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Opportunities and Headwinds for Indian Textiles in 2026

Opportunities and Headwinds for Indian Textiles in 2026

The Indian textile industry, a foundation of our economy employing millions and contributing significantly to exports, stands at a pivotal juncture in 2026. Recent global trade shifts, ranging from U.S. tariff adjustments to domestic budgetary measures and emerging bilateral deals, present a mix of tailwinds and turbulence.

U.S. tariff reductions on select textile inputs and finished goods, announced in late 2025, offer tangible benefits for Indian exporters. By lowering duties on man-made fibres and apparel, these changes reduce production costs for value-added products such as technical textiles and composites, where India excels.
Domestically, Budget 2026 delivers mixed signals. Enhanced PLI scheme allocations and incentives for sustainable fibres like bamboo underscore the government's commitment to R&D in performance fabrics. However, higher GST on synthetic yarns (from 12% to 18%) and subdued export rebates could squeeze margins for SMEs, particularly in Gujarat's Surat hub, known for polyester processing. Industry must pivot toward high-value segments like composites to mitigate these pressures.

India's New Cotton Import-Export Policy, effective February 2026, liberalises exports (minimum export price scrapped) while imposing stricter quality norms via mandatory testing. As of early 2026, the landscape for cotton trade has shifted significantly, particularly in India. The policy environment is currently a tug-of-war between protecting domestic farmers and keeping the textile industry competitive against global rivals

This editorial observes key developments, highlighting opportunities for growth amid persistent challenges. These dynamics crystallize broader opportunities and challenges for Indian textiles. To thrive, the industry must advocate for policy refinements, such as cotton export quotas and invest in innovation. The Textile Association urges stakeholders to collaborate on sustainability and tech-upgradation, transforming 2026's headwinds into a launchpad for global leadership.

With best wishes,

Dr. Aadhar Mandot
Hon. Editor
JTA Editorial Board

R. K. VIJ, President

How can India's Textiles & Garment sector leverage have concluded and ongoing trade agreements?

The priority should be operational execution and not just signing FTAs. Exporters need product-level playbooks that MAP tariff phase-outs, rules of origin, and compliance requirements for priority markets such as the EU and UK. Firms should reconfigure sourcing and processing to qualify for preferential access and institutionalise documentation to raise FTA utilisation rates which remain suboptimal. Cluster-level FTA help desks can support MSMEs with certificates of origin, customs procedures, and buyer compliance.

At sector level, targeted market-entry strategies should focus on categories where tariff differentiates materially improve price competitiveness versus regional peers.

Government can accelerate uptake through trade facilitation, logistic upgrades in PM MITRA Parks, and buyer-seller missions aligned to FTA markets. Finally, industry bodies should provide structured feedback on ongoing negotiations to secure pragmatic staging for sensitive products and smoother transition pathways.

What measures are necessary to deepen sustainability and innovation adaptation?

Adoption requires aligned incentives, financing, and capability building. Policy should prioritise cluster-level green infrastructure such as CETPs, water recycling, renewable energy integration, and shared testing facilitates. Dedicated green finance lines and blended finance can improve the business case for MSMEs investing in zero-liquid-discharge, energy efficiency, and circular technologies. On invention, scale R&D translation through industry-academia programs for technical textiles, and faster commercialisation under existing missions.

Digital traceability and lifecycle data systems should be mainstreamed to meet buyer and regulatory expectations. Public procurement and export incentives can be conditions on verifiable sustainability benchmarks to accelerate diffusion. Finally, skills programs focused on process automation, advanced materials, and quality systems are essential to embed innovation at the factory floor, not just in anchor firms.

Which segments offer the highest growth potential?

Three segments stand out. Technical Textiles offer multi-year growth across healthcare, infrastructure, automotive, and agriculture, supported by domestic demand and policy focus. Man-made fibre value chains and MMF apparel are structurally advantageous due to shifting global demand away from cotton-heavy portfolios and India's improving upstream capacity. Premium home textiles also present strong export potential as global buyers diversify sourcing and demand higher compliance and design capability.

Adjacent opportunities include nonwovens for medical and hygiene applications, recycled fibres and circular materials, and smart textiles linked to wearables and industrial use cases. Growth will accrue to segments where India can combine scale, cost competitiveness, compliance with sustainability standards, and shorter lead times through integrated parks and modernised processing.

How can India attract greater foreign direct investment?

FDI will respond to speed, certainty, and a bankable ecosystem. Plug-and-play industrial parks with reliable utilities, common processing facilities, design centres, and logistic hubs. Time-bound approvals, land aggregation, and utility reliability materially influence investment outcomes. States can offer targeted operating-cost relief, faster refunds, and export facilitation to improve MSME cash flows.

Customer-anchored skilling programs should focus on compliance, automation, and quality systems to raise productivity without eroding employment, establishing state-level textile cells to coordinate investor facilitation, FTA compliance support, and buyer engagement to professionalise on-ground execution. Finally, performance-linked incentives for cluster upgrades and sustainability compliance can accelerate diffusion of best practices, ensuring competitiveness is built across the supply chain rather than concentrated in a few large firms.

What Indian Government should take measure for growth of downstream MMF and cotton apparel & clothing, and to create more jobs of 2 codes by 2030?

- Ease of doing business by removing invested duty structure in MMF production. Govt. had taken a good step to reduce GST from 12% & 18% on fibre, filament yarn and garment to all at 5%. (Garment up-to Rs. 2,500/- per piece) but left out inverted duty from PTA/MEG to MMF fibre, filaments (PSF, POY, DTY, FDY, IDY). 80% to 85% of PTA/MEG, which are the main prime raw materials, are used directly and indirectly to make MMF, fibre yarn, filament, cloths, garment, which are at 18% and fibre filament at 5% leading to duty inversion causing blocking of working capital and permanent blocking of 10% to 15% GST on partly new projects or doing expansion. This capital is unnecessary lying in the books. If Govt. need more new units to come in MMF to meet the target of 350 US Billion dollar by 2030, then Govt. has to remove this inverted duty structure by keeping PTA/MEG at 5% GST rate.

- PTA/MEG and Cotton are in short supply in India and availability of these raw materials is crucial for the increased exports of Cotton & MMF fabric and garments. Govt. should remove custom duty on PTA/MEG and cotton to Zero % till 2030.

- Govt. should stop illegal import of finished fabric by putting MIP on a few HS codes where there is no MIP. Finished fabric is being imported illegally in India under 60064300 and 60061020 codes at a yarn price. India is losing worth of Rs. 10,000 crores towards custom duty in 6 years of MIP were put on these HS codes.

Conclusion: Year 2026 is the year in which we can take all the benefits of schemes and policies which Govt. has been done in the last one to two years. Now the Textile Industry dose not need any major changes and concessions but only ease of doing business.

R. K. VIJ
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Development of Smart Bandages and Hydrogel-Based Wound Dressings for Advanced Wound Care

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Abstract:

Wound care has advanced from basic gauze dressings to smart bandages and hydrogel-based dressings that actively enhance healing. These modern solutions integrate nanotechnology, smart materials, and drug delivery systems to track wound conditions, release medication as needed, and maintain optimal moisture levels. Smart bandages use biosensors to detect pH changes, temperature variations, and bacterial infections, allowing timely intervention and precise drug administration. Hydrogel dressings provide a moist environment, promote cell regeneration, and are particularly effective for burns, chronic wounds, and post-surgical recovery. Many are infused with silver nanoparticles to prevent infections and speed up healing. Despite their advantages, challenges such as high production costs, complex manufacturing, and regulatory approvals limit widespread adoption. Future advancements focus on AI-driven wound monitoring, bioengineered dressings with growth factors and stem cells, and the development of biodegradable materials for sustainable medical applications. These innovations are transforming wound care by improving patient outcomes, reducing hospital stays, and making treatments more efficient and accessible.

Keywords: *biodegradable materials, biosensors, drug delivery, hydrogel dressings, infection control*

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1. Introduction

Wound care has evolved dramatically from passive gauze dressings to sophisticated, sensor-integrated smart technologies capable of actively monitoring and treating wounds in real time. Multiple studies highlight significant advancements in modern wound dressings [1]. Smart bandages now incorporate microelectronic sensors that track critical wound parameters such as temperature, pH, and moisture, enabling precise, on-demand therapeutic interventions [2, 3] Hydrogel dressings further enhance these systems by providing moisture-rich, biocompatible environments that support healing, particularly for burns, ulcers, and surgical wounds [4]. Collectively, these innovations represent a major leap from traditional wound management, offering real-time monitoring, targeted drug delivery, and personalized treatment strategies that have the potential to transform patient care and wound-healing outcomes.

Smart wound dressings are especially promising in chronic wound management, where real-time monitoring and personalized treatment can significantly improve healing trajectories. Recent studies demonstrate rapid technological progress in this field [5, 6]. Innovations include the integration of biosensors capable of detecting wound parameters such as temperature, pH, and inflammatory markers [2] enabling adaptive and responsive therapeutic approaches.

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Despite these advancements, key challenges remain, including high production costs, mechanical design limitations, and regulatory hurdles [7]. However, emerging solutions such as AI-driven analytics [8], nanotechnology-enhanced materials, and next-generation hydrogels [9] offer promising pathways forward. These technologies aim to reduce the need for frequent medical interventions, improve patient comfort, and accelerate wound healing, positioning smart bandages as a potential cornerstone of future wound-care systems.

Nanomaterials play a pivotal role in these innovations. There is a document the therapeutic potential of various nanoparticles incorporated into wound dressings, including silver-based nanoparticles for infection prevention and specialized nanostructured materials designed for targeted drug delivery [18]. The integration of multiple functional components—such as antimicrobial agents, growth factors, and stimuli-responsive materials further demonstrates the sophistication of modern wound-care technologies [19]. Together, these advancements position smart bandages and hydrogel systems as highly promising tools for next-generation wound management.

This study presents an experimental prototype fabrication and feasibility assessment of hydrogel-based smart bandages using electrospinning, 3D printing, and microfluidic techniques. The work involves the development and structural integration of functional components including drug-loaded hydrogels and sensing elements. Comparative analysis with reported literature is included to benchmark the functional performance of the fabricated prototypes. The present study focuses on material fabrication, structural design, and functional validation.

2. Materials

The experimental study was conducted using a range of natural and synthetic polymers. Natural polymers such as alginate, chitosan, and gelatin were incorporated alongside synthetic polymers like polyethylene glycol for hydrogel synthesis. Silver nanoparticles and growth factors served as bioactive additives to enhance antimicrobial activity and promote tissue regeneration. Fabrication of the smart bandage prototypes employed electrospinning units, microfluidic chip systems, and crosslinking equipment.

Electro-spun nanofibrous mats represent an advanced wound-healing platform that closely mimics the extracellular matrix, supports cell proliferation, and enables controlled drug delivery. In this study, electrospinning was used to fabricate nanofibrous mats designed to replicate the structural and functional characteristics of the extracellular matrix, thereby improving cellular attachment and therapeutic delivery [10, 11]. The nanofiber scaffolds were engineered to provide controlled and sustained drug release through their high surface area and interconnected porosity [12, 13].

Hydrogels were synthesized using both physical and chemical crosslinking techniques, resulting in stable polymeric networks capable of absorbing wound exudates and maintaining a moist healing environment [14, 15]. Antimicrobial agents and bioactive compounds were incorporated into both the hydrogels and nanofiber matrices to enhance infection control and improve overall healing efficacy [12, 16 & 15].

2.1 Materials used in Smart Bandages

Smart bandages and hydrogel dressings represent a revolutionary advancement in wound management, integrating multiple high-performance materials to enhance healing efficiency and improve patient outcomes. Some researchers highlight that nanotechnology has significantly transformed wound care by accelerating tissue repair and effectively combating bacterial infections [17]. Natural polymers such as chitosan and collagen offer excellent biodegradability and biocompatibility, closely mimicking the extracellular matrix and supporting tissue regeneration. Silver nanoparticles were incorporated as antimicrobial agents due to their well-established antibacterial properties and effectiveness in preventing wound infection [16–18].

3. Methodology

This study involved experimental fabrication of smart bandage prototypes using hydrogel synthesis, electrospinning, extrusion-based 3D printing, and microfluidic drug loading techniques. All fabrication processes were carried out under controlled laboratory conditions. The objective was to develop functional prototype bandages and evaluate their structural and functional feasibility for wound care applications.

3.1 Material Selection and Preparation

Biocompatible and non-toxic polymers including sodium alginate, chitosan, gelatin, polyethylene glycol (PEG), and medical-grade polyurethane were selected based on their proven wound healing efficiency, biocompatibility, biodegradability, antimicrobial activity, and mechanical stability [1, 10, 13–15 & 19]. Sodium alginate provides excellent moisture retention and gel-forming ability, while chitosan contributes antimicrobial protection. Gelatin enhances cell adhesion and biological compatibility, PEG improves flexibility and swelling capacity, and polyurethane provides mechanical strength and structural durability.

All polymer materials were purified through repeated washing with distilled water followed by ethanol sterilization (70% v/v) to remove contaminants, residual solvents, and microbial impurities. Structural modifications were carried out through polymer blending, ionic crosslinking using calcium chloride (2% w/v), and incorporation of polyethylene glycol (PEG) to enhance mechanical strength, flexibility, and swelling capacity. Chitosan and gelatin were blended to improve antimicrobial activity and biocompatibility, while silver nanoparticles (0.05% w/v) were incorporated to enhance antibacterial performance. These modifications improved structural stability, mechanical integrity, and biomedical functionality of the fabricated smart bandages. Material preparation and purification procedures were conducted in accordance with ASTM F2063-18 standards to ensure safety, structural integrity, and biomedical suitability for wound dressing applications.

