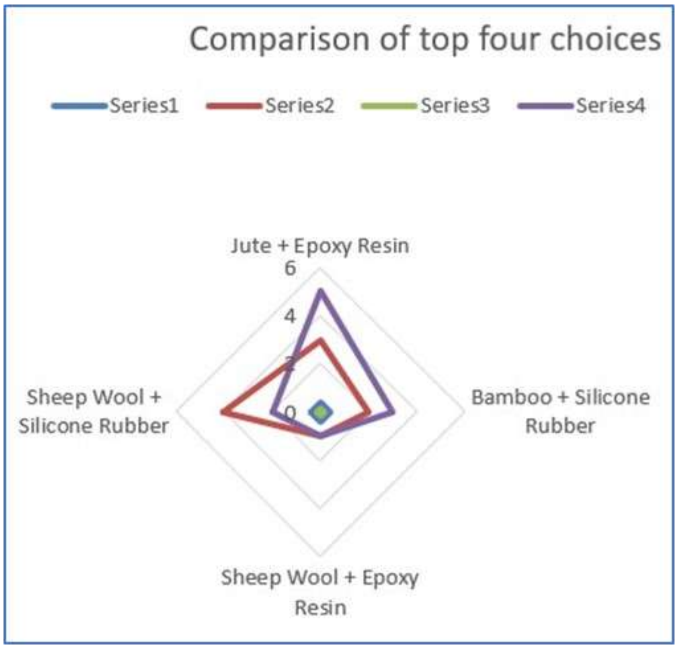

Figure 2: Rank comparison of topmost 4 choices using radar chart

5. Conclusion

This research was initiated to address the complex challenge of selecting optimal materials for sustainable engineering applications from a field of promising natural fiber composites. By using a solid framework based on the R-Method and a detailed discussion of the Bharat Method, this study evaluated eight composite alternatives against a full set of performance criteria.

The main finding of this analysis is the clear identification of sheep wool-based composites as better material choices. In the R-Method analysis, Sheep Wool + Silicone Rubber and Sheep Wool + Epoxy Resin ranked as the top alternatives. Their high rankings came from an excellent balance of mechanical strength, thermal stability, and low density, which makes them very appealing for various applications. The strength of this conclusion was also backed by a discussion of sensitivity analysis and an example of an objective weighting method.

The broader significance of these findings is important. This research offers strong evidence that sheep wool, often seen as an agricultural by product, is a practical and high-performing reinforcement fiber for polymer composites. It aids in developing new sustainable materials that can lessen the need for synthetic, non-renewable resources and supports the principles of a circular economy by making use of waste. This organized approach to material selection serves as a helpful model for engineers and designers aiming to make informed, data-driven decisions for sustainable innovation.

Acknowledgement

We gratefully acknowledge the assistance of Mr. Ashok Bhagat, Praj Metallurgical Laboratory, Pune, India (material testing expert), Dr. Sajjan Lal and Dr. R. Gode, Mumbai university (Academic researcher) for guiding on accurate data and expert opinion used in this research article.

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Journal of the TEXTILE Association
ISSN 0368-4636

Statistical Optimisation of Catechu Dyeing of Cotton Fabric using Gallnut and Potash-alum Bio-mordanting

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Abstract:

This study investigates the statistical optimisation of six key dyeing parameters for dyeing cotton fabric using a dual bio-mordanting process with gallnut and potash-alum, followed by catechu natural dyeing, using response surface methodology with the Box-Behnken statistical optimisation model. Thus, six dyeing process variables viz. dual bio-mordant concentration, dye concentration, dye bath pH, substrate-to-liquor ratio, dyeing time and temperature were statistically optimised to obtain a maximum colour strength. Finally, statistical optimization results and ANOVA analysis showed to achieve a maximum K/S value of 12.20 under the finally determined optimized dyeing conditions: with overall 15% concentration of potash alum and gallnut (in 75:25 ratio) for dual bio-mordanting and subsequently dyeing with 30% catechu extract, at dye bath pH 4, 70 °C dyeing temperature, 60 minutes dyeing time and an MLR of 1:20. These findings thus provide a standardized practical dyeing conditions for sustainable eco-friendly low salt catechu dyeing of cotton achieving a maximized color strength in this newer gallnut and potash alum dual bio-mordanting technique, easily implentable for industrial dyers.

Keywords: *Box-Behnken design, Catechu, Gallnut, Natural Dye, Potash-alum, Statistical Optimisation*

Citation: Pubalina Samanta, Asis Mukhopadhyay, Amiya Kumar Singha, Adwaita Konar, "Statistical Optimisation of Catechu Dyeing of Cotton Fabric using Gallnut and Potash-alum Bio-mordanting", *Journal of the Textile Association*, **86/4** (Nov-Dec'25), 467-475, https://doi.org/10.63665/jta.v86i4.5

Article History : Received : 09-09-2025, Revised:25-10-2025, Accepted: 31-10-2025

1. Introduction

The global textile industry is now in demand to adopt sustainable, natural products and processing. This transition has occurred due to the rise of consumers' awareness of green products' compliance with stringent environmental regulations. This leads to the reawakening of eco-friendly natural mordants, natural dyes and natural finishes as a replacement of harmful synthetic counterparts. These natural substances are mostly non-toxic without having any negative impact on the environment [1] and hence are preferred for complete eco-friendly product development.

Natural dyes hold considerable environmental appeal, yet their broad-scale commercial adoption remains constrained by significant technical challenges like non-reproducibility. Lower colour fastness and low dye fixation. This deficiency typically leads to low dye uptake, non-uniform colouration, poorer colour fastness characteristics to wash, light and lesser abrasion resistance, rendering naturally dyed cotton fabrics less durable and less viable in commercial applications as compared to those dyed with synthetic dyes [2]. To meet these challenges, a newer technique of using two eco-friendly mordants, i.e. called dual or double bio-mordanting, was adopted to obtain higher colour fixation, improved colour fastness, and to obtain a more uniform shade by overlapping dyeing effect by two types of mordants used together in sequence by using gallnut and potash alum dual bio-mordanting.

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Moreover, the use of conventional metallic mordants such as chromium, copper and tin has prompted profound environmental and health hazards [3] and hence alternate methods like enzyme pre-treatment, bio-cationization, and bio-mordanting have become so important. Hence, many researchers have taken interest in naturally derived bio-mordanting, bio-cationization, etc., for subsequent eco-friendly natural dyeing and finishing as non-toxic alternatives with ecological footprint, as mentioned in our earlier work [4-6], besides a few reports by other researchers [7-9] too.

Considering the environmental context, natural potassium alum (K-alum) was selected as a relatively eco-friendly mordant along with tannin-rich gallnut as bio-mordants to be applied before Dyeing. Preliminary investigations on the dyeing of pre-bio-mordanted cotton with plant-extracted catechu colourant have been reported in our earlier work [4, 5]. The present study can be regarded as a continuation of that earlier research for enhancing colour strength and fastness by optimising dyeing parameters. Based on our prior experimental results published elsewhere [4, 5], statistical optimisation was thought to be essential for standardising all dyeing conditions as independent process variables, using a suitable statistical method like Box–Behnken Design (BBD) under response surface methodology (RSM), which enabled a systematic optimisation of dyeing parameters. A similar work was reported earlier [6] for optimizing dyeing with catechu for soya-bean based bio-cationized cotton by using the same Box and Behnken Design of experiment to obtain uniform and maximum possible color yield where, K /S value achieved was only up to 6.75 (too low), and hence another new technique of double bio mordanting with gallnut and potash alum is attempted in the present work to achieve reproducible and higher shade depth using optimized dyeing conditions.

2. Materials and Methods

2.1 Fabric

Plain-woven scoured and bleached 100% cotton fabric having 200 ends/dm and 190 picks/dm, with warp and weft yarn counts of 9.8 Tex and 10.7 Tex respectively, a thickness of 0.25 mm and an areal density of 145 g/m².