3.2 Fabrication of Smart Bandages

3.2.1 Electrospinning of Nanofiber Mats

Electrospun nanofibers were fabricated using polyurethane (10% w/v), gelatin (4% w/v), and chitosan (1% w/v) polymer solutions prepared in appropriate solvent systems. The polymer solution was loaded into a syringe fitted with a 21G stainless steel needle and electrospun using a high-voltage electrospinning unit. Electrospinning was performed at an applied voltage of 18 kV, flow rate of 0.8 mL/h, and needle-to-collector distance of 15 cm. Nanofibers were collected on a rotating drum collector and dried under ambient laboratory conditions for 24 hours.

This process produced uniform porous nanofiber mats mimicking the extracellular matrix, which supports cellular growth and enhances wound healing performance. The detailed fabrication parameters are summarized in Table 1.

3.2.2 3D Printing and Microfluidic Integration

Three-dimensional (3D) printing and microfluidic techniques were used to fabricate hydrogel-based smart bandages with controlled geometry, uniform drug loading, and integrated sensing capability. A hydrogel bioink composed of sodium alginate (3% w/v), polyethylene glycol (PEG, 2% w/v), and gelatin (2% w/v) was prepared under continuous stirring at 40°C to achieve suitable viscosity. The bioink was printed using an extrusion-based bioprinter with a 22G nozzle under optimized conditions to produce bandages with thickness of 1.5–2.0 mm and grid architecture for improved flexibility and oxygen permeability. The printed structures were crosslinked using calcium chloride (2% w/v) to enhance structural stability. Microfluidic PDMS chips were employed for controlled polymer mixing, uniform drug loading using silver nanoparticles (0.05% w/v), and integration of flexible temperature, pH, and moisture sensors for real-time wound monitoring. These techniques ensured precise bandage architecture, uniform drug distribution, and reproducible fabrication. Mechanical properties were evaluated according to ASTM D5034 (tensile strength) and ASTM D882 (thin-film durability) to confirm suitability for wound care applications.

3.3 Hydrogel Synthesis and Crosslinking

Hydrogel dressings were synthesized using sodium alginate (3% w/v) and PEG (2% w/v) dissolved in distilled water under continuous stirring at 40°C for 60 minutes. The homogeneous polymer solution was cast into molds with a uniform thickness of 2 mm and crosslinked using calcium chloride solution (2% w/v) for 15 minutes to form stable polymer networks.

Chitosan and gelatin were incorporated to enhance antimicrobial activity and biological compatibility. Silver nanoparticles were integrated into selected formulations to improve antibacterial performance. The crosslinked hydrogels were washed and dried under controlled laboratory conditions.

Water absorption, swelling behavior, and biodegradability were evaluated according to ASTM D570 and ASTM F1635 standards. The hydrogel fabrication process and structural characteristics are illustrated in Figure 1.

Figure 1: Hydrogel synthesis and crosslinking process schematic

3.4 Integration of Active Components and Sensor Calibration

Bioactive components including antimicrobial agents, drug delivery elements, and biosensors were integrated into smart bandage prototypes. Silver nanoparticles were incorporated to provide antimicrobial protection. Temperature, pH, and moisture sensors were embedded to enable real-time wound monitoring.

Temperature sensors were calibrated at 25°C, 37°C, and 45°C. pH sensors were calibrated using standard buffer solutions (pH 4, 7, and 10). Moisture sensors were calibrated using controlled saline volumes to simulate wound exudate conditions. These calibration procedures ensured reliable and reproducible sensor performance. Antibacterial performance was evaluated according to ASTM E2149 standards.

Sensor integration and smart bandage architecture are shown in Figure 2.

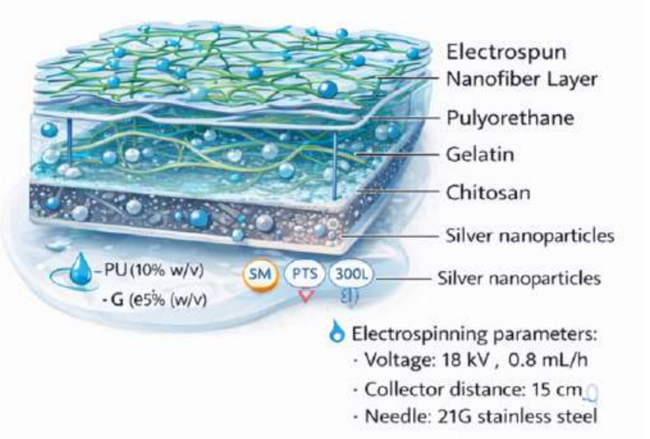

Figure 2: Smart bandage structure with sensor integrationschematic

3.5 Performance Evaluation and Experimental Testing

Mechanical, functional, and biological performance of fabricated bandages was evaluated experimentally. Mechanical properties including tensile strength, elongation, and elastic modulus were tested according to ASTM D5034 and ASTM D882 standards. Functional performance including moisture retention, exudate absorption, adhesion strength, and water vapor transmission was evaluated using standard biomedical testing methods. Biocompatibility and cytotoxicity were assessed according to ASTM F895 standards. All experiments were conducted using six independent samples per dressing type (n = 6), and results were reported as mean ± standard deviation. Hydrogel dressings demonstrated moisture retention of 82.3 ± 4.8%, while conductive smart bandages exhibited tensile strength of 2.25 ± 0.48 MPa. These results confirm the mechanical stability, functional efficiency, and biomedical suitability of the fabricated smart bandage materials.

Table 1 : Fabrication parameters, material composition, and experimental conditions of smart bandages and hydrogel dressings

Component	Material	Composition / Concentration	Processing Technique	Processing Parameters	Purpose / Function
Hydrogel matrix	Sodium alginate	3% (w/v)	Solution casting and ionic crosslinking	Stirring at 40°C for 60 min; crosslinking with $CaCl_2$ (2% w/v) for 15 min; thickness: 2 mm	Moisture retention and wound hydration
Hydrogel modifier	Polyethylene glycol (PEG)	2% (w/v)	Polymer blending	Mixed under controlled stirring	Improves flexibility and swelling capacity
Nanofiber matrix	Polyurethane	10% (w/v)	Electrospinning	Voltage: 18 kV; Flow rate: 0.8 mL/h; Collector distance: 15 cm; drying: 24 h	Provides mechanical strength and structural stability
Bioactive polymer	Gelatin	4% (w/v)	Electrospinning blend	Mixed with polyurethane solution	Enhances biocompatibility and cell adhesion
Antimicrobial polymer	Chitosan	1% (w/v)	Electrospinning blend	Mixed with polymer solution	Provides antimicrobial activity
Crosslinking agent	Calcium chloride ($CaCl_2$)	2% (w/v)	Ionic crosslinking	Immersion crosslinking for 15 min	Improves hydrogel structural stability
Antimicrobial agent	Silver nanoparticles	0.05% (w/v)	Embedded into hydrogel matrix	Mixed during polymer preparation	Provides antibacterial protection
Sensor component	Temperature sensor	—	Sensor integration	Calibration at 25°C, 37°C, 45°C	Real-time wound temperature monitoring
Sensor component	pH sensor	—	Sensor integration	Calibration using buffer solutions (pH 4, 7, 10)	Detects wound infection and healing status
Sensor component	Moisture sensor	—	Sensor integration	Calibrated using saline solution volumes	Monitors wound exudate level
Sample size	All dressings	n = 6 samples per type	Experimental testing	Mean ± standard deviation reported	Ensures statistical reliability
Mechanical testing	All fabricated dressings	—	ASTM D5034, ASTM D882	Tensile and elongation testing	Evaluates mechanical performance
Functional testing	Hydrogel and smart bandages	—	ASTM D570, ASTM F1635	Moisture retention and biodegradability testing	Evaluates wound healing performance

4. Result and Analysis

The fabricated smart bandage prototypes were evaluated and their performance was compared with reported smart wound dressing systems in the literature to validate material selection and design suitability.

Table 2 : Consolidated Properties of Smart Bandages

Property	Hydrogel	Hydrocolloid	Alginate	Foam	Antimicrobial	Conductive
Moisture Retention (%)	70-90	50-70	30-50	50-70	50-70	30-50
Exudate Absorption (%)	50-70	70-90	90-100	90-100	50-70	30-50
Antimicrobial Property	None	None	None	None	High	High
Flexibility	High	Moderate	Low	High	Moderate	High
Biodegradability	Moderate	High	High	Low	Low	Low

The comparison reveals that hydrogel dressings excel in moisture retention (70–90%) and flexibility, making them ideal for dry wounds requiring hydration. Alginate and foam dressings are superior in exudate absorption (90–100%), suitable for heavily exuding wounds, though alginate is less flexible. Antimicrobial and conductive dressings stand out for their high antimicrobial properties, making them effective against infections, but they retain less moisture and absorb less exudate. In terms of flexibility, hydrogel, foam, and conductive dressings are more adaptable to body contours, enhancing patient comfort. For biodegradability, hydrocolloid and alginate are the eco-friendliest, while antimicrobial and conductive dressings have lower biodegradability, raising environmental concerns. Overall, dressing selection should be based on wound characteristics, infection risk, and sustainability needs.

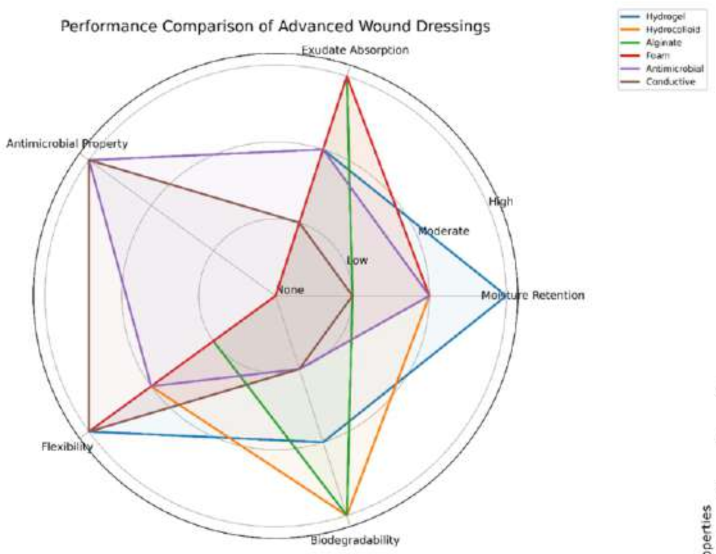

Figure 3: Performance Comparison of Advanced wound dressings

The graphical representation of these properties is shown in Figure 3, which illustrates the comparative performance of different smart bandage materials based on moisture retention, exudate absorption, antimicrobial activity, flexibility, and biodegradability. The figure clearly demonstrates that hydrogel dressings provide superior moisture retention and flexibility, while alginate and foam dressings exhibit higher exudate absorption capacity. Conductive and antimicrobial dressings show enhanced antimicrobial performance, highlighting their suitability for infection-prone wounds. The visual comparison in Figure 3 improves understanding of the functional differences between dressing materials and supports appropriate material selection based on wound requirements.

Smart bandages show diverse properties based on material type. Hydrogels excel in moisture retention and oxygen permeability but have low strength. Hydrocolloids and alginates are biodegradable with good absorption, though alginates lack flexibility. Foams provide balanced absorption, strength, and flexibility. Antimicrobial and conductive dressings offer high infection control and superior mechanical strength, with conductive types also showing high adhesion and water vapour transmission. However, both have low biodegradability. Overall, conductive and antimicrobial bandages suit advanced applications, while hydrocolloid and alginate are ideal for eco-friendly, moderate wound care. Material choice should match wound type, treatment goals, and sustainability needs.

Figure 4 presents the graphical and radar chart representation of mechanical strength properties, including tensile strength, elastic modulus, and elongation. The radar chart clearly illustrates that conductive dressings exhibit superior mechanical performance compared to other materials, due to reinforced polymer structures and conductive nanomaterial incorporation. Hydrogel dressings show lower tensile strength but offer sufficient flexibility for sensitive wound applications. The graphical visualization in Figure 4 provides a clear comparison of mechanical behavior, highlighting the structural stability and durability of conductive and antimicrobial smart bandages.

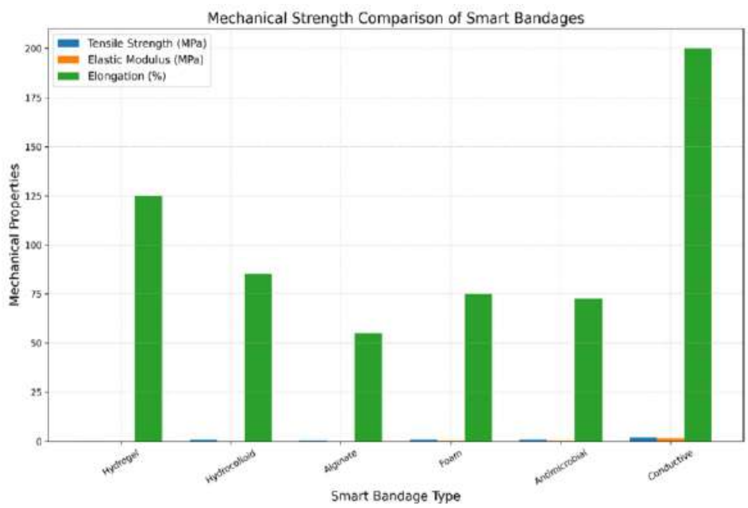

Figure 4: Mechanical Strength of Smart Bandages

Smart bandages exhibit distinct functional characteristics. Hydrogel and conductive materials offer high oxygen permeability, promoting faster healing, while alginate provides low permeability, limiting its use for aerobic wound environments. Water vapour transmission is highest in

Table 3: Mechanical Strength of Smart Bandages

Property	Hydrogel	Hydrocolloid	Alginate	Foam	Antimicrobial	Conductive
Tensile Strength (MPa)	0.1-0.5	0.5-1.5	0.2-1.0	0.3-2.0	0.5-1.8	1.0-3.0
Elastic Modulus (MPa)	0.05-0.2	0.1-0.3	0.1-0.5	0.2-0.8	0.2-0.7	0.8-2.5
Elongation (%)	50-200	20-150	10-100	30-120	15-130	100-300

Table 4: Functional Characteristics of Smart Bandages

Characteristic	Hydrogel	Hydrocolloid	Alginate	Foam	Antimicrobial	Conductive
Oxygen Permeability	High	Moderate	Low	High	Moderate	High
Water Vapor Transmission (g/m²/day)	500-2000	200-800	100-500	300-1500	250-1000	800-2500
Adhesion Strength (N/cm)	0.2-1.0	0.5-2.0	0.3-1.5	0.4-2.0	0.6-2.5	1.0-3.0

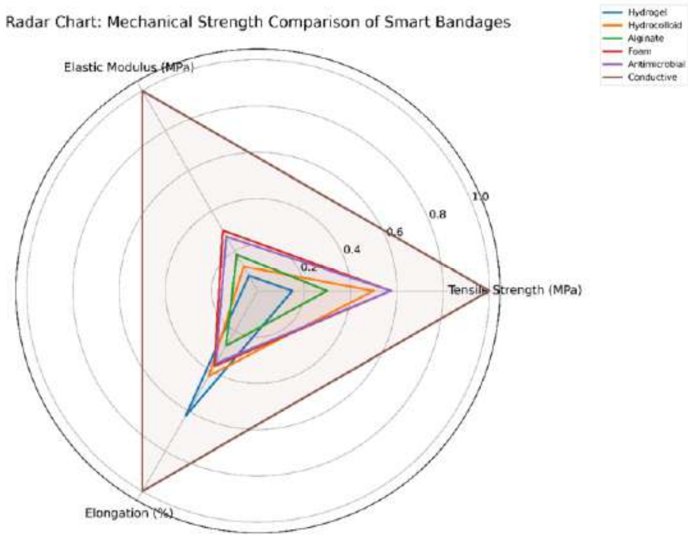

Figure 5: Radar Chart: Mechanical Strength of Smart Bandages

conductive dressings (800–2500 g/m²/day), aiding in moisture balance, whereas alginate has the lowest range. Adhesion strength is greatest in conductive types (1.0–3.0 N/cm), ensuring secure placement, while hydrogel shows the weakest adhesion (0.2–1.0 N/cm), making it suitable for sensitive skin. Overall, conductive and foam dressings balance breathability and adhesion well, while hydrogel suits low-trauma applications and alginate fits high-exudate but less-oxygen-demanding wounds.

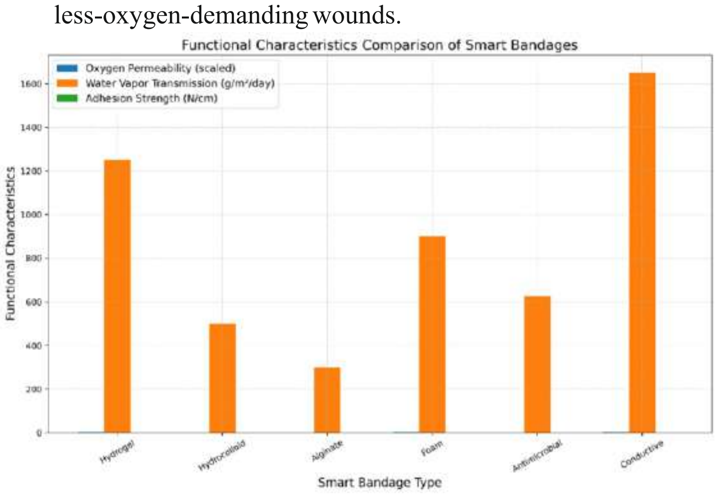

Figure 6: Functional Characteristics of Smart Bandages

The functional characteristics of smart bandages are graphically illustrated in Figures 5 and 6. Figure 5 shows the comparative analysis of oxygen permeability, water vapor transmission rate, and adhesion strength, while Figure 6 presents the radar chart visualization of these functional parameters. Conductive dressings demonstrate superior performance in oxygen permeability and water vapor transmission, supporting optimal wound healing conditions. Hydrogel dressings exhibit lower adhesion strength, making them suitable for sensitive skin applications. The graphical representations provide clear visualization of functional performance and support the selection of appropriate smart bandage materials for different wound care applications

5. Results and Discussion

The performance evaluation of smart bandages and hydrogel dressings was carried out through in-depth analysis of their physical, mechanical, and functional properties. The aim was to understand the suitability of each dressing type for different wound care applications based on parameters such as moisture retention, exudate absorption, antimicrobial efficacy, mechanical strength, and functional attributes like oxygen permeability and adhesion.

5.1 Comparative Analysis of Key Properties

5.1.1 Moisture Retention and Exudate Absorption

Hydrogel dressings demonstrated the highest moisture retention capacity (70–90%), making them ideal for dry or necrotic wounds that require a consistently moist environment to support autolytic debridement and cell regeneration. Foam and alginate dressings excelled in exudate absorption (90–100%), critical for managing wounds with heavy discharge such as pressure ulcers and venous leg ulcers. While hydrocolloid dressings offered moderate performance in both aspects, antimicrobial and conductive dressings had lower moisture management capabilities (30–50%), but compensated through infection control.

5.1.2 Antimicrobial Efficacy and Flexibility

Antimicrobial and conductive dressings were infused with silver nanoparticles and other bactericidal agents, resulting in high antimicrobial properties. These are beneficial in reducing bioburden and preventing wound infections. Hydrogels, despite lacking intrinsic antimicrobial properties, could be enhanced through the addition of active agents. In terms of flexibility, hydrogels, foam, and conductive dressings adapted well to body contours, improving patient comfort and reducing dressing displacement, especially in mobile body parts.

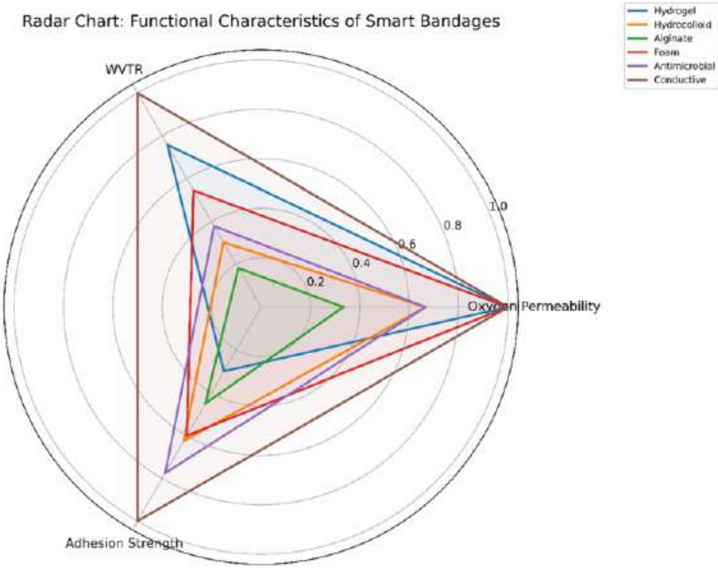

Figure 7: Radar Chart: Functional Characteristics of Smart Bandages

5.1.3 Biodegradability

Eco-friendly considerations highlighted hydrocolloid and alginate dressings as the most biodegradable options. This makes them suitable for sustainable medical practices. Conductive and antimicrobial dressings, often integrated with metallic and synthetic nanomaterials, showed lower biodegradability, posing disposal challenges in clinical settings.

5.2 Mechanical Performance Evaluation

5.2.1 Tensile Strength and Elastic Modulus

Mechanical strength is essential to withstand physical stress during dressing application and wear. Conductive dressings showed the highest tensile strength (1.0–3.0 MPa) and elastic modulus (0.8–2.5 MPa), attributed to the incorporation of graphene oxide and reinforced polymer structures. These dressings can endure greater mechanical load without tearing. In contrast, hydrogel dressings displayed the lowest tensile strength (0.1–0.5 MPa), suitable for fragile skin but not for high-friction areas.

5.2.2 Elongation

Conductive bandages also exhibited the highest elongation (100–300%), allowing them to stretch and conform to complex body shapes without compromising integrity. Hydrogels had moderate elongation (50–200%), which, while offering comfort, may limit their use in joints or areas experiencing dynamic movement. Alginate showed the least elongation (10–100%), limiting its adaptability in high-motion zones.

5.3 Functional Characteristics

5.3.1 Oxygen Permeability and Water Vapor Transmission (WVT)

High oxygen permeability, as found in hydrogel and conductive dressings, facilitates aerobic cellular activity and faster wound closure. Conductive dressings had the highest WVT (800–2500 g/m²/day), enabling effective moisture regulation while avoiding wound maceration. In contrast, alginate dressings showed low oxygen permeability and WVT, which could hinder healing in aerobic wounds but benefit anaerobic bacterial control.

5.3.2 Adhesion Strength

Conductive dressings outperformed in adhesion strength (1.0–3.0 N/cm), ensuring better placement stability even in high-friction areas like joints. Hydrogels, on the other hand, had the lowest adhesion (0.2–1.0 N/cm), making them gentle and suitable for pediatric or geriatric patients with sensitive skin. However, low adhesion requires secondary dressings to secure placement.

5.4 Limitations and Future Scope

Despite their advantages, high production costs, regulatory barriers, and environmental concerns limit large-scale adoption. Conductive and antimicrobial dressings especially pose disposal challenges due to low biodegradability. Moving forward, integrating biodegradable conductive materials, developing self-powered biosensors, and reducing the cost of fabrication through scalable techniques like roll-to-roll processing or 3D printing could pave the way for broader clinical implementation.

The use of AI and IoT for predictive wound monitoring and the application of machine learning to analyze healing data will further personalize and enhance care. Biodegradable hydrogel dressings embedded with stem cells and oxygen-releasing compounds represent the next generation of smart wound care solutions that are both effective and eco-conscious.

6. Conclusion

The evolution of wound care from traditional gauze to smart bandages and hydrogel-based dressings represents a major leap in medical technology, shifting the focus from passive wound protection to active healing and enhanced patient comfort. This study comprehensively evaluated the structural, mechanical, and functional characteristics of various advanced wound dressings, highlighting the importance of selecting materials tailored to specific wound types and healing stages.

Hydrogel dressings demonstrated excellent moisture retention and flexibility, making them particularly suitable for dry or sensitive wounds. Alginate and foam dressings showed superior performance in exudate management, making them ideal for heavily discharging wounds. Antimicrobial and conductive dressings provided strong infection control and mechanical stability, although concerns remain regarding their biodegradability. The integration of biosensors, nanomaterials, and controlled drug-delivery systems in smart dressings enables real-time monitoring and precise therapeutic intervention, offering a highly personalized approach to wound care.

Despite the significant improvements these technologies bring—such as accelerated healing and reduced clinical intervention—challenges persist in terms of cost, large-scale manufacturing, and regulatory approval. Future advancements should prioritize sustainable materials, scalable fabrication methods, and AI-driven wound diagnostics to enhance accessibility, affordability, and environmental safety.

This study demonstrates the feasibility of fabricating smart hydrogel-based bandage prototypes using advanced manufacturing techniques. Future work will include detailed quantitative experimental validation, statistical analysis, in-vitro biological testing, and in-vivo evaluation to further establish clinical applicability and performance.

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Emerging Sustainable Natural Fibres in India: Reviewing Underutilized Plant-Based Fibres for Eco-Friendly Innovation

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Abstract*:*

Background: *The textile and fashion is a very resource-consuming sector, which causes the pollution of water and chemical load, releasing carbon emissions and growing textile waste. In reaction, the sustainable fashion trend has been on the rise, and there is a growing interest in natural, biodegradable and underutilized plant-based fibres, which can be used to sustain the circular and low-impact textile systems, especially in developing economies such as India.*

Methods: *The approach of this review is based on systematic literature analysis, including research articles, review papers, government reports and industry publications that were published during 2015-2025. Keywords were used to search databases like Google Scholar, Scopus, Springer Link, Elsevier Science Director, and Wiley Online Library that included sustainable fashion, circular textile, eco-friendly material, green manufacturing and textile sustainability. About 60 studies were shortlisted and the thematic grouping was based on sustainable natural fibres, fibre extraction and modification, textile and agro-textile uses, and policy or socio-economic views.*

Findings: *According to the literature, fibres are increasingly being investigated including Himalayan nettle, banana and other fibres made of plant-based agricultural residues, which demonstrate renewability, a positive level of bio-degradation, and the appropriate mechanical properties of fibres to be used in the apparel sector, technical textile and composite industries. Several extraction and modification processes have been studied in order to enhance spin ability, interface bonding and performance and applications are also being extended into fashion, agro-textile packaging and natural fibre composites.*

Conclusion: *Natural fibres lie untapped, but have great potential to facilitate the eco-friendly textile innovation, and to improve rural livelihood in India, which must be combined in terms of cultivation, processing technology, quality assurance, and market development. Further efforts in working on optimized extraction and modification protocols, scalable spin and fabric production, life-cycle analyses, and policy guidelines that promote the incorporation of these fibres in mainstream textile and agro-textile value chains need to be done in the future.*

Keywords : *Circular Textiles, Consumer Behavior, Eco-Friendly Materials, Green Manufacturing, Sustainable Fashion, Textile Sustainability*

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1. Introduction

The textile and fashion trade is a highly resource-demanding sector in the world, which causes a significant share of environmental degradation through excessive use of water, the use of chemicals, carbon, and waste of textiles, which are growing in number [1]. The increasing awareness of climate change, the government regulation, and the increasing consciousness of the consumers have only worsened the need in more responsible production and consumption patterns in the fashion ecosystem [2]. Consequently, sustainable fashion has become an important model that supports environmental responsibility, ethical production, cyclicality, and less significant ecological footprint.