2.2 Chemicals

Acetic acid (CH_3COOH), buffer of Sodium Acetate + Acetic acid for pH 4-5, Sodium hydroxide (NaOH), Sodium Chloride and Hydrochloric acid, etc., all of commercial grade were obtained from E-Merck (India) / local market.

2.3 Natural Mordant

Fit-kiri (Potash Alum), chemically $K_2SO_4.Al_2(SO_4)_3.24H_2O$ was used as a natural mineral-based first mordant.
Also, natural plant resource-based Gallnut (Oak-gallnut) was used as 2nd natural bio-mordant.

2.4 Natural Dye (Catechu)- extraction and purification

Natural dye Catechu (Acacia catechu) was extracted from the heartwood of the catechu tree, containing mainly Flevo-tannin (catechu-tannic acid), catechin, catechu red (catechol), etc. [3].

The catechu powder was subjected to aqueous extraction at pH 10 with a substrate-to-liquor ratio of 1:20 for 60 minutes at 70ºC, adding 1% NaOH solution as optimised earlier [4], followed by filtering and cooling. The filtrate was then neutralised with acetic acid to obtain a 30% (on a bone-dry weight basis) catechu extract. Purification was done by Soxhlet extraction /distillation with a 1:1 ethanol + benzene mixture at 10 cycles for 6 hrs.

2.5 Extraction process of Gallnut

Gallnut powder was subjected to aqueous extraction at pH 11 with a substrate-to-liquor ratio of 1:20, maintaining 80°C for 45 minutes. The resulting mixture was filtered through a 60-mesh nylon fabric, yielding some pale-yellow filtrate rich in Gallo-tannins. This extract was subsequently utilised as a natural bio-mordant for dyeing cellulosic cotton fabrics with catechu dye, either independently or in conjunction with potash alum as a dual mordanting system.

2.6 Dyeing with Catechu

In this present experiment, dyeing of cotton fabrics with catechu natural dye, after the said gallnut and K-alum dual bio pre-mordanting, was carried out using 30% Catechu dye extract at pH 4, substrate to liquor ration of 1:20 for of 60 min at 70º C temperature using fixed low salt (5 g/L) addition as standardized in our preliminary earlier work [4]. Each of the dyeing parameters was also varied when needed, as per the Box and Behnken experimental design requirement. Six dyeing parameters were divided into two separate groups for statistical optimisation as SET-1 and SET-2 by taking three dyeing conditions together in each set for maximising the K/S value in both sets of dyeing.

After each dyeing experiment was over, the catechu dyed cotton fabrics were rinsed with water, followed by soap wash using 1-2 g/L neutral surfactant at 60ºC for 10-15 min to remove any unfixed surface dye and then air dried.

2.7 Testing Methods

2.7.1. Colour Strength (K/S) and Colour Difference Index (CDI) measurement

Colour strength represents the relative depth of shade in a dyed textile sample and is typically quantified using the 'K/S value by Kubelka-Munk equation [10] and is expressed as a percentage (%) relative to a standard at maximum absorbance wavelength. In this ratio, 'K' denotes the absorption coefficient and 'S' represents the scattering coefficient of the dyed substrate. The calculation of K/S values is derived from the Kubelka–Munk equation,

$$\frac{K}{S} = \frac{(1 - R\boldsymbol{\lambda max})^2}{2R\boldsymbol{\lambda max}} = \propto C_D$$

Where $R_{\lambda max}$ denotes surface reflectance (R) of the dyed sample at the wavelength corresponding to maximum absorbance (λ_{max}), C_D refers to the dye concentration in the substance, while α represents an empirical constant specific to a particular dye-fibre system under study.

The 'Colour Difference Index' (CDI) quantifies the deviation in colour between two samples as determined through colourimetric analysis. It is calculated using the prescribed empirical formula, independent /irrespective of the sign of the ΔE, ΔH, ΔC and MI values of colourimetric deviations [11], representing colour variation across the fabric surface.

$$Colour\ Difference\ Index\ (CDI) = \frac{\Delta E\ X\ \Delta H}{\Delta C\ X\ MI}$$

Where ΔE denotes the total colour deviation, ΔH represents the variation in hue, ΔC refers to the change in chroma, and MI indicates the metamerism index. This formulation represents uniformity of shade depth for visual perception.

2.7.2. Colour fastness

Colour fastness to laundering was assessed in compliance with the ISO-II standard (IS: 3361–1979), while colour fastness to rubbing was evaluated following the IS: M766–1988 procedure and colour fastness to Sunlight/ simulated UV light was evaluated as per IS:2454:1985 method [12].

2.7.3. Statistical Optimization through RSM Based on the BBD of Experiments

To predict the output responses from selected independent input variables and to statistically optimise these responses, the Central Composite Response Surface Design [13], i.e., CCRD) It is a commonly employed, reliable statistical tool.

Within this framework, the Box and Behnken [14], i.e. in short BBD, is considered the most reliable approach for such statistical optimization, as it requires comparatively fewer experimental runs while still ensuring reliable results of optimization.

According to the BBD model, each selected independent variable must be tested at three levels (−1, 0, +1) with a minimum of three input variables required for optimization. The design incorporates mid-level values situated between the highest and lowest experimental data to establish coefficient factors for a second-order (quadratic) regression equation [15] representing the Box–Behnken design as follows:

$$Y_i = \beta_0 + \sum_{i=1}^{i=k} \beta_i x_i + \sum_{i=1}^{i=k} \beta_{ii} x_i^2 + \sum_{i=1}^{i=k} \sum_{j=1}^{j=k} \beta_{ij} x_i x_j$$

$(Regression\ Equation)$

Where **Y** denotes the dependent or response variable. The term **k** indicates the number of patterns considered, while **i** and **j** serve as index numbers for the input variables (with $\mathbf{x}_i$ corresponding to x_1, x_2 and x_3 for the three selected independent variables). The constant β_0 represents the intercept. The coefficients β_i, β_{ii} and β_{ij} correspond to the linear, quadratic and interaction effects, respectively. β_i includes β_1, β_2, β_3; β_{ii} includes β_{11}, β_{22}, β_{33} and β_{ij} includes β_{12}, β_{13}, β_{23} in the regression equation [15]. The statistical analysis and data processing were performed using the computer-aided software Minitab version 20.4 (trial version).

On the basis of prior experimental observations, all six independent dyeing variables (except salt concentration, which was fixed as 5 g/L) have a significant influence on the dyeing performance. These include concentration of mordant (x_1), concentration of dye (x_2), pH (x_3), time of dyeing (x_4), temperature of dyeing (x_5) and Substrate to Liquor ratio (x_6). These six dyeing process parameters were therefore selected as the independent input variables for the BBD experiment. The corresponding output response chosen for optimization is the K/S value, as Y_1).

Though the BBD model enables the simultaneous assessment of all six input dyeing variables, its application required a total of 46 experimental runs. The subsequent analysis of the results proved challenging, as the combined influence of multiple cross-interacting factors introduced considerable complexity into the output data prediction.

To address this limitation, the chosen six independent dyeing variables were divided into two groups, i.e. **Set I** (first three input dyeing variables vs. K/S value as the selected chosen output response and **Set II** (remaining three independent input dyeing variables vs. the same output response of K/S value). This approach facilitated a clearer interpretation of the experimental outcome to predict output response precisely against standardised input variables.
Accordingly, for each set comprising three input dyeing variables and one output response, the BBD model required 15 experimental runs for each set with varying input dyeing variables, following our previous reported work [6].

3. Results and Discussion

3.1. Preliminary Results for the effect of dual bio mordants ratio for catechu dyeing as dyeing input variable

The colorimetric summary data from our earlier preliminary work [5] for untreated bleached control fabric, after dual gallnut and potash alum dual bio pre-mordanted with overall 15% combination of Gallnut and K-Alum (in 25:75 ratio) applied in sequence one by one on control cotton fabric (with and without dyeing with catechu) for the said dual pre-bio-mordanting and subsequently dyeing with catechu natural dye are presented in Table-1."