According to the latest scholarly sources, there is currently a considerable advancement in the creation of sustainable materials, recycling-related design solutions, and green technologies in manufacturing eco-friendlier fabrics included bio-based fibres, recycled yarns, and low-impact dyeing processes, as well as digital supply-chain transparency solutions [3]. Consumer behavior is also in the current transformation, the younger generations especially Gen Z showing even greater inclinations to transparency, ethical sourcing, and environmentally conscious brands [4].

Amidst these new opportunities, there are still some challenges to large-scale implementation of sustainable fashion, with the high costs of production, scarcity of recycling facilities, absence of consumer awareness, and the fast-fashion culture being some of the factors (notably) [5]. Such impediments are marked especially in developing economies such as India where infrastructure and policy backing are low. Thus, the review is based on the synthesis of

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modern literature to study the progress of sustainable fashion, the main forces, and obstacles, as well as opportunities to develop a low-impact and circular system of textiles.

This study provides a synthesized literature review of the sustainable natural fibers, process of extracting plant-based fibre and its suitability to modern textile science. The review gives a summary of the top academic input and identifies insights, empirical evidence, and research findings that have been made in prominent studies. This chapter aims at developing a theoretical basis of the thesis and finding the gaps that exist in current scholarship that warrant the current investigation [6].

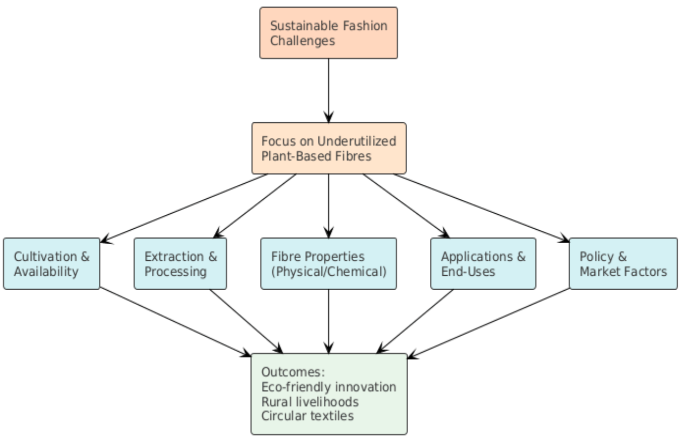

Figure 1: Conceptual Framework for Emerging Sustainable Natural Fibres in India

Figure [1] represents the general idea of the conceptual framework connecting the issues of sustainable fashion with the specific review of underused plant-based fibres in India. It demonstrates that the combination of five main dimensions' cultivation, extraction/processing, fibre properties, applications, and policy/market forces can bring about the desired outcomes in terms of innovative and environmentally-friendly development, rural livelihoods and circular textiles.

2. Sustainable natural fibres and types

Individual projects in individual states and organizations also exist, which must be extended to large scales of nettle cultivation. The existing technological methods of nettle fibre are at the laboratory scale or in small scale which means that they have to be developed further. The nettle fibre needs a great impetus to be able to achieve the maximum in the textile sector by mass growth, manufacturing, and sales of the fibre. It is significant that the work gives a valuable insight into the wider discussion of the production of fibres that are environmentally responsible and how this can be applied to the world of textile and composite materials [7].

Figure [2] shows the categorization of natural fibres that can be used in the textile innovation as sustainable. It separates classic natural fibres (cotton, jute, hemp, flax) and underutilized or newly discovered plant fibres (including Himalayan nettle, banana bract, Caltrops, and PALF), placing them in relative context to other fibres. The paper shows that the extracted fiber has a good physical, mechanical, chemical, thermal, and morphological property that can be mixed with viscose fiber. The designed blended yarns and fabrics are not just trendy but also entirely biodegradable and this means that the apparel textile is sustainable. The study recommends the economic importance of the Himalayan nettle which would serve as a substitute in the textile sector. The piece has a valuable insight to the overall discussion on fibre production that is environmentally responsible and its relevance in the field of textile and composite materials.

In the article, discussed called Nettle (Utica spp.) phytology and applications: Crop variety selection and advanced product development manufacturing of natural fibre composites and made an important contribution to the knowledge related to sustainable fibre development. The work contains the revelation that the paper is discussing the possibility of stinging nettle as a long-lasting source of natural fibers, which is better in terms of thermal and mechanical characteristics. It highlights the importance of the selection of the kinds of crops, their growing and the procedures of harvesting of the fibers to enhance the output and quality so as to render the composite environmental-friendly. It also talks about the cultural and medicinal significance of nettle in India, which presupposes the fact that the traditional applications of the biodegradable substance can be used as the model of new applications in the field of the natural fibers composites. It gives a detailed description of morphology, anatomy, and the taxonomy of stinging nettle enhancing the current knowledge on the characteristics of the plant [7, 8]. The phytochemical composition of stinging nettle has been discussed with a focus on its far-reaching

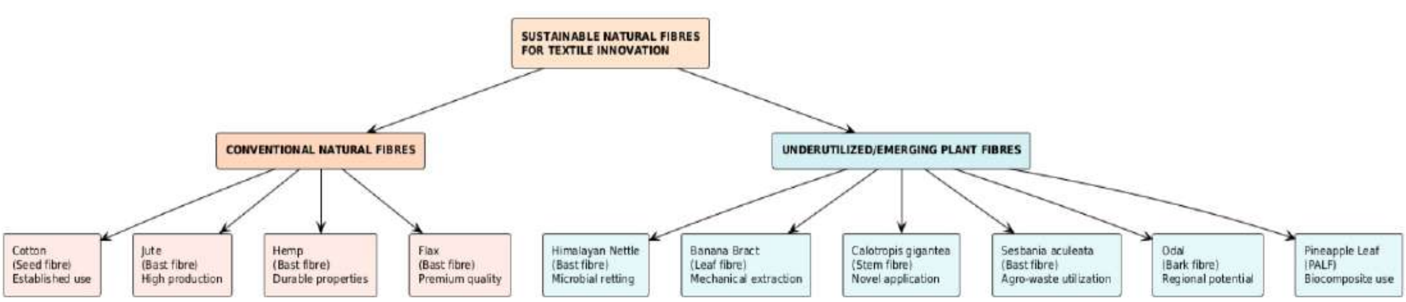

Figure 2: Classification of Sustainable Fibers

therapeutic use and cultural values, especially in Ayurveda medicine in India. The study presents efficient growth strategies, harvesting, and fibers isolation procedures that are necessary in enhancing crop production and acquiring high quality fibers [8].

The article on the subject matter The Utilization of Natural Plant Fibers as a Sustainable Substitute Material for Textile and Other Uses provides some insight into the development of sustainable fibres. The paper provides the knowledge that the rising importance of natural fibers as alternative materials to synthetic ones is discussed in the paper, with its outstanding qualities and possible applications in both textiles and non-textiles. It presents the advantages of the natural fiber composites, which include renewability, biodegradation and eco-friendliness, and so are applicable to diversified uses including textiles. Although it does not directly deal with underutilized plant based fibers in India, it highlights how the world is moving towards sustainable materials as part of the environmental issues and the lack of petroleum resources. The results also point out the fact that Natural fibers are becoming more acceptable as sustainable substitute to the traditional synthetic fiber based on their high physical and mechanical characteristics and can be applied in a wide variety of uses in textile and non-textile industries, including automotive, building, and furniture [9].

The article under analysis deals with the theme of Sustainable Raw Materials, which made a significant contribution to the knowledge of sustainable fibre development. The research offers the information that the paper is concerned with sustainable raw materials in textiles, including natural fibers like flax, hemp, jute, and so on, which corresponds to the trends of using underutilized plant based fibers and eco-friendly innovation in textiles. It focuses on cultivation and processing methods of these fibers, their biodegradability, and their sustainability as a source of yarns. Although it does not particularly target the indigenous Indian fibers or agricultural waste, it points out the necessity of experimenting with new natural fibers and practices in the textile industry [9, 10]. The results also emphasize the fact that the chapter gives the overview of the different sustainable raw materials of circularity in textiles such as natural fiber like flax, hemp, jute, and synthetic fibers such as lyo cell and Poly lactic acid, including their different properties, growth, and manufacturing processes, which make them sustainable in producing a textile. The authors came to the conclusion that the chapter deals with the significance of finding sustainable raw materials (natural fibers (flax, hemp, jute, etc.), synthetic fibers (alginate, lyo-cell, etc.) to reduce the environmental impact and make the textile industry more circular by focusing on their specific properties and ways of cultivation. It addresses the environmental impact and advantages of these materials, biodegradability, recyclability, and carbon footprint, and outlines future trends in sustainable practice in textiles, including new technologies in fiber processing and new design principles. The work offers a significant insight into the context of the overall discussion on environmentally responsible fibre manufacturing and its relevance to the sphere of textile and composite materials [10].

3. Fibre extraction and processing methods

The study aimed at the topic entitled Extraction and modification of natural plant fibers: A comprehensive review, which led to a significant contribution to the knowledge on sustainable fibre development. The article offers the observation that the paper is about the benefits of natural plant fibers, where it is pointed out that these fibers are biodegradable and renewable hence are applicable in ecofriendly applications. It places emphasis on the means of extraction and processing of the same as more convenient and non-hazardous than synthetic materials. It however also mentions that it has limitations including non-uniformity in properties and poor interfacial adhesion. These issues can be overcome by appropriate methods of modification, which encourages the implementation of unused plant based fibers in innovative production and creation of biodegradable textiles. The results also indicate that Natural plant fibers and their composites have been identified to compete with the synthetic materials because they are biodegradable and renewable. It is pointed out that the extraction and the processing of plant fibers are less painful and easier than artificial materials [11]. The benefits of the natural plant fibers are that they are nonabrasive, low density and have good chemical, thermal, and mechanical characteristics. Some shortcomings that have been found with plant fibers are variability of certain properties, roughness of their surfaces, lack of interfacial adhesion with the matrices and the fact that they are hydrophilic. The paper proposes that these constraints could be dealt with by using a proper extraction and processing techniques and an appropriate way of modifying them. The authors also found out that Natural plant fibers are known to be biodegradable and natural, and thus, they are an alternative to synthetic materials, and the benefits of such fibers include low density and good mechanical properties [12].

The article discussed the issue of The Extraction of Lingo cellulosic Fibre out of a Green Maturing Crop (S. aculeate) to produce Sustainable Bio composite Product, which became an important addition to the body of knowledge on sustainable fibre production. The research makes the revelation that the paper will be dealing with S. aculeate which is a lingo cellulosic biomass that was used to produce quality textile fibre using the process of biological retting [11, 13]. The leguminous crop is also important in sustainable bio composite products besides enriching the soil with nitrogen, phosphorus, and potassium, which facilitate environmental friendly production of agriculture. The fibre extracted has desirable physical, chemical and mechanical properties, which make it suitable in technical textile. The paper identifies potential in using such untapped plant based fibres by replacing the use of synthetic fibres and promoting sustainable textile technology in India. The findings further highlight that the research demonstrated that S. aculeate, a green maturing crop, can be effectively utilized for extracting quality textile fibre through a biological retting method. The crop produced a significant amount of green biomass (387 quintals per hectare) and dry biomass (50.5 quintal per hectare), yielding 4% fibre by weight of the green plants [13].

The two-month old S. aculeate was determined to have made significant contributions to the nutrient level of the soil such as 143.9 kg/ha of nitrogen, 28.3 kg/ha of phosphorous and 54.3 kg/ha of potassium. The fibre thus obtained had coarse mechanical characteristics with a density of 1.26 g/cc and the chemical, mechanical and thermal characteristics saw it fit in fibrous reinforcement when developing bio composite. The paper has brought out the dual purpose of S. aculeate to enrich soils with green maturing and at the same time offer a viable alternative to synthetic fibre in the textile sector. The authors deduced that the authors end up making the conclusion that S. aculeate can be successfully exploited as a source of lingo cellulosic fibre to produce sustainable bio composite products. The fibre that is extracted has good physical, chemical, mechanical, and thermal characteristics that make it applicable in fibrous reinforcement in the development of bio composite. The crop enhances land fertility since in its green maturity it supplies the soils with required nutrients like nitrogen, phosphorus and potassium. The use of S. aculeate should be encouraged to curb carbon footprints and ecological risks linked to synthetic fibre in the textile industry [14].

The paper highlights the dualism of S. aculeate to improve soil health and also to be a good resource to the technical textile industry. The work offers a valuable insight into the overall discussion on the subject of environmentally responsible fibre manufacturing and its relevance to the fields of textile and composite materials.