3.2. Optimisation of dyeing process parameters

In Set-1, concentration of dual mordant, concentration of dye and pH were considered as 1st set of three independent dyeing variables, while in Set-2, dyeing time, dyeing temperature and substrate-to-liquor ratio were chosen as 2nd set of remaining three independent input dyeing variables. As required by the BBD, three different levels, i.e. low, medium and high levels of data for each dyeing parameter were chosen, based on their relative CDI values and dyeing performances and K/S data, etc., and these 3 levels of data for each dyeing parameter are given in Table 2.

Based on the previous reported preliminary studies on gallnut and potash alum dual bio-mordanting, showing also the dyeing mechanism [4], as a continuation, this present part of the work focused on the statistical optimisation of six key

Table 1: Preliminary Colourimetric data showing the effect of dual bio-mordant ratio for catechu dyeing

Sample and Mordant, and their concentrations	K/S *(after Mordanted only, no dyeing)*	K/S *(after dyed with 30% Catechu*	ΔE*	ΔL*	Δa*	Δb*	ΔC*	ΔH*	MI (LABD)	CDI
Scoured and Bleached Control cotton	0.02	0.05	-	-	-	-	-	-	-	-
K-alum + Gallnut (25:75) -Total 15%	1.30	9.20	3.41	3.6	-2.02	3.49	3.29	2.33	2.48	1.54
K-alum + Gallnut (50:50) -Total 15%	1.75	10.83	3.55	2.14	-2.36	1.57	1.84	2.05	2.38	1.66
K-Alum + Gallnut (75:25)-Total 15%	**1.82**	**12.19**	**3.54**	**0.76**	**-2.39**	**-0.38**	**1.44**	**2.38**	**3.41**	**1.76**

dyeing parameters using the BBD technique. The objective was to maximize the color strength (K/S) and to develop a predictive regression equation for this fiber–mordant–dye system by Response Surface Methodology.

Table 2: Three experimental levels of selected key

Process Variables		Low (-1)	Medium (0)	High (+1)
1st set				
Mordant Concentration (%)	(x_1)	10	15	20
Dye Concentration (%)	(x_2)	20	30	40
pH	(x_3)	3	4	5
2nd set				
Dyeing time (min)	(x_4)	30	60	90
Dyeing temperature (°C)	(x_5)	50	70	90
MLR (Substrate to Liquor ratio)	(x_6)	10	20	30

3.2.1 Analysis of Response Surface effect to maximise Colour Strength (K/S)

Based on the BBD, 15 experimental results for the selected independent variables and the corresponding dependent output variables from **Set-1** and **Set-2** were presented in Table 3.

3.3.2. Response Surface Analysis for K/S for 1st Set

The ANOVA results for Set-1 under varying dyeing conditions are presented in Table 4. The model summary and estimated regression coefficients with their corresponding standard errors were provided in Tables 5 and 6, respectively.

The ANOVA (Table 4) results showed that the calculated p-values for the model and all parameters were lower than the tabulated value at 9 degrees of freedom, indicating that both the model and the parameters had a substantial effect on the K/S value. The model summary (Table 5) showed a low standard deviation, a high R^2 value (percentage of variation in the response) and a deviation of lower than 0.2 between the projected and adjusted R^2 values, showing that the model was statistically significant and provided the best fit for the given parameters [2].

Regression coefficients (Table 6) confirmed that all variables significantly influenced K/S, and the predicted K/S value was derived from the quadratic regression model as follows:

K/S (Y_1) = 23.842+ 0.586 * Mordant Concentration + 0.633 * Dye Concentration + 0.054 * pH – 0.960 * Mordant Concentration * Mordant Concentration – 1.252 * Dye Concentration * Dye Concentration – 0.710 * pH * pH + 0.710 * Mordant Concentration * Dye Concentration – 0.168 * Mordant Concentration * pH – 0.445 * Dye Concentration * pH = 12.20

Table 3: Experimental runs according to Box-Behnken Design for 3 chosen independent input variables and the corresponding response variable

Code	Results of 1st set of varying dyeing conditions				Results of the 2nd set of varying dyeing conditions			
	1st set of independent input variables			Output variable*	2nd set of independent input variables			Output variable*
	Concentration of Mordant (potash-alum) (%)	Concentration of catechu dye (%)	pH of dye liquor	K/S	Time of dyeing (min)	Temperature (°C) of dyeing	MLR	K/S
	x_1	x_2	x_3	Y_1	x_4	x_5	x_6	Y_2
S1	20 (+1)	20 (-1)	4 (0)	9.23	90(+1)	50(-1)	20(0)	12.04
S2	15 (0)	40(+1)	3 (-1)	11.26	60(0)	90(+1)	10(-1)	11.84
S3	10 (-1)	30 (0)	5 (+1)	10.16	30(-1)	70(0)	30(+1)	12.05
S4	10 (-1)	40 (+1)	4 (0)	9.32	30(-1)	90(+1)	20(0)	11.83
S5	15 (0)	40 (+1)	5 (+1)	10.48	60(0)	90(+1)	30(+1)	11.90
S6	15 (0)	20 (-1)	5 (+1)	10.10	60(0)	50(-1)	30(+1)	11.97
S7	10 (-1)	30 (0)	3 (-1)	9.72	30(-1)	70(0)	10(-1)	11.58
S8	10 (-1)	20 (-1)	4 (0)	9.48	30(-1)	50(-1)	20(0)	11.78
S9	20 (+1)	30 (0)	3 (-1)	11.23	90(+1)	70(0)	10(-1)	12.12
S10	20 (+1)	30 (0)	5 (+1)	11.00	90(+1)	70(0)	30(+1)	12.03
S11	15 (0)	20 (-1)	3 (-1)	9.10	60(0)	50(-1)	10(-1)	11.64
S12	20 (+1)	40 (+1)	4 (0)	11.91	90(+1)	90(+1)	20(0)	12.11
S13	15 (0)	30 (0)	4 (0)	12.20	60(0)	70(0)	20(0)	12.20
S14	15 (0)	30 (0)	4 (0)	12.19	60(0)	70(0)	20(0)	12.19
S15	15 (0)	30 (0)	4 (0)	12.20	60(0)	70(0)	20(0)	12.20

* All displayed data in the table indicate actual experimental results.

Table 4: ANOVA results with respect to the Response Surface effect of shade depth (K/S) for the variation of concentration of mordant, concentration of dye and pH (Set-1)

Analysis of Variance				
Source	**DF**	**F- Value**	**P-Value**	**Remarks**
Model	9	72887.18	0.000	As tabulated P-value is much lower than charted value for DF-9, the model is Significant.
Linear	3	70271.47	0.000	
Mordant Concentration (%)	1	97041.62	0.000	
Dye Concentration (%)	1	112957.06	0.000	
pH	1	815.74	0.000	
Square	3	114028.61	0.000	
Mordant Concentration (%) x Mordant Concentration (%)	1	119995.68	0.000	
Dye Concentration (%) x Dye Concentration (%)	1	204299.21	0.000	
pH X pH	1	65615.59	0.000	
2-Way Interactions	3	34361.47	0.000	
Mordant Concentration (%) x Dye Concentration (%)	1	71167.06	0.000	
Mordant Concentration (%) X pH	1	3960.88	0.000	
Dye Concentration (%) X pH	1	27956.47	0.000	

Table 5: Model summary for K/S Values with varying concentration of bio-mordants, concentration of dye and pH

	S	R-Sq.	R-Sq. (adj)	R-Sq. (Pred.)
Model Summary	0.0053229	100%	100%	99.99%

Table 6: Regression coefficients for the effect of independent input variables for shade depth (K/S) for the variation of mordant concentration, dye concentration and pH

Process Variables	CC	RC	SEC	T-Value	P- Value
Term					
Constant	β_0	23.842	0.003	3968.74	0.000
Mordant Concentration (%)	β_1	0.586	0.002	311.52	0.000
Dye Concentration (%)	β_2	0.633	0.002	336.09	0.000
pH	β_3	0.054	0.002	28.56	0.000
Mordant Concentration (%) X Mordant Concentration (%)	$\beta_{1,1}$	-0.960	0.003	-346.40	0.000
Dye Concentration (%) X Dye Concentration (%)	$\beta_{2,2}$	-1.252	0.003	-451.99	0.000
pH X pH	$\beta_{3,3}$	-0.710	0.003	-256.16	0.000
Mordant Concentration (%) X Dye Concentration (%)	$\beta_{1,2}$	0.710	0.003	266.77	0.000
Mordant Concentration (%) X pH	$\beta_{1,3}$	-0.168	0.003	-62.94	0.000
Dye Concentration (%) X pH	$\beta_{2,3}$	-0.445	0.003	-167.20	0.000
CC- Coded Coefficient, RC- Regression Coefficient, SEC- Standard Error Coefficient					

Substitution of the three independent variables (i.e., concentration of mordant, concentration of dye and pH) into the regression equation yielded a predicted K/S value of 12.21, compared with an experimental value of 12.20 under identical conditions, demonstrating the model's accuracy.

Using BBDM statistical analysis in software (Minitab 20.4), 3D surface plot and 2D contour diagram illustrating the interaction effects were generated and are presented in Figures 1(a) and 1(b).

Surface Plot K/S vs Dye Concentration and Mordant Concentration

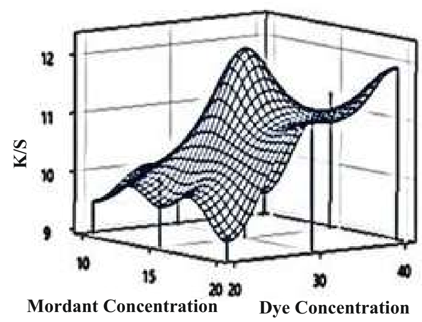

Figure 1(a) - Three-Dimensional Surface plot for the impact of the concentration of Mordant and concentration of Dye on K/S

Contour Plot of K/S K/S vs Dye Concentration and Mordant Concentration

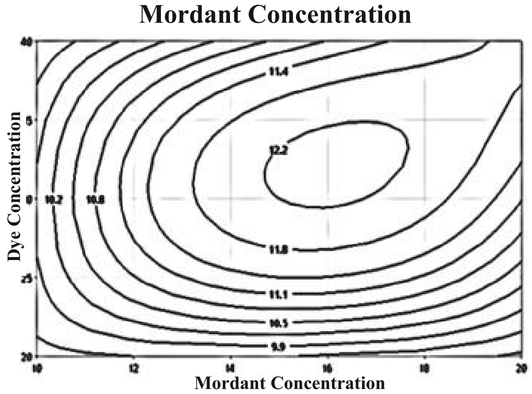

Figure 1(b) - Two-Dimensional Contour diagram for the impact of concentration of Mordant and concentration of Dye on K/S

Figure 1(a) represents the three-dimensional Surface plot showing the impact of mordant (Y-axis) and dye concentrations (X-axis) on colour strength (K/S) (Z-axis). K/S increased with rising concentrations of both variables, reaching a maximum at an optimal point, after which further increases led to a decline.

Figure 1(b), the corresponding 2D contour plot, confirmed this trend and indicated an optimal K/S value of 12.20+ at a mordant concentration of about 15% and a catechu dye concentration of ~30%.

Figures 2(a) and 2(b) showed the three-dimensional Surface plot and two-dimensional Contour diagram, respectively, of mordant concentration and dye-liquor pH on K/S. The

Surface Plot of K/S vs pH and Mordant Concentration

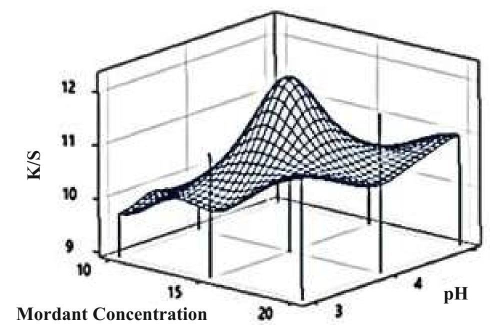

Figure 2(a) - Three-Dimensional Surface plot for the impact of concentration of Mordant and pH on K/S

Contour Plot of K/S K/S vs pH and Mordant Concentration

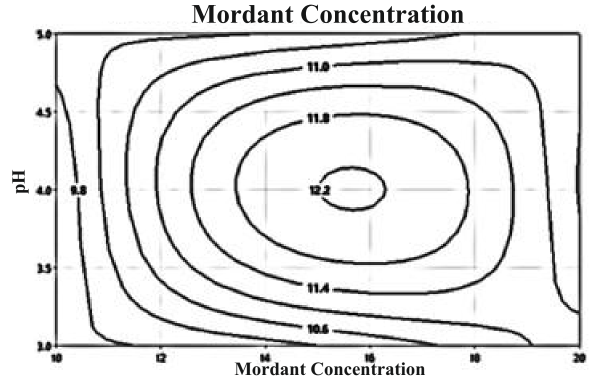

Figure 2(b) - Two-Dimensional Contour diagram for the impact of concentration of Mordant and pH on K/S

surface plot (Figure 2a) displayed a peak at the critical point, indicating the optimum K/S value. The contour plot (Figure 2b) further revealed that an optimal K/S of 12.20+ was achieved at 14–16% mordant concentration at a pH of approx. 4.

Figures 3(a) and 3(b) represented the three-dimensional Surface plot and two-dimensional Contour diagram, respectively, showing the impact of dye concentration and dye-liquor pH on K/S. The surface plot (Figure 3a) exhibited a peak, indicating the optimum K/S value. The contour plot (Figure 3b) confirmed that an optimal K/S of 12.20+ was achieved at a dye concentration of 30–32% and a pH of approx. 4.0.

Surface Plot of K/S vs pH and Dye Concentration

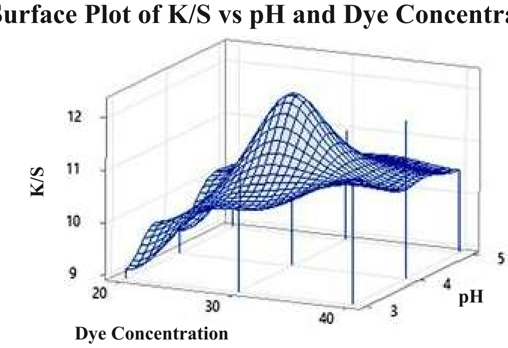

Figure 3(a) - Three-Dimensional Surface plot for the impact of Dye concentration and pH on K/S

Contour Plot of K/S vs pH and Dye Concentration

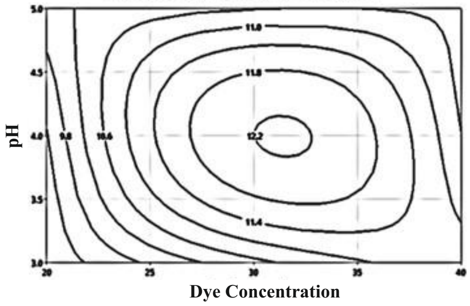

Figure 3(b) - Two-Dimensional Contour diagram for the impact of Dye concentration and pH on K/S

3.3.3 Response Surface Analysis for K/S for 2nd Set

Table 7 reports the ANOVA outcomes for Set-2 under different dyeing conditions; Table 8 presents the model summary, and Table 9 details the regression coefficients along with their standard errors.

The ANOVA (Table 7) results showed that the calculated p-values for the model and all parameters were lower than the tabulated value at 9 degrees of freedom, indicating that both the model and the parameters had a substantial effect on the K/S value.

The model summary (Table 8) showed a low standard deviation, a high R^2 value and a deviation of lower than 0.2 between the projected and adjusted R^2 values, showing that the model was statistically proven as the best fit for this.