3.1 Fibre characteristics and performance

Highlighting the subject of the article titled Extraction of bast fibres from odal (Sterculia villosa) and assessment of Physical characteristics, which adds to the insights into the sustainable fibre development. One of the perspectives provided in the study is that the paper is devoted to the extraction of bast fibres of Odal, which can be used as a sustainable natural fibre in India. It describes the decortication process and water retting methods and showed that the maximum fibre yield (2.8%) and quality was obtained after 21 days of retting. The paper focuses on the physical characteristics of Odal fibres, including tensile strength and extension, to the discussion on environmentally friendly materials and sustainability of textile innovation in the area of underutilized plant based fibres. The results also show that using the decortications process and water retting, the extraction of Odal fibre was effectively performed on the Sterculia villosa. Optimal production of fibre (2.8%) was realized after twenty-one days retting thus showing that the longer the retting time, the better the fibre. The largest retted Odal fibre length was documented to be 2.31mm with the possibility of obtaining longer fibres through effective processing. The results indicate that Odal fibres have admirable characteristics to be applied in different industries, and retting time plays a significant role in the quality of fibres. The work offers a worthwhile insight into the larger discussion of environmental friendly production of fibre and its viability in the sphere of textile and composite materials [14].

In the article, have investigated the issue named Application Potential of Novel Natural Cellulosic Fibers in Sustainable Composites: A Short Review of Research Progress between 2020 and 2024 and provided a valuable contribution to the field of understanding sustainable fibre development. The paper does not ignore the study which introduces the understanding that the paper is concerned with the potential of natural cellulosic fibers in sustainable composites with focus being on their renewable, biodegradable, and carbon-neutral properties. It discusses characteristics of such fibers, such as extraction techniques and mechanical characteristics, the latter of which are vital to the ecofriendly textile development. Although the specifics of underutilized plant based fibers in India are not explicitly discussed, it also emphasizes the potential of lingo cellulosic fibers and its potential in creating sustainable materials which is in line with the themes of green innovation and biodegradable textiles. The results continue to point out that the review reveals a dire requirement of green and sustainable alternatives to synthetic materials as a result of environmental pollution [15].

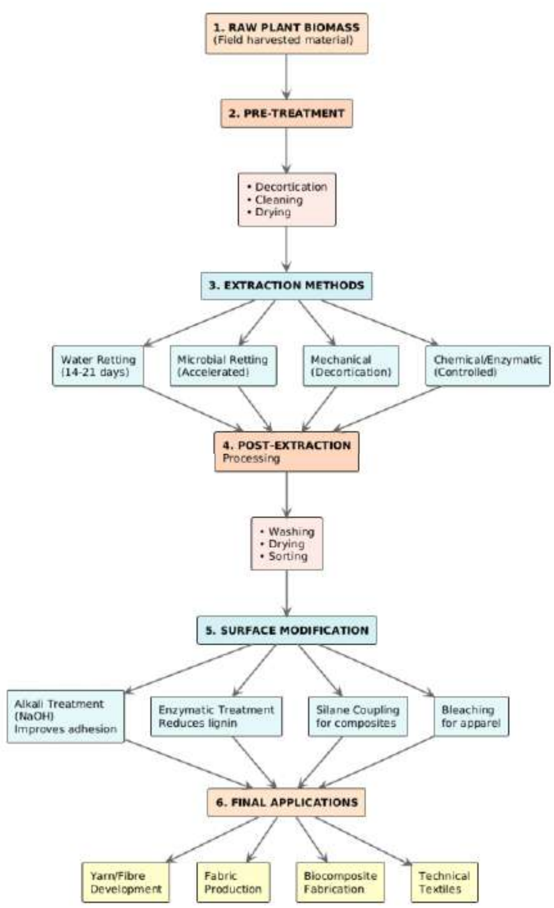

Figure 3: Process flow of Fibre Extraction & Modification for underutilized plant Fibers

Figure [3] illustrates the flow process of the extraction and modification of plant fibre that have not been fully utilized. It follows the path of raw plant biomass to pre-treatment, various extraction techniques, post-extraction process and surface treatment to the eventual finish of the process with yarn/fibre development, fabrics, bio composites and technical textiles. Natural cellulosic fibers are recognized as renewable, biodegradable and carbon neutral substances, which will be effective to reinforce polymer composites. The paper gives an extensive discussion of the physical and chemical, thermal, and mechanical properties of natural cellulosic fibers, which have been poorly represented in literature [14, 15]. Natural cellulosic fibers are described as the renewable, biodegradable, and carbon-neutral materials that have a high potential to reinforce polymer composites. The paper gives a meaningful discussion of the physical, chemical, thermal and mechanical properties of natural cellulosic fibers as relates to their application in the sustainable composite materials. It is also projected the future trend of cellulose fibers development in composite material which implies that there are still aspects to study in this field [16]. The proposed research will aid in the formulation of sustainable composite materials since the research paper will support the environmental protection and expand the list of materials. The article is an informative addition to the greater body of knowledge on the subject of fibre production processes that are ecologically safe and how they can be relevant in the field of textile and composite materials.

The topic of the Extraction and Characterization of Fibre from Musa Plant Bract contributed to the idea of sustainable fibre development greatly. The paper reveals the eye opener that the research is devoted to the extraction and characterization of banana bract fibres, their environmental benefits and opportunities of their application to the world of sustainable textiles production. Mechanical and chemical procedures were used to remove fibres that have appropriate properties like length (1424 cm), tensile strength, and moisture regain (8.5111.63%). These characteristics imply that they were raw materials of biodegradable yarn, which can be applied to the ecofriendly textile development and the application of agricultural waste in India. The results also indicate that the separation of fibres of the banana bracts was done by using mechanical treatments and chemical treatments which underscore an environmentally friendly method of using the wastes [15, 16]. Bract fibre yield percentage values were found to be between 1.02 and 1.84, which is a demonstration of variability in the extraction efficiency. Most of the bract fibres extracted measured 14-24 cm in length which is sufficient to make textile staple spun yarn.

The moisture regain of the fibres of the banana bract was observed to be 8.51 per cent to 11.63 per cent indicating that it has good moisture management properties. Using a miniature laboratory model rotor spinning machine, it was possible to create 6(s) Ne rotor staple spun yarns out of bract fibre, proving that biodegradable yarn could possibly be produced. The authors assumed that the authors find that banana bract fibres utilized are easily extractable and usable, which makes them green and sustainable. The percent of the bract fibres is between 1.02 and 1.84 which means that this is a good source of fibre [17].

These properties of the fibres including length (14-24 cm), tensile strength, and moisture regain (8.5111.63%), indicate that they are suitable in the creation of biodegradable yarn. The practical use of bract fibres in the textile manufacturing is evidenced by the successful production of 6(s) Ne rotor staple spun yarns with the use of bract fibres. The paper focuses on the possibility of transforming agricultural wastes into useful raw materials, which can help the textile industry to be sustainable. This piece of writing contributes to a constructive insight into a wider discussion about the production of fibre in an environmentally responsible manner and the field in which it can be used in textile and composite materials [16, 17].

The article is named Extraction of plant based natural fibers A mini review and it enriches the knowledge of sustainability fibre development. The research gives the revelation that the paper is about the extraction of plant based natural fibers, which is more sustainable as well as beneficial to the environment compared to synthetic fibers. It puts an emphasis on the different ways of extracting it like mechanical decortications, water retting, etc that are essential to extracting fibers of other parts of the plant. The extraction method that is used heavily affects the characteristics of the composites that are obtained. Although the paper does not directly focus on underutilization of Indian fibers or ecofriendly textile innovation, it gives initial information on the extraction of fibers in terms of sustainable textile creation. The results also indicate that the article focuses on the fact that natural fibers are better than synthetic ones in the aspects of sustainability and environmental benefits. It points out that natural fibers can be obtained at low cost and can be recycled or degraded and therefore they are more sustainable. Different ways of extracting fiber are also mentioned such as mechanical decortications, water retting and manual extraction whereby the type of extraction applied influences the nature of the composite obtained. The extraction is carried out through a retting and then decortication process that is necessary in reinforcing fiber. The analysis determines the viability of various extraction processes on various plants and fibers, meaning that extraction method are vital in determining the characteristics of ultimate composite materials [17, 18]. The authors came up with the conclusion that the paper finds that natural fibers are more sustainable than synthetic fibers because of the benefits they offer to the environment and cost effectiveness. It highlights that the process of extracting fibers is very important in reinforcing them in composites and this process affects the nature and attributes of the end products. Generally, the review highlights the significance of learning how to extract the fibers so as to increase the use of natural fibers in different applications. The work offers a valuable input to the overall discussion regarding the environmentally friendly manufacturing of fibre and its implementation to the sphere of textile and composite materials [18].

4. Social-economic and environmental factors

The subject under the title Advanced Extraction and Comprehensive Characterization of Sustainable Textile Fibers out of Mango Waste, the article is quite significant in terms of sustainable fibre maturation. The paper offers the following insight in the study that the paper will look at the innovative use of the mango waste i.e. the peel, seed and fibrous waste into sustainable textile fibers. It focuses on the extraction method that entails the use of alkaline hydrolysis in order to minimize the lignin composition to produce fibers that can be used in the ecofriendly production of textiles. The results also indicate that the experiment utilized mango wastes, namely peel, seed, and fibrous wastes to produce textile fibers, which were useful in the textile industry, in response to the issue of environmental pollution in the textile industry. It promoted the untapped possibilities of mango seed and fibrous content, which were never used before to apply in the textile industry [16, 17 & 18]. The study was successful in reducing the lignin level (83 percent) under the ideal alkaline hydrolysis requirements, with the 10 percent concentration of NaOH and 30 ml/kg liquid: solid ratio, within six hours.

The resulting mango fiber was very comparable in nature to the conventional natural fibers including the favorable aspect ratio and could be used in the manufacturing of textiles. A softening process using propylene glycol enhanced the spin ability of the fibers, resulting in the production of strong, textural fabric that could be used in the creation of the eco conscious fashion apparel. The authors found out that the study concludes that mango waste particularly peel, seed, and fibrous waste can be well used to produce useful textile fibers, which would enhance sustainability in the textile industry. The research indicates that there is a possibility of using agricultural wastes in the context of circular economy, i.e. mango waste, to minimize environmental degradation. The existence of the optimum conditions of lignin dissolution, which are achieved through the alkaline hydrolysis, has been known to drastically improve the quality of fibers obtained, which can be used to produce textile. The fibers manufactured have the same property as the traditional natural fibers implying that they can be used in the manufacture of eco conscious fashion products such as bags, shoes, and accessories. The results highlight the significance of waste revalorization towards enhancing sustainability and innovation in the textile industry. The presented piece of work offers a significant insight in the wider discussion about environmentally-friendly fibre manufacturing and its relevance in the area of textile and composite materials [19].

The article entitled Organic fibers: sustainable solution to the textile industry, which makes its contribution to the knowledge of developing sustainable fibres. The research states the fact that the paper explores the sustainable and organic fibers, including organic cotton, bamboo, soya, hemp, and jute, which are usable in the textile industry to facilitate the ecofriendly approach. It highlights the relevance of utilizing these fibers as a way of reducing pollution and environmental impact especially in India where the textile industry is a major contributor to pollution. These fibers do not use any synthetic chemicals in their production so they are a possible solution to sustainable textile innovation and biodegradable textiles [18, 19]. Results also indicate that the textile processing industry has contributed a lot to environmental pollution through release of untreated effluents, which contain harmful heavy metals and chemicals that pollute the ground water, air, and surface water. This underscores the necessity to practice sustainability in the industry to control waste management and environmental impact. It is state that the production of sustainable and organic fibers, including organic cotton, bamboo, soya, hemp, and jute, can be one of the promising steps to reduce pollution. Such fibers are manufactured in the absence of synthetic chemicals, thus they are eco-friendly substitutes that will keep the earth clean and solve the environmental issues created by the conventional production of textile.

The article called Revolutionizing Sustainable Nonwoven Fabrics: The Potential Use of Agricultural Waste and Natural Fibres for Nonwoven Fabric, which has added a lot to the topic of sustainable fibres development. The paper outlines the knowledge in the study as the potential of lingo cellulosic fibres of agricultural and forestry waste as ecofriendly feedstock to nonwoven fabrics in the textile industry. It highlights the trend of making use of natural and renewable raw materials, especially as a by-product of waste to develop high performance, biodegradable textiles [20]. The results also point out that the paper identifies the possibility of using lignocellulose fibres in agricultural and forestry waste streams as an ecofriendly feedstock to the textile industry, in the quest to develop high performance nonwoven fabrics, which will minimize dependence on synthetic materials that constitute approximately 66 percent of the nonwoven fabric industry. The authors have concluded that the article demonstrates the possibility of using lignocellulose fibre of agricultural and forestry waste as a ecofriendly feedstock in the textile industry, with the focus on the transition to using natural and renewable resources in the production of nonwoven fabrics instead of synthetic ones [21]. It concludes that the introduction of low-cost fibres derived from waste residues can lead to the development of high performance nonwoven fabrics, representing a significant move towards environmentally sustainable practices and offering ecological and cost effective alternatives to traditional petroleum derived materials. This work provides a meaningful perspective within the broader discourse on environmentally responsible fibre production and its applicability in textile and composite material domains [22, 23].

5. Challenges and research gaps

Across the literature, several recurring technical challenges are reported, including inconsistent fibre dimensions, variability in mechanical properties, hydrophilic behavior and weak bonding with polymer matrices. These issues are often linked to non-standardized extraction processes, differences in plant varieties and environmental conditions, and limited optimization at industrial scale. Economic and organizational barriers are equally significant: many underutilized fibers are processed only at laboratory or pilot scale, with limited investment in machinery, supply-chain development or quality certification systems. There is also a shortage of comparative performance data, life-cycle assessments and long-term durability studies that could reassure industry stakeholders and justify substitution of conventional fibres [1, 4, 7 & 16].