By putting determined values of regression coefficients (from Table 9) confirmed that all variables significantly influenced K/S, and the predicted K/S value was derived from the quadratic regression model as follows:

K/S (Y2) = 4.926 + 0.133 * Dyeing Time (Min) + 0.031 * Dyeing Temperature (ºC) + 0.096 * MLR – 0.075 * Dyeing Time (Min) * Dyeing Time (Min) + 0.118 * Dyeing Temperature (ºC) * Dyeing Temperature (ºC) – 0.177 * MLR * MLR + 0.005 * Dyeing Time (Min) * Dyeing Temperature (ºC) – 0.140 * Dyeing Time (Min) * MLR – 0.068 * Dyeing Temperature (ºC) * MLR = 12.20

Table- 7: ANOVA results with respect to Response Surface effect of shade depth (K/S) against variation dyeing time, dyeing temperature and substrate-to-liquor ratio (Set-2).

Analysis of Variance				
Source	**DF**	**F- Value**	**P-Value**	**Remarks**
Model	9	2153.85	0.000	As tabulated P-value is much lower than charted value for DF-9, the model is Significant.
Linear	3	2616.18	0.000	
Dyeing Time (Min)	1	4957.06	0.000	
Dyeing Temperature (ºC)	1	275.74	0.000	
MLR	1	2615.74	0.000	
Square	3	2707.43	0.000	
Dyeing Time (Min) X Dyeing Time (Min)	1	724.91	0.000	
Dyeing Temperature (ºC) X Dyeing Temperature (ºC)	1	4320.57	0.000	
MLR X MLR	1	4086.54	0.000	
2-Way Interactions	3	1137.94	0.000	
Dyeing Time (Min) X Dyeing Temperature (ºC)	1	3.53	0.001	
Dyeing Time (Min) X MLR	1	2767.06	0.000	
Dyeing Temperature (ºC) X MLR	1	643.24	0.000	

Table 8: Model summary for K/S value for variation of dyeing time, temperature and MLR (Set-2)

	S	R-Sq.	R-Sq. (adj)	R-Sq. (Pred.)
Model Summary	0.0053230	99.97%	99.93%	99.75%

Table- 7: ANOVA results with respect to Response Surface effect of shade depth (K/S) against variation dyeing time, dyeing temperature and substrate-to-liquor ratio (Set-2).

Process Variables	CC	RC	SEC	T-Value	P- Value
Term					
Constant	β_0	4.926	0.003	3968.74	0.000
Dyeing Time (Min)	β_1	0.133	0.002	70.41	0.000
Dyeing Temperature (ºC)	β_2	0.031	0.002	16.61	0.000
MLR	β_3	0.096	0.002	51.14	0.000
Dyeing Time (Min) X Dyeing Time (Min)	$\beta_{1,1}$	-0.075	0.003	-26.92	0.000
Dyeing Temperature (ºC) X Dyeing Temperature (ºC)	$\beta_{2,2}$	0.118	0.003	56.73	0.000
MLR X MLR	$\beta_{3,3}$	-0.177	0.003	-63.93	0.000
Dyeing Time (Min) X Dyeing Temperature (ºC)	$\beta_{1,2}$	0.005	0.003	1.88	0.001
Dyeing Time (Min) X MLR	$\beta_{1,3}$	-0.140	0.003	-52.60	0.000
Dyeing Temperature (ºC) X MLR	$\beta_{2,3}$	-0.068	0.003	25.36	0.000
CC- Coded Coefficient, RC- Regression Coefficient, SEC- Standard Error Coefficient					

Substitution of the three independent variables (i.e., dyeing time, dyeing temperature and MLR) into the regression equation yielded a predicted K/S value of 12.20, compared with an experimental value of 12.19 under identical conditions, demonstrating the selected BBD model's accuracy and fit to this statistical optimisation experiment.

Surface Plot of K/S vs Dyeing Time, Temperature

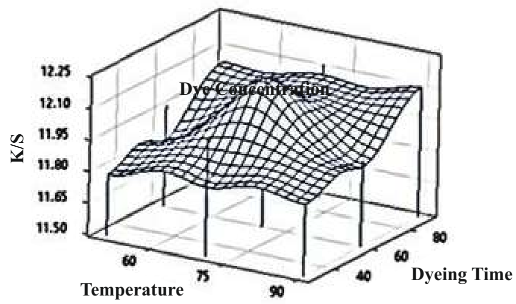

Figure 4(a) - Three-Dimensional Surface plot for the impact of Dyeing Time and Dyeing Temperature on K/S

Contour Plot of K/S vs Dyeing Time, Temperature

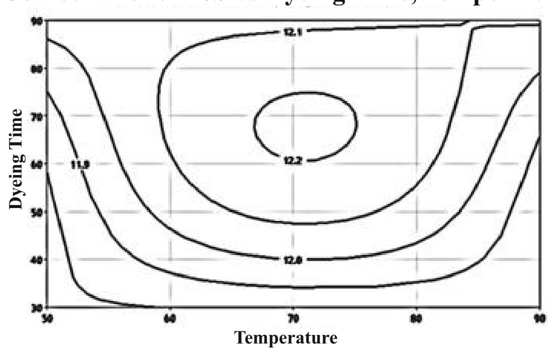

Figure 4(b)- Two-Dimensional Contour diagram for the impact of Dyeing Time and Dyeing Temperature on K/S

Figures 4(a) and 4(b) show the three-dimensional Surface plot and Two-Dimensional Contour diagram of dyeing time and dyeing temperature on K/S, generated using Minitab 20.4. The surface plot (Figure 4a) indicated that K/S increased with rising dyeing time and temperature, reaching an optimum at the critical point, after which further increases caused a decline. The contour plot (Figure 4b) confirmed these interaction trends in two dimensions. From the contour plot, it was found that the statistically optimised K/S value could be achieved up to 12.20+ at 60-70 min of dyeing time at 68-75ºC dyeing temperature.

Figures 5(a) and 5(b) present the three-dimensional Surface plot and two-dimensional Contour diagram showing the effect of dyeing temperature and substrate-to-liquor ratio on K/S. The surface plot (Figure 5a) displayed an upward peak, indicating the maximum achievable K/S. The contour plot (Figure 5b) confirmed that an optimum K/S value of 12.20+ was attained at a dyeing temperature of 68-72ºC and an MLR range of 20-22.

Figures 6(a) and 6(b) show the three-dimensional Surface plot and Two-Dimensional Contour diagram of dyeing time and substrate-to-liquor ratio on K/S. The surface plot (Figure 6a) exhibited a peak, indicating the maximum attainable K/S. The contour plot (Figure 6b) further demonstrated that a K/S value around 12.20 was optimally achieved at a dyeing time of 65–72 min and substrate-to-liquor range of 19–22.

Surface Plot of K/S vs Temperature, MLR

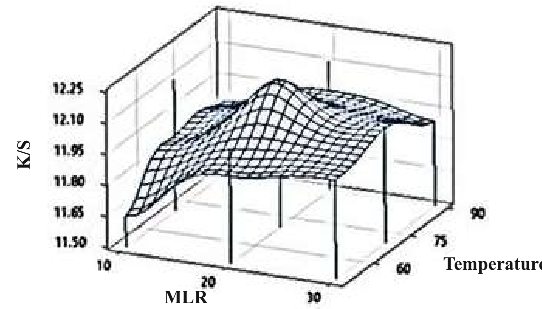

Figure 5(a -) Three-Dimensional Surface plot for the impact of Dyeing Temperature and MLR on K/S

Contour Plot of K/S vs Temperature, MLR

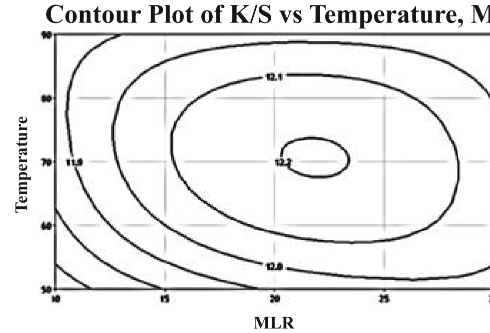

Figure 5(b) - Two-Dimensional Contour diagram for the impact of Dyeing Temperature and MLR on K/S

Surface Plot of K/S vs MLR, Dyeing Time

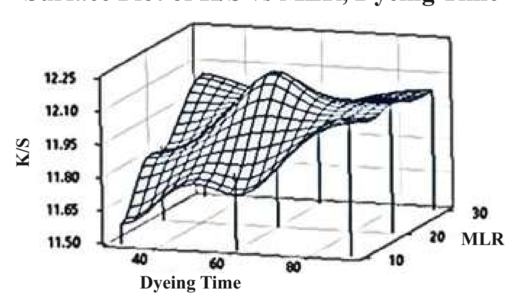

Figure 6(a) - Three-Dimensional Surface plot for the impact of Dyeing Time and MLR on K/S

Contour Plot of K/S vs MLR, Dyeing Time

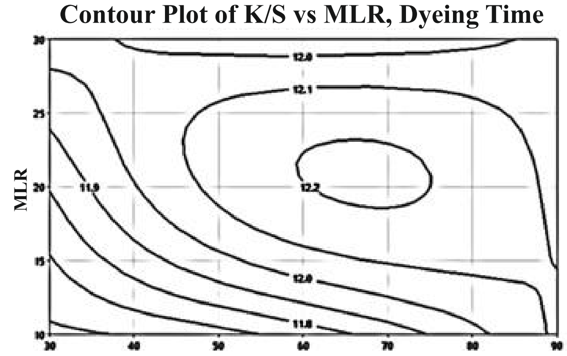

Figure 6(b) - Two-Dimensional Contour diagram for the impact of Dyeing Time and MLR on K/S

3.3 Analysis of Colour Fastness Properties to wash, light and rubbing

Results of colour fastness to wash, light and rubbing for respective samples are shown in Table 10.130

Table 10: Results of Colour Fastness Properties to wash, light and rubbing

Description of Samples	Wash fastness		Light Fastness	Rubbing Fastness	
	LOD	Staining		Dry	Wet
15% [Gallnut + K-alum (75:25)] + Catechu-30 %	3	3	2-3	3	2-3
15% Gallnut + K-alum (50:50)] + Catechu-30 %	3-4	3-4	3	3-4	3
15 % [Gallnut + K-alum (25:75)] + Catechu-30 %	4	4	4	4	3-4

From Table 10, it was observed that application of an increased amount of K-alum (natural metallic mordant) in Gallnut + K-alum dual bio-mordant combination applied on cotton before catechu dyeing at optimised dyeing conditions, resulted in noticeable improvement in colour fastness properties to wash, light and rubbing. There was approximately.1/2 grade enhancement of wash fastness, light fastness and dry rubbing fastness rating for increase of K-alum proportions from 25 to 50% and also there is further additional 1/2 grade enhancement of wash fastness, light fastness and dry rubbing fastness rating for further increase of K-alum proportions from 50 to 75% in ratio of overall application of 15% of gall nut and K-alum dual bio-mordant application in sequence on cotton before dyeing with 30% catechu. These enhancements may be viewed as due to strong coordination power of aluminium of K-alum than that of weekly bonded gallnut via complex formation through its gallic acid content or by Hydrogen bonding for fixing catechu dye by these two dual bio-mordant application, when catechin from catechu also donated electrons to the aluminium ions of K-alum, facilitating the formation of a bigger coordinated complex [Fibre-Gallnut-K-alum-catechu dye] formation [5,6] enhancing more and more catechu dye fixation and improving overall color fastnesses rating with increase in K-alum ratio, forming a giant bigger fibre-2-mordants-dye complex.

4. Conclusions

The present study establishes that cotton fabric can be efficiently dyed with natural catechu extract using gallnut and potash alum as dual bio-mordants, yielding high colour intensity under low salt at acidic conditions (at pH 4).

Statistical optimisation through the Box–Behnken Design model coupled with ANOVA analysis determined precise optimum dyeing conditions to obtain maximum/optimum K/S value up to 12.20, which is matching with the practical experimental results. Thus, the statistically optimized dyeing parameters for the present study were identified as: 15% combination of potash-alum and gallnut (in 75:25 ratio) for the said dual bio-mordanting, optimum catechu dye concentration as 30% aqueous extract, dye bath pH 4, 60 minutes dyeing time at 70 °C dyeing temperature and MLR of 1:20 along with 5g/L low salt concentration, as optimum dyeing conditions for this case.

This precise statistical optimization of dyeing conditions for this fibre-bio-mordants-dye system results in reproducible, uniform and maximized colour strength is easily adoptable as standard dyeing conditions for the industry dyers and hence, it will be easier for them to adopt such a process of optimum dyeing recipe as per need.

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Mr. R. K. Vij elected as National President of TAI

The Textile Association (India) has been elected the New Office Bearers for the term 2025-2027 during their Governing Council Meeting held on 22-11-2025 at Hotel Le Meridien, Coimbatore.

After the fair and transparent procedure from the valid nominations received, Dr. G. S. Nadiger, appointed Returning Officer for conducting the election, has declared **Mr. R. K. Vij** has been unanimously elected as **President** and **Mr. Mahendrabhai G. Patel** has been unanimously elected as **Vice President** for the term 2025-2027.

K. Vij
l President

Mr. R. K. Vij
National President

Shri R. K. Vij has extensive experience of over 46 years in successfully managing business of Textiles and Fibers in dynamic and competitive business environment.

He is the Advisor - Polyester at M/s Indorama Synthetics (India) Limited.

Shri R. K. Vij is an MBA from Delhi University, Post Graduate Diploma in Management from YMCA, New Delhi and Bachelor of Technology in Textiles from The Technological Institute of Textile & Sciences (TITS), Bhiwani (Haryana).

The history of Indo Rama Synthetics (India) Limited dates back to 1995, when it first forayed into the business of polyesters.
He was the National President of the Association in 2021-2023 and then President (Emeritus) in 2023-2025. Then he was honored with Service Gold Medal in 2017 at All India Textile Conference held at Nagpur.

Shri R. K. Vij, on behalf TAI is representing to Ministry of Textiles and other Govt. organization on various issues related Textile and Man-made Fibers etc. He is a Secretary General for Polyester Textiles & Apparel Association, India and also Vice Chairman for PHD Chamber of Commerce and Industry (PHDCCI),

Mr. Mahendrabhai G. Patel
Vice President

Mr. Mahendrabhai G. Patel was in Textile Business from last 45 years and he was the owner and run Open End Spinning Mills about 25 years and Presently he is doing the business of Import of Spinning Machinery since last 15years.

He was elected as a Governing Council Member of the Textile Association (India) Ahmedabad Unit in 2019 and then was entrusted responsibility as a Jt. Hon. Gen. Secretary of TAI Central Office for the term 2019-2021.

After that he has been taken over as a Hon. Gen. Secretary for the term 2021-2023 and being continuing for the term 2023-2025.

Mr. V. D. Gotmare
Chairman

Dr. Vijay Gotmare holds a Ph.D. (Tech.) in Textile Technology from the Institute of Chemical Technology (ICT, formerly UDCT), University of Mumbai. He began his career with Raymonds and Jamshri Textiles Ltd., gaining valuable industrial experience before joining Veermata Jijabai Technological Institute (VJTI), Mumbai, where he served for over three decades as Professor and Head of the Department of Textile Manufactures.

Dr. Gotmare was conferred the prestigious Hon. Fellow of The Textile Association (Hon. F.T.A.) award in 2017. His research interests include chemical modification of fibers, technical textiles, nanomaterial applications in textiles, recycling and reuse of textile waste, and sustainable textile materials.

He has published more than seventy-two research papers in national and international journals and conferences and has guided over thirty-five postgraduates and three doctoral students. He has authored two book chapters on "Recycling of Textile Mill Waste" and "Reuse of Textile Chemicals," holds one granted patent on mosquito-repellent textile materials, and has three more patent applications under review.