6. Opportunities, policy implications and future research

The reviewed work indicates substantial opportunities to position underutilized plant-based fibres as key enablers of sustainable fashion, technical textiles and agro-textile solutions in India and globally. Potential niches include eco-labeled apparel, biodegradable packaging, natural fibre composites and blended yarns with enhanced functionality [18, 19 & 20].

- optimized, low-impact extraction and surface modification techniques tailored to Indian fibre resources;
- pilot-scale spinning, weaving and knitting trials for selected underutilized fibres and blends;
- comprehensive life-cycle and techno-economic assessments; and
- Socio-economic studies assessing impacts on farmer livelihoods, women's employment and regional development.

7. Conclusion

The body of literature reviewed demonstrates that emerging sustainable natural fibres, particularly underutilized plant-based fibres such as Himalayan nettle and banana, offer credible pathways to reduce environmental footprints and diversify material bases in textiles and agro-textiles. These fibres combine renewability and biodegradability with mechanical properties that can be tuned through processing and blending, making them attractive for eco-friendly apparel, packaging and composite applications. For India, the strategic adoption of such fibres aligns with national priorities on sustainability, circular economy and rural development, yet requires deliberate efforts to overcome technical, infrastructural and market-related barriers. Strengthening research, policy support and industry–academia–community collaborations will be essential for moving from scattered pilot initiatives to a robust value chain that integrates underutilized natural fibres into mainstream textile innovation.

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Evaluation of Seacell & Cotton Fiber Blended Knitted Fabrics

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Abstract :

In the present work, influence of fibers type, blend and yarn count on fabrics made from blends of cotton and seacell fiber has been studied. The properties of these blends are also compared with properties of fabrics made from 100 % cotton and 100% seacell fiber. Two linear densities (20s and 30s Ne) yarn were produced on short staple ring spinning machines. Blends of cotton- seacell (50/50& 70/30) were produced with same twist multiplier. These blended yarns are used to produce weft knitted fabric samples. It was found that bursting strength and abrasion resistance of 100% seacell fabric is higher than 100 % cotton and cotton/ seacell blended fabrics. Coarser yarn exhibits more bursting strength. Fabrics made from 100 % seacell fibers have lesser tendency to form pills. 100% seacell fabric shows higher air permeability and water vapor transmission rate values than 100% cotton fabrics. Fabrics made from 100 % seacell fiber have more vertical wicking tendency than 100 % cotton and cotton/ seacell blended fabrics. Fabrics made from seacell fiber are found better than equivalent cotton fabric

Keywords: *Abrasion, Bursting, Cotton blending, Pilling, Seacell fiber, Water vapor transfer*

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1. Introduction

With the great changes in technology in the last decade, the demands from fabrics have changed and the changes include clothing comfort which have psychological, sensorial and thermo-physiological comfort. It is now not only about style and durability. These days, fabric not only fulfills the basic need of style and durability but also used as a symbol of status, wellness, occupation and eco-friendliness. In the present era awareness about sustainability has increased globally. Increase in the demands of the hygienic lifestyle of the current generation has led to development of the range of new sustainable products. So many developments have been done in field of sustainable fibre production because fibre is a basic raw material for the production of all kinds of clothing material.

Presently there is increasing demand for sustainable objects such as Seacell fibers, encouraged by growing awareness of ecological issues and the need for hygienic lifestyles. This ensures the development of new varieties of sustainable products. Seacell fiber is one such product which is high in demands because of its unique structure and properties. Seacell fibers have unique properties like brilliant luster, moisture absorption, antimicrobial and low pilling tendency [1, 2].

Seacell fiber is an enhanced form of third-generation of modified regenerated cellulosic fiber. This type of fiber offers several advantages, such as an eco-friendly production process, along with attributes like softness, drapability and antibacterial properties [3, 4].

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Seacell fibres are made by mixing powdered seaweed and natural cellulose fibres with different proportions. This method preserves the healthy elements of seaweed in the fiber, this means that can still be found in the end product and will not be easily washed off even after repeated washes [4, 5].

All regenerated cellulosic fibers share a common fundamental unit; however, they vary significantly in aspects

Figure 1: Manufacturing process of Seacell fiber

such as polymerization degree, molecular structure, molecular weight, orientation, and crystallinity [6]. Seacell fiber features a circular cross-section and a smooth longitudinal surface compare to other cellulosic fiber like Viscose rayon & bamboo.

Although considerable research work has already been done to explore application of Seacell fibers for apparel applications but less work is available on blending of seacell fibers with cotton fiber. Hence, in this research work, properties of fabrics made from blends of cotton and Seacell fibers have been studied and analyzed. Keeping in view the demand for knitted garment these days, knitted fabrics have been produced and studied.

2. Material & Methods

2.1 Material for Yarn & Fabric Production

Two types of fibers-cotton and Seacell were used to prepare 30s Ne and 20s Ne yarns on short staple ring spinning machine. BT cotton of 30 mm length 4.5 micronaire and seacell fiber of 38 mm length, 1.5 denier were used in this study. Seacell fibers were blended with cotton in two different blend ratios 50/50 and 70/30. At the same time 100% cotton and seacell yarns are also prepared for comparison purpose. Eight different fabric samples were prepared from 100% cotton and 100%seacell, 50/50 cotton/ seacell, 70/30 cotton/ seacell yarns of 30s Ne and 20s Ne yarns. The yarn samples were prepared on cotton spinning system with twist multiplier 3.8.The fabric samples were prepared on single jersey 20 inches diameter circular knitting machine having gauge 24.

2.2 Methods

The yarns & fabrics samples were conditioned at a standard atmospheric condition of 65 ± 2% RH and 25 ± 2 °C temperature for 24 hours.

2.2.1 Tensile Strength Measurement

Tensile strength measurements were performed using a Premier Tensomaxx Instrument. Specimens measuring 500 mm in length were tested at a constant rate of 5000 mm/min. Each yarn sample was tested in accordance with ASTM D2256 [7], and the force required to break each specimen was recorded. A minimum of 20 replicates were conducted for each blending ratio, and the mean tensile strength & elongation was measured. The machine was calibrated prior to testing with standard weights to ensure accuracy.

2.2.2 Yarn Unevenness (U%)

Yarn unevenness was evaluated using an Uster Tester 6, a device that measures variations in yarn mass along the spinning length. The testing parameters were set to capture the % of mean deviation across a minimum testing length of 800 meters per sample. Following the procedures described by Uster Technologies [8], the device automatically corrected for external interferences including ambient fluctuations. Each sample was tested in triplicate to ensure reproducibility, and the resulting CV% values were used as a quantitative measure of yarn evenness.

For accuracy, the yarn samples were preconditioned and aligned in the tester's feed mechanism to avoid twisting or stretching during measurement. The use of a high-speed sensor ensured that variations in mass were captured in real time, providing a detailed representation of yarn consistency for each fiber blend.

2.2.3 Hairiness

Hairiness was quantified using Uster Tester 6, which measures the number and length of protruding fiber ends from the yarn surface. Following the method described Uster Technologies [8], yarn samples were mounted on a stand & hairiness automatically counted the number of hairiness filaments per unit length of yarn.

2.2.4 Co-efficient of Friction

Friction properties were assessed using a Reseda Friction Tester, a device specifically adapted for textile applications. The test procedure involved a standard and friction coefficients were calculated based on the resistance encountered by the yarn sample. The friction coefficient and wear behavior were recorded over the length of the test. This method, based on the standardized procedure provided in ASTM D3108/D3108M-13 [9], allowed for the comparative analysis of surface friction among the different yarn blends.

The friction evaluation was carried out under controlled conditions, ensuring that the effects of static electricity and ambient conditions were minimized. Data was logged digitally and cross-verified with manual observations, ensuring that the friction coefficients reported were consistent and reliable.

2.2.5 Bursting Strength

This method for the determination of diaphragm bursting strength of knitted, nonwoven and woven fabrics is being used by the textile industry for the evaluation of a wide variety of end use. ASTM D3786 test method is used for determination of bursting strength. In this test Method D3786 is considered satisfactory for acceptance testing of commercial shipments of textile fabrics for bursting strength on Ubique bursting strength tester, since the method has been used extensively in the trade for acceptance testing.

2.2.6 Abrasion Resistance

All the tests were carried out according to the ASTM standards (D4966-98). Martindale abrasion and pilling tester was used for measuring abrasion resistance of the fabric. 38 mm diameter standard cutter was used for cutting the sample. Rubbing cycles noted down at which the fabrics sample torn out.

2.2.7 Pilling Resistance

Pilling resistance of test samples were determined according to ASTM standards (D4970-99) on Martindale abrasion and pilling tester was used for measuring the pilling of the fabric. For cutting the sample, standard template was used. After 1000 rubbing cycle pills/inches measured and grading of the samples carried out from the standard photographs.

2.2.8 Air Permeability

Air permeability test is carries out as per ASTM D373 standard. This test method covers the measurement of the air permeability i.e. the rate of air flow passing perpendicularly through a known area under a prescribed air pressure differential between the two surfaces of a material of textile fabrics. It is applicable to most fabrics including woven fabrics, air bag fabrics, blankets, napped fabrics, knitted fabrics, layered fabrics, and pile fabrics. Air permeability test was performed on TESTEX TF 164 An air permeability tester.

The air permeability is expressed by the following relationship:

$$\text{Air permeability} = \frac{V}{A.T.(\Delta p)}\ \text{cm}^3/\text{cm}^2\text{s}$$

Where V is the capacity of the flowing medium, A is the area through which the medium is flowing, T is the time of flow and Δρ is the drop in pressure of the medium.

2.2.9 Water Vapor Permeability

Water vapor permeability of fabric was calculated by ASTM E96 cup method. In this method the specimen is sealed over the open mouth of a dish containing water and placed in the standard testing atmosphere. After a period of time to establish equilibrium, successive weightings of the dish are made and the rate of water vapor transfer through the specimen is calculated.

2.2.10 Total Absorbency

Total absorbency, which measures the water holding capacity of the fabrics, was determined by using ISO 20158 test method. A sample of size 20 cm x 20 cm was dipped in the solution for five minutes and then hung vertically to allow any extra water to drop down for a five minutes period. It was then weighted and the percentage gain weight of the fabric sample was taken as the total absorbency of the fabric.

2.2.11 Vertical Wicking

The vertical wicking test of the fabric was carried out according to TAPCC standard. The conditioned specimen of 20cm X 2.5cm was cut both along the direction wale and course. Setup was installed which had a ring holder were the fabric was hanged vertically. A beaker having color solution of 2gpl blue dye was taken for clear wicking height identification on grey fabric samples. Dye is soluble in water & no adverse effect on absorbency. Each specimen was marked with a line 3cm away from its edge along its length. The specimen was then dipped inside the solution till the mark and the wicking height was noted down after an interval of 1 min.

3. Results & Discussion

Properties of yarn samples made from blends of cotton and Seacell fibers have been analyzed. Table 1 shows values of unevenness, total imperfections, hairiness, tenacity, elongation and coefficient of friction of yarns made from 100% Seacell, 100% cotton and their blends.

It is clear from Table 1 that yarn made from 100% Seacell fiber show higher yarn tenacity, elongation & lower unevenness and imperfections values as compared to 100% cotton yarn. This may be due to uniform length of seacell fiber. Yarns made from 100% cotton and its blends with Seacell fiber, show lower value of tensile strength and elongation while higher values of unevenness and imperfections. Coefficient of friction of seacell yarn is greater than cotton yarn due to their surface properties but over all COF is less than 0.20 which is not objectionable for any kind of yarn. Higher content of Seacell fiber results in improvement of yarn properties. In general, yarns made from Seacell fiber & its blends exhibit properties better than cotton yarn. After analyzing the all properties it may aspects that 100% seacell & blended yarn may perform better during knitting.

The fabric properties- bursting strength, abrasion resistance, pilling resistance, air permeability, water vapor permeability,

Table 1 - Properties of yarns made from 100% seacell, 100% cotton and their blends

Count	Blend Type	Blend Ratio	Un-evenness (U %)	Total imperfection (IPI)	Hairiness (H)	Breaking Elongation (%)	Tenacity (gm/tex)	Coefficient of Frictions
20^S	Cotton	100	11.69	218	6.52	4.29	15.12	0.11
	Seacell	100	9.75	78	6.65	8.59	20.85	0.15
	C/SC	50/50	11.07	133	7.81	5.48	18.54	0.17
	C/SC	70/30	11.13	157	8.02	4.61	17.51	0.17
30^S	Cotton	100	15.07	530	5.54	3.83	12.65	0.13
	Seacell	100	11.2	95	5.35	7.4	17.97	0.19
	C/SC	50/50	12.21	298	6.14	5.22	16.89	0.18
	C/SC	70/30	12.61	462	6.35	5.03	19.19	0.18

Table 2 - Influence of count, blend & fiber type of blended fabrics

Count	Fiber	Blend Ratio	Bursting Strength	Abrasion Resistance	Pilling Rate	Air-Permeability	Water vapor Permeability	Total Absorbency	Wicking (Wale Wise)	Wicking (Course wise)	GSM
20S	Cotton	100	7.06	9481	3.5	88.67	1079	66.77	2	2	148
	SeaCell	100	9.14	13728	5	208.41	1107	65.66	6.3	6.5	162
	C/SC	50/50	8.79	11491	3	97.87	982	68.28	4.6	4.7	148
	C/SC	70/30	8.18	9982	3	90.96	970	68.61	3.4	3.5	160
30S	Cotton	100	5.67	5971	3	177.21	1191	69.04	2	2	102
	SeaCell	100	6.68	7605	4.5	401.07	1194	67.48	5.5	5.7	103
	C/SC	50/50	5.92	7415	3.5	161.62	1057	68.41	4.4	4.6	124
	C/SC	70/30	5.21	6659	3.5	128.12	1004	68.92	2.5	2.8	114

total absorbency and wicking have been analyzed. The results have been shown in Table in 2.