Dr. Gotmare has contributed extensively to professional and governmental bodies, having served as Chairman, Textile Association of India (Central Unit); Governing Council Member, TAI–Mumbai Unit; Hon. Chairman, Journal of the Textile Association Editorial Board; and Hon. Treasurer, Textile Association of India. He has also served as Chairman of the Eco-Mark Committee of KVIC, Government of India, and as a member of several academic and advisory bodies, including BTRA, CIRCOT (ICAR), SNDT Women's University, and the RKVY-RAFTAR Incubation Committee under the Ministry of Agriculture. He has evaluated research projects for DBT and DST, Government of India, and visited several countries, including the USA, Australia, Germany, France, South Africa, Egypt, Mauritius, and Thailand, for training and academic purposes. Currently,

Dr. Gotmare serves as the Representative Director (India) for Frontier.cool Inc., Taiwan, an organization pioneering AI-based digital textile platforms.

Mr. D. K. Jain
Hon. Gen. Secretary

Mr. D. K. Singh is a Textile Graduate from The Technological Institute of Textile & Sciences, Bhiwani. He did his B. Tech. in the year 1984. During his long career of 40 years, he has been prominently involved in Synthetic Textile Industry. Presently, he is working as Director of Radici Group, Switzerland and is heading its operations in India. Apart from his contribution to TAI - Delhi, he is also actively associated with the activities of Alumni Association of TIT&S, Bhiwani. Mr. Singh has been associated with TAI - Delhi since 2013. He served as Vice President of TAI – Delhi for the term 2013-15 and President of TAI Delhi for the term 2017-19 & 2019-21. Governing Council Member of the Textile Association (India) for the term 2021-23 & 2023-25. He is also National Vice President of The Textile Association (India) – Central Office for the term 2023-25.

Mr. A. T. Shahani
Hon. Treasurer

Mr. A. T. Shahani is having Diploma in Textile Technology from M. S. University, Vadodara in the year 1960, securing First Class, worked at Arvind Mills, Ahmedabad as Maintenance in-charge for 12 years in Spinning Department during 1960 to 1972; Bombay Textile Research Association (BTRA), as Senior Textile Technologist for 16 years during 1972 to 1988. He owned consultancy for 2 years. He also worked at Churchgate group Nigeria for 22 years during 1989 to 2010 as Technical Director and Head of Bombay Office. He introduced the system of Maintenance Audit for the first time in Textile Industry.

In 1972, through BTRA developed BTRA spindle topping apparatus and by using which resulted saving of oil in huge quantity. He had presented about 80 papers on maintenance subject at various conference and published Books on the same subject. He has widely travelled in the world and attended various Textile Exhibitions, Conferences. He has conducted many training programs for Textile Technicians.

He received many awards but the main award is from NRDC, Govt. of India in 1981. He also received Excellent Industrial Contribution award by TAI in the year 2008.

Also following Members are elected for the term 2025-2027

Mr. K. Gandhiraj
Vice Chairman

Mr. Rajendra Randive
Hon. Jt. Gen. Secretary

Mr. A. D. Patel
Hon. Jt. Gen. Secretary

Following Co-opted Members are elected for the term 2025-2027

Dr. G. S. Nadiger,
Chairman - PAC

Dr. Deepa Raisinghani
Chairman – JTA EB

Following Members of Trustee are are elected for the term 2025-2027

Dr. B. K. Behra

Dr. G. S. Nadiger

Mr. J. B. Soma

Mr. Haresh A. Patel

Mr. Kannan Krishnamurthy

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Shri Subhash Bhargava Honoured with Distinguished Alumni Award at TIT&S Bhiwani Convocation

Bhiwani, Haryana – The Technological Institute of Textile & Sciences (TIT&S), Bhiwani, held its prestigious Convocation Ceremony on 8th November 2025 with great academic fervour and dignity. His Excellency Prof. Ashim Kumar Ghosh, Hon'ble Governor of Haryana, graced the occasion as the Chief Guest and presided over the ceremony.

The highlight of the convocation was the Distinguished Alumni Award being presented by Prof. Ashim Kumar Ghosh to Shri Subhash Bhargava, Managing Director, Colorant Limited and three other alumni's in recognition of their exemplary contribution to the textile industry and advancement of technology. The honour acknowledges Shri Bhargava's visionary leadership, sustained commitment to innovation, and his significant role in strengthening industry–academia collaboration, thereby contributing meaningfully to the growth of the textile and colorant sector.

The ceremony was further graced by Prof. Rajbir Singh, Vice-Chancellor, Maharshi Dayanand University (MDU), Rohtak, as Guest of Honour, and Prof. Deepti Dharmani, Vice-Chancellor, Chaudhary Bansi Lal University (CBLU), Bhiwani, as a special invited guest. The event began with the lighting of the ceremonial lamp, followed by the National Anthem.

During the convocation, around 300 undergraduate and postgraduate students from various disciplines were awarded degrees. TIT&S Bhiwani also felicitated other distinguished alumni for their notable contributions to industry and society, reaffirming the institute's commitment to academic excellence and industry relevance.

Mr. R. K. Dalmia, Chairman, Board of Governors, and Prof. B. K. Behera, Director, TIT&S Bhiwani, were present during the ceremony, which concluded on an inspiring and celebratory note for graduating students.

Rieter SERVOpack: Modular System for Efficient Packaging

The future is within reach: In 2027, fully automated Rieter spinning mills with only three operators for every 10 000 spindles will become a reality. This means maximum efficiency with minimum personnel costs. Smart automation solutions like the fully automatic packaging system SERVOpack are paving the way.

Short-staple spinning mills are under increasing pressure due to rising production costs, a growing shortage of skilled workers and increasing traceability requirements. The fully automatic packaging system SERVOpack is a significant improvement as it takes over physically demanding tasks, increases process reliability and saves operator costs.

Streamlined packaging solution

SERVOpack is a complete solution, streamlining the entire packaging process, including transport, quality control, palletizing, steaming and packaging. With maximum performance and flexibility, it integrates seamlessly at the end of any spinning line. Its modular design allows for

The intelligent and economical packaging system SERVOpack

Different variants of SERVOpack meet different customer requirements

optimal adaptation to the production environment, tailored to each customer's specific requirements.

Economical and durable system

SERVOpack optimizes the workflow, reduces manual labor and ensures consistent performance. At the end of the process, pallets, boxes, or bags are weighed automatically, and labels are printed and attached for easy identification and traceability. The system's proven components and customized design make SERVOpack durable and low maintenance, supporting long-term operational reliability.

Ensuring quality from spinning to shipping

The integrated quality control system ensures that each yarn package is placed on the correct pallet and reaches the intended addressee by verifying the yarn material and identifiers on the tubes. Contactless transport from the spinning machine to the final packaging preserves yarn quality, while the optional steaming function relaxes the yarn, improves color absorption, and sterilizes the product for consistent quality.

Flexible packaging solutions tailored to customer needs

SERVOpack provides versatile packaging options to meet diverse customer requirements, including palletizing, box packaging and bag packaging. It supports both centralized and individual palletizing, covering a wide range of operational needs. In addition, Rieter remote support ensures fast, secure and reliable assistance whenever it is needed.

With SERVOpack, spinning mills can achieve a fully automated, efficient, and high-quality yarn packaging process, redefining the standard for modern textile production.

For further information, please contact:

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ITMA ASIA + CITME Makes Successful Presentation

The region's leading textile and garment technology exhibition, ITMA ASIA made a successful return to Singapore after two presentations in 2001 and 2005.

Combined with CITME, the four-day ITMA ASIA + CITME exhibition at the Singapore Expo concluded on 31 October 2025 with participants praising the international mix of visitors and strong turn-out of buyers from the region. From the supply side, the exhibition was well represented by companies from key textile technology manufacturing regions, thus offering buyers a balanced selection of solutions.

The Singapore exhibition attracted visitorship of over 26,600 from 109 countries and regions, reaffirming its reputation as the region's most influential showcase of textile and garment manufacturing technologies.

Some 92% of the visitors came from overseas, with 35% of them from South Asia and 30% from Southeast Asia. The top three visitor countries were: India (19%), China (11%) and Indonesia (10%). Other countries in the top 10 list included Bangladesh, Pakistan, Vietnam and Malaysia.

The show owners – CEMATEX (the European Committee of Textile Machinery Manufacturers), China Textile Machinery Association (CTMA), The Sub-Council of Textile Industry, CCPIT (CCPIT TEX) attributed its strong showing to Singapore's ideal location, conducive business environment and seamless visitor experience.

Mr. Alex Zucchi, President of CEMATEX, said: "Exhibitor feedback has been very positive as the high-quality visitorship and serious business discussions are greatly appreciated. The exhibition has created a strong sense of

optimism about the opportunities ahead amid current economic challenges."

Mr. Gu Ping, President of CTMA remarked: "Asia, the world's largest textile hub, boasts a vast industrial scale and plays a key role globally. With the successful conclusion of the ITMA ASIA + CITME, Singapore 2025, it is clear that the Asian textile industry, encompassing regions such as East Asia, Southeast Asia and the Middle East, is experiencing rapid development. This also reflects the global textile industry's demand for exploring emerging markets."

Many of the exhibitors were elated by the outcome of their participation. Mr. Tobias Schaefer, Vice President of Andritz Nonwoven & Textile, enthused: "The combined exhibition in Singapore proved to be a truly pivotal platform, bringing together a remarkably international audience. The high visitor numbers, the quality of discussions, and the strong focus on innovation and sustainability reflected the industry's evolving priorities."

Mr. Stephane Picard, Sales & Marketing Manager at Pierret Industries, opined: "We are very pleased with the overall quality of the visitors at the exhibition. Despite the current market challenges, the event exceeded our expectations. The main objective of holding this show in Singapore was to attract people from Southeast Asia and Middle East markets, and the results were truly impressive."

Sharing the same sentiment, Canlar Mekatronik Board Member Mr. Kaan Cakici said: "We're delighted with the overwhelming response received at the exhibition. The show days were filled with serious enquiries from buyers who came ready to invest and we concluded business deals during the show. The quality of discussions with visitors at our stand has given us confidence to expand our presence and support in the region."

Underscoring the significance of the 2025 exhibition for the Indian market was Mr. Rohit Kansal, Additional Secretary, Ministry of Textiles of India who led a 30-member-strong government delegation.

Mr. Kansal remarked, "India is one of the largest participants and exhibitors in this exhibition here in. This reflects our strategic vision in driving our textile industry's growth through innovation, manufacturing excellence and sustainability. The fair provides a good meeting ground for people to exchange ideas, to look at new technologies, discuss business propositions and to see the latest innovations."

Later, speaking at the co-located ITMA Sustainability Forum, Mr. Kansal highlighted the Indian textile industry's green transformation.

The comprehensive showcase of textile and garment making technologies at ITMA ASIA + CITME, Singapore 2025 occupied more than 70,000 square metres of gross space and featured over 840 exhibitors from 30 countries and regions.

ITMA ASIA + CITME, Singapore 2025 is organised by ITMA Services and co-organised by Beijing Textile Machinery International Exhibition Company.

The next ITMA ASIA + CITME exhibition will be held in Shanghai, China from 20 to 24 November 2026.

For more information, please visit www.itmaasia.com or www.citme.com.cn.

Journal of the TEXTILE Association

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Shri M. Sankar Conferred Honorary Membership at 78th All India Textile Conference

At the 78th All India Textile Conference held in Coimbatore, Mr. M. Sankar, Director Operations of LMW Limited, received the prestigious Honorary Membership of the Textile Association India in recognition of his four decades of contribution to the textile machinery sector. The conference took place on November 21 and 22, 2025, at Hotel Le Meridien under the joint aegis of The Textile Association of India South India Unit and AATCC.

The award was presented by Shri T. Rajkumar, Vice Chairman of the Council of Administration, SITRA and Chairman of Sri Mahasakthi Mills Limited, in the presence of leading industry professionals, technologists and academic experts from across the country.

Mr. Sankar began his career at LMW in 1985 and currently leads operations at its Textile Machinery Division. His leadership played a pivotal role in strengthening LMW position as the largest textile machinery supplier in India and in building a strong global footprint across China and the Middle East. He also serves key industry bodies including CII, INDIA ITME Society and TMMA.

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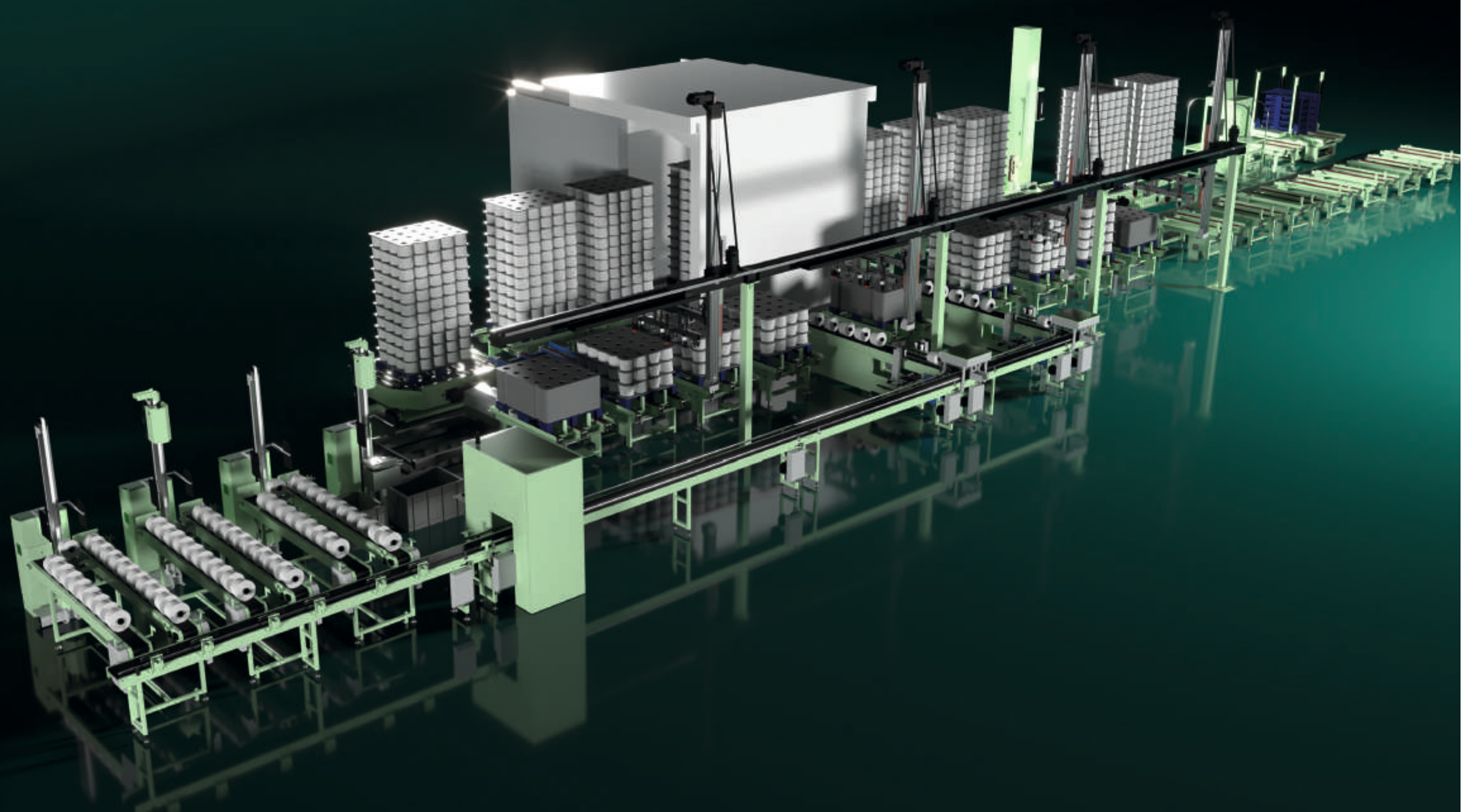

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The fully automatic packaging system SERVOpack is a comprehensive solution for the efficient and precise packaging of yarn packages in a spinning mill. Thanks to its modular design, the system can be easily integrated into the environment according to individual customer requirements. The optimized process flow reduces the workload to a minimum and saves operator costs.

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Regd. No. R. N. 11386/57 (Formally Textile Digest)

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