3.1 Bursting Strength

The effect of blend percentage and fineness on bursting strength of the fabrics has been shown in Table 2. The values have also been shown in Figure 2. It is observed from Figure 2 that bursting strength of 100% seacell fabric is maximum among all fabrics studied in this study. As the percentage of cotton fiber is increasing in the blend, bursting strength reduces. This is due to the fact that bursting strength of the fabric is dependent on fiber properties- tenacity and elongation. We have already observed that Seacell fiber and yarn have higher tenacity as compared to cotton and hence bursting strength of Seacell fabric is highest.

It is further observed that fabric made from coarser yarn exhibits more bursting strength. This may be due to more coherence among fibers in case of coarse yarns.

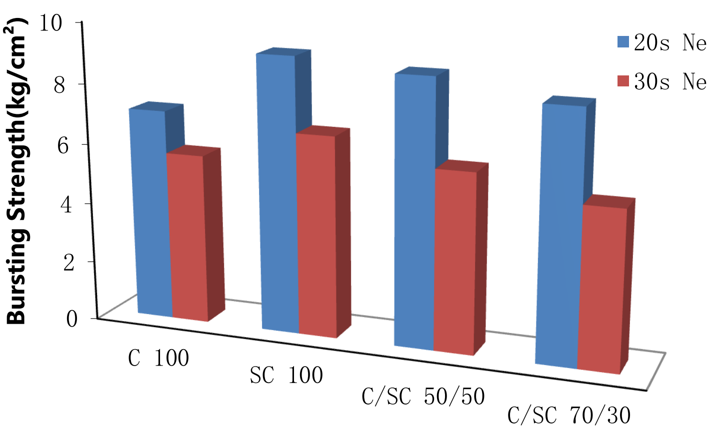

Figure 2 - Variation in fabrics bursting strength (kg/cm²) with count, blend &fiber type

3.2 Abrasion Resistance

The influence of count, blend and fiber type on the abrasion resistance of the fabric has been shown in Table 2. It is clear from Figure 3 that 100 % seacell and its blended fabrics shows higher abrasion resistance as compared to cotton fabrics. This is due to higher tensile strength of seacell yarn. As the cotton proportion increases in blends rubbing cycles reduces which implies reduction in abrasion resistance. Abrasion resistance of fabric is directly related with the tensile strength of yarns. Fabrics which are made from higher tensile strength yarns resist more during abrasion.

It is also observed that coarser counts fabrics have high values of rubbing cycles at which the fabric tear during rubbing. Coarser count fabrics have high GSM values and thickness so they resist longer to abrasion in comparison to finer counts. Another factor is that coarser yarns fabrics have high strength compare to finer count due to the yarn properties.

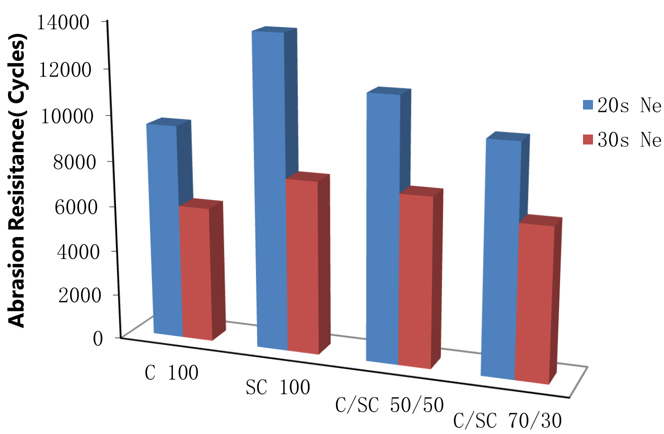

Figure 3 - Variation in fabrics abrasion resistance (cycles) with count, blend &fiber type

3.3 Pilling

The pilling grading of the fabrics has been shown in Table 2. As shown in Figure 4 fabrics made from 100 % Seacell fiber have higher pilling rating as compared to cotton and its blended fabrics. Pilling tendency is affected by type of the fiber and twist. As the twist is same for all the samples, hence pilling is affected by fiber properties in this study. 100% cotton fabrics and cotton blended fabrics have low pilling rating as compared to 100 % seacell fabrics. Seacell fibers are long staple fiber and have uniform length in comparison to cotton fiber. Cotton fiber has short fibers which have more tendencies to form pills. Seacell fiber doesn't contain short fibers which helps to maintain smooth surface and minimizes the formation of pilling during wear and washing.

It is further observed that the finer count fabric have high higher pilling rating as compared to coarse count fabrics, which implies more pilling tendency for coarser yarn. This is due to the more hairiness in case of coarser yarn as already observed in Table 1. Coarser yarns have high hairiness, so coarser count fabrics have more protruding fiber ends on the fabric surface. These fiber ends get entangled and lead to the formation of pills on fabric surface.

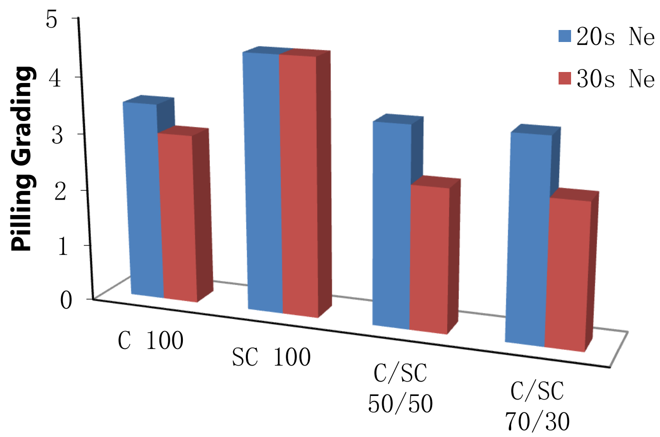

Figure 4 - Variation in fabrics pilling grading with count, blend &fiber type

3.4 Air Permeability

The influence of count, blend & fiber type on the air permeability of the fabric has been shown in Table 2. As shown in Figure 5 100% seacell fabrics show higher air permeability values than 100% cotton fabrics. This is due to the surface properties of seacell fiber. It has smooth circular cross section with smooth longitudinal surface [5], which allows more air to pass from the fabric. So as the cotton proportion increases in blends air permeability reduces.

The air permeability of the fine count fabrics is high in all blends as compared to coarse count fabric. Fine count fabrics have lower GSM and thickness in comparison to coarse count, hence it allows more air to pass from it.

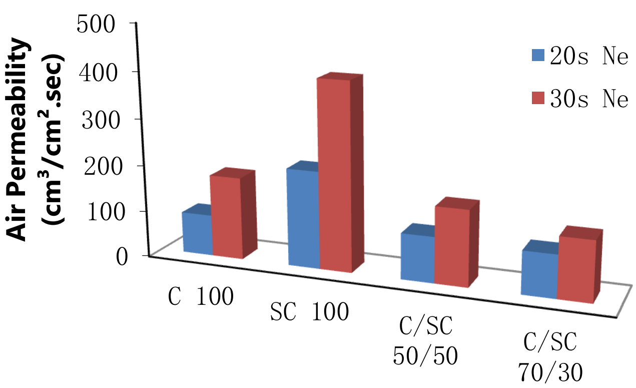

Figure 5 - Variation in fabrics air permeability with count, blend &fiber type

3.5 Water Vapor Permeability

The influence of count, blend and fiber type on water vapor permeability of the fabrics has been shown in Table 2. Water vapor transmission rate is directly affected by fiber surface and fiber cross-section. As shown in Figure 6, 100% seacell fabric exhibits slightly higher values of water vapor transmission rate. This may be due to smoother surface of Seacell fiber in comparison to cotton fiber.

It is further observed that water vapor permeability of the fabrics is higher in finer count fabrics. Finer count fabrics have lower GSM which allow more water vapor to pass from it, in comparison to coarse count. So fine count fabrics are more breathable.

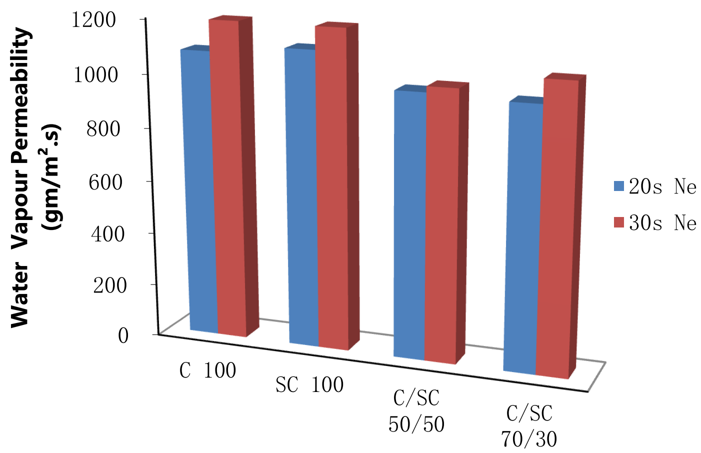

Figure 6 - Variation in fabrics water vapor permeability% with count, blend &fiber type

3.6 Total Absorbency

The results of total absorbency of the fabrics have been shown in Table 2. As shown in Figure 7, 100% cotton and its blended fabric have slightly higher absorbency rate. As the Seacell fiber content decreases total absorbency increases. Both fibers are cellulosic in nature so both fabrics absorb water in similar way.

The absorbency of the fabrics is slightly more in finer count. As count became coarser, fabric becomes thick which results in lesser space or gap between yarns and lesser space for water to penetrate and spread through the material.

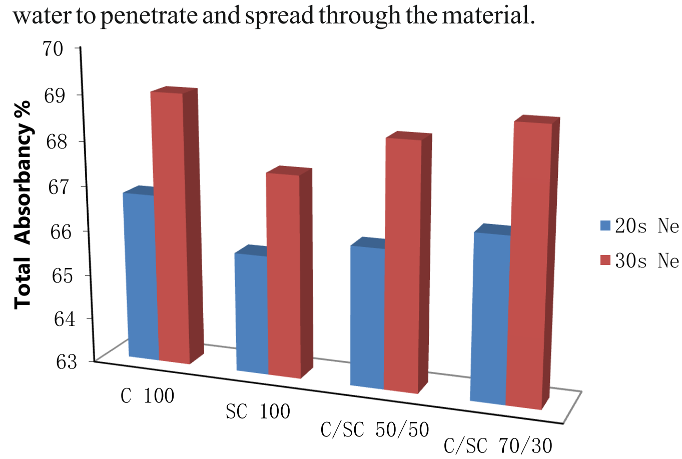

Figure 7 - Variation in fabrics absorbency % with count, blend &fiber type

3.7 Vertical Wicking (Wale wise & Course wise)

The results of vertical wicking behavior of cotton and Seacell blended fabrics in wale wise and course wise directions have been shown in Table 2, Figure 8 (wale wise) and Figure 9 (course wise). As shown in Figure 8, 9, 100% seacell and blended fabrics have very high vertical wicking in comparison to 100% cotton fabrics. As the cotton % increase vertical wicking decreases in both directions (wale wise & course wise). This is due to surface properties of fiber. Seacell fiber have smooth surface with circular cross section and more homogenous pore distribution which promotes better wicking compare to cotton and blended fabrics [5].

Coarse count fabrics have high wicking rate as compared to fine count fabrics. Coarse count fabrics have thicker yarn which having greater diameter compared to fine count which creates more capillary channels, resulting in faster movement of moisture through the fabric.

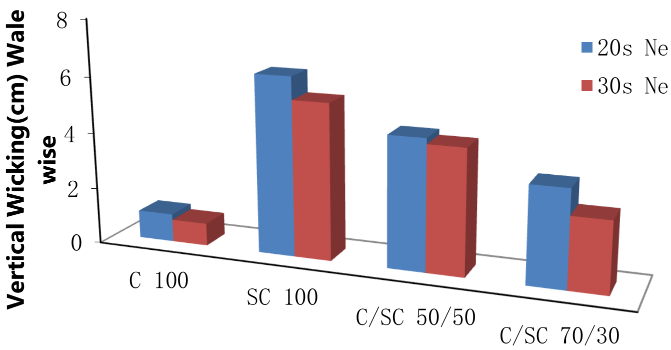

Figure 8 - Variation in fabrics vertical wicking (wale wise) with count, blend &fiber type

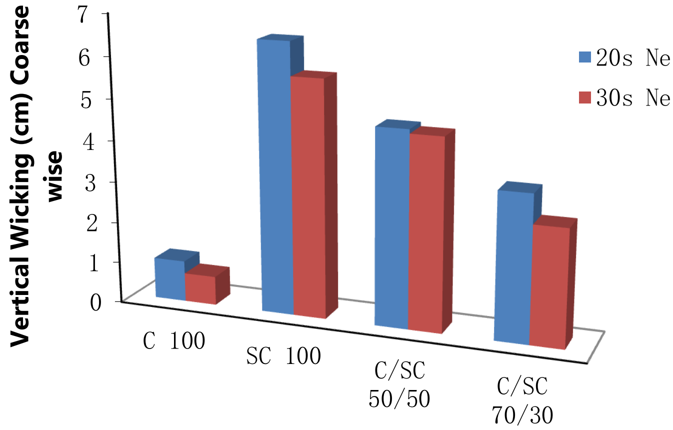

Figure 9 - Variation in fabrics vertical wicking (course wise) with count, blend &fiber type

4. Conclusion

After analysis it is concluded that fabrics made from Seacell yarns have better performance characteristics compared to regular cotton and blended cotton/Seacell fabrics in various critical parameters. More specifically, the fact that 100% Seacell fabric has superior bursting strength, which is improved by using coarser yarns, and demonstrates higher abrasion resistance compared to their cotton variants is evident and verified. Moreover, the pilling ability is decreased significantly due to the longer fiber length of Seacell compared to the shorter fiber length and higher pilling properties of the cotton variant. On the basis of comfort and moisture management properties, the Seacell fabric has been found to perform better compared to cotton with higher values for air permeability; improved water vapor transmission rate due to the smoother surface of the Seacell fiber compared to cotton, and enhanced vertical wicking properties.

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Eco-friendly Textile Coloration and Garment Development using Coffee Waste-Derived Colorants

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Abstract :

Background: *Growing environmental pressures on the textile and fashion sectors have intensified the search for renewable, nontoxic coloration alternatives. Spent coffee grounds (SCG), generated in large volumes as post-consumer waste, contain pigment rich compounds suitable for low impact dyeing. This study evaluates the feasibility of repurposing SCG as a sustainable natural colorant for textiles and assesses its suitability for material development and garment construction within circular design frameworks.*

Methods: *SCGs from local cafés were dried, powdered, and extracted to prepare dye liquors of two strengths. Four cellulosic fabrics Single Jersey, Double Jersey, Linen and Cotton Crimp were dyed using the exhaustion method with alum as the eco-safe mordant. Dyed samples were evaluated for colour strength and wash, rub, perspiration and light fastness. Guar gum paste was then used for natural printing on selected fabrics, followed by prototype garment development. User feedback from participants aged 18-35 provided insights into aesthetic appeal, comfort and acceptance.*

Results: *Higher concentration extracts produced deeper browns, while alum markedly enhanced colour strength and fastness. Wash fastness reached 3-4 and rub fastness 4-5, with printed samples showing clear stable motifs. Cotton Crimp and Linen performed best for garment use and consumer ratings above 4.0 indicated strong acceptance of both aesthetics and sustainability.*

Conclusion: *The findings show that SCG can be used as a stable natural dye for cellulosic fabrics without affecting comfort or performance and its successful use in prototype garments demonstrates practical viability for sustainable circular textile applications.*

Keywords: *circular fashion, eco-textile innovation, natural colorants, natural dyeing, spent coffee grounds, sustainable materials*

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1. Introduction

The global environmental crisis continues to escalate due to rapid industrial growth, excessive consumption, and unsustainable production systems, with industrial activity contributing over one-fifth of global water pollution and significant greenhouse gas emissions [1, 2]. The textile and apparel sector is among the most resource intensive industries, responsible for 8-10% of global carbon emissions, exceeding international aviation and shipping combined [3]. Dyeing and finishing alone generate nearly 20% of industrial wastewater because of synthetic dyes and chemicals while the sector produces about 92 million tons of solid waste annually projected to reach 134 million tons by 2030 [4, 5]. Yet, only around 14.7% of discarded textiles are recycled, with most ending up in landfills or incinerators [6]. These challenges highlight the urgent need for sustainable materials, cleaner coloration processes and circular practices. Among all impacts dyeing is consistently identified as one of the most harmful due to toxic effluents and long-term environmental accumulation. This has shifted research interest toward renewable biodegradable colorants particularly those derived from agricultural waste. Coffee is the second most traded global commodity generating over 10 million tons of waste each year including spent grounds, husks and silver skin which can become pollutants when unmanaged [7, 8 & 9]. However, these residues contain polyphenols, chlorogenic acids, melanoidins and lignin-based pigments with natural coloration potential [10]. Thus, spent coffee grounds present a circular low impact alternative for sustainable dye development. Using SCG diverts waste reduces reliance on synthetic dyes and supports Sustainable Development Goal 12 by promoting resource efficiency and responsible production. Accordingly, this study examines the feasibility of SCG as a natural dye for textile applications focusing on dyeing and surface printing of 100% cotton fabrics. The research integrates laboratory testing, design experimentation and user perception to evaluate SCG-based colouration for performance, aesthetics and sustainability offering practical insights for low-impact transformation in the textile and fashion industries.

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2. Literature Review

The valorisation of agro industrial residues has gained momentum for reducing environmental impact and creating new material streams with spent coffee grounds (SCGs) emerging as a promising bio resource. Coffee by products pulp, husk, silver skin and SCGs contain lignocellulosic matter, melanoidins, chlorogenic acids, tannins and polyphenols suitable for applications such as bioenergy, adsorbents and natural pigments [9, 10]. Reviews highlight their potential for recovering bio-oils and functional biomolecules for non-food sectors [11]. SCG extracts yield warm brown hues due to phenolics and melanoidins and studies show their successful application on cotton, wool and silk with added functional benefits [12, 13]. Dye performance depends on extraction conditions, fibre type, and mordanting with cotton requiring pre-treatments or bio low toxicity mordants to enhance uptake and fastness [4, 12 & 14]. Cationization combined with eco-friendly mordants significantly improves K/S values and durability [15]. Research shows SCG dyes produce better colour yield with optimized extraction parameters and fibre specific treatments [15]. Screen printing using thickened SCG extracts has also demonstrated good definition and stable earthy motifs suitable for sustainable fashion [16]. Broader analysis show that while coffee to textile pathways offer environmental advantages, scale and process optimization remain challenges [17]. Market studies indicate increasing consumer interest in naturally dyed apparel, though reproducibility and cost remain key adoption barriers [5, 9, 16 & 18].

2.1 Research Gap

Existing studies show rising interest in natural dyes, but large-scale textile use of coffee waste remains limited. Most SCG research focuses on biofuel, composting, adsorption or antioxidant extraction rather than dyeing [16, 19]. Work on coffee pigments is mostly small scale with limited optimization, fastness testing and sustainability evaluation, and cotton's low affinity for polyphenolic compounds remains underexplored [15, 20]. Research also rarely covers printing designs with coffee-based colorants while consumer acceptance and environmental assessments (LCA/TEA) are largely missing [9, 17, 18 & 21].

3. Objective of the Study

1 To develop an eco-friendly dye extraction process from SCGs.

2 To assess dyeing performance on cotton and linen using exhaustion and printing methods.

3 To examine the effect of mordants on colour yield and fastness.

4 To evaluate washing and rubbing fastness of dyed fabrics.

5 To analyze consumer acceptance of SCG-dyed garments for their aesthetic and eco-friendly appeal.

4. Materials and Methods

4.1 Collection and Preparation of Spent Coffee Grounds (SCGs)

Spent coffee grounds collected from five cafés in Dehradun were dried for three days, finely powdered, and used for aqueous dye extraction ensuring uniformity and supporting circular use of local organic waste.

4.2 Fabric Selection

Four greige' cellulosic fabrics namely Single Jersey, Double Jersey, Linen and Cotton Crimp were selected to compare how different constructions respond to SCG dyeing in terms of shade variation and surface behaviour.

4.3 Dye Extraction

Two SCG water ratios (Table 2) were extracted at 90°C for one hour with continuous stirring, then cooled and filtered to yield smooth dye liquors. Controlled heating enhanced melanoidin and polyphenol release and the optimized parameters were used for all subsequent dyeing [14 & 20].

4.4 Fabric Mordanting

Alum ($Al_2(SO_4)_3 \cdot 18H_2O$) was used as a safe, effective cellulose mordant, applied at a 1:40 MLR under controlled

Table 1 - Shade Intensity and Dye Uptake of Fabrics Dyed with Spent Coffee Grounds

Trial No.	SCG Weight (g)	Water (ml)	Temperature (°C)	Time (min)	Resultant Extract Colour	Extraction Notes
Trial 1 (High Concentration)	250	200	90	60	Dark brown	High SCG-to-water ratio for concentrated extraction
Trial 2 (Low Concentration)	120	250	90	60	Light brown	Lower SCG concentration for comparative study

Table 2: Three experimental levels of selected key independent input variables

Fabric Type	Mordant Type	Mordant Concentration (g/l)	Material-to-Liquor Ratio (MLR)	Temperature (°C)	Time (min)	Remarks
Sample 1	Alum	5	1:40	80	30	Standard mordanting
Sample 2	Alum	5	1:40	80	30	Standard mordanting
Sample 3	Alum	5	1:40	80	30	Standard mordanting
Sample 4	Alum	5	1:40	80	30	Standard mordanting

heating following ISO 105-Z01:1993, with unmordanted samples retained as controls (Table 1).

4.5 Dyeing

SCG dye liquors were applied to alum-mordanted and control fabrics using a 1:40 material-to-liquor ratio. Samples were heated to 90 °C for 45 minutes with gentle stirring, then cooled, rinsed and shade-dried. A 2% vinegar bath improved solubility and uptake. All dyeing was performed under controlled conditions, following ISO 105-C06 and AATCC 61 for consistency and reproducibility.

4.6 Printing Process

A guar-gum thickened SCG paste was prepared (8-10 g guar gum, 70 ml extract, 20-25 ml water, 1-2% acetic acid) and applied using stencils, mug base stamps, brushes and screen printing, prints were air dried and heat-set at 90-100 °C for 3-5 minutes with full formulation details in Table 3.

4.7 Washing

Post dye washing was performed using 2 g/l non-ionic detergent at 40 °C for 15 minutes, followed by rinsing and shade drying to remove unfixed colour. The procedure followed ISO 105-C06:2010 with elements of AATCC laundering standards to ensure reliable evaluation of dye fixation and wash fastness in SCG-dyed fabrics [15 -& 22].

4.8 Colour Measurement

Colour measurements were performed using a Discolour 650 spectrophotometer under D65 illumination with a 10° observer, following ISO 7724-1/2/3 (1984) and ISO 11664-4:2019. Reflectance was recorded from 400-700 nm and colour strength (K/S) was calculated using the Kubelka–Munk equation, $K/S = (1-R)2/(2R)$ where R is the reflectance at maximum absorption. Three readings per sample were averaged to compare shade depth across fabric types and dye concentrations. This method ensured objective evaluation of colour uniformity and was appropriate for assessing natural dye performance as noted in [23].

4.9 Colour Fastness Evaluation

The dyed fabrics were tested for washing, rubbing, light and perspiration fastness using relevant ISO and AATCC standards under controlled conditions, with results summarised in Table 4.

4.10 Fabric Drape Evaluation

Drape behaviour of four fabrics Cotton Single Jersey (120 GSM), Cotton Double Jersey (150 GSM), 100% Linen (150 GSM) and Cotton Crimp (150 GSM) was measured using a Cusick Drape Tester following ISO 9073-9:2008. Pre conditioned samples were draped on the test disc and shadow areas were used to calculate the Drape Coefficient. Each fabric was tested in triplicate including untreated and alum-mordanted SCG-dyed samples under controlled laboratory conditions to ensure repeatability.

4.11 Motif Development and Range Planning

Before producing the final dyed and printed samples, design ideation was done to develop motifs for surface printing. After this, Design Process was carried out to develop a range of fashion garments inspired from the chosen theme of coffee. This step ensured that the developed designs complemented the study's focus on sustainability and the use of natural dyes.

4.12 Survey

A consumer survey in Dehradun (N = 45, age 18-35) rated SCG-dyed garments highly, with all attributes scoring above 4.0 on the Likert scale. Younger users liked the novelty, mid-age groups valued comfort, and older participants appreciated the natural aesthetic supporting earlier findings on strong consumer interest in sustainable apparel [3, 24 & 25].

Table 3 – Formulation and Preparation of Coffee-Based Natural Printing Paste

Component	Quantity	Function	Key Step
SCG Extract	70 ml per 100 ml paste	Natural dye base	Use freshly prepared extract as colourant.
Guar Gum	8-10 g	Natural thickener for viscosity & definition	Dissolve in warm water (60-70 °C).
Distilled Water	20-25 ml (adjustable)	Consistency adjustment	Add gradually to obtain smooth paste.
Acetic Acid (1-2%)	2 ml	pH stabilizer; improves dye fibre bonding	Add after gum fully swells.

Table 4 - Standard test methods used for colour fastness evaluation

Test Type	Standard	Conditions / Equipment	Assessment
Washing	ISO 105-C10:2006	Launder-Ometer; 5 g/l detergent, 50 °C, 30 min	Grey Scale (colour change & staining)
Rubbing	ISO 105-X12:2001	Crockmeter (dry & wet)	Grey Scale (staining)
Light	ISO 105-B02:2014	Xenon Arc exposure, 20 h	Blue Wool Scale
Perspiration	ISO 105-E04:2013	Acidic/alkaline solution, 37 °C, 4 h	Grey Scale (colour change & staining)

5. Results and Discussion

5.1 Influence of Fabric Structure and Dye Concentration on Colour Yield

Table 5 - Shade Intensity and Dye Uptake of Fabrics Using SCG Dye

Sample	High Conc. (250 g SCG)	High Conc. (250 g SCG)	Low Conc. (120 g SCG)	Low Conc. (120 g SCG)	Shade Observation
1	85%		65%		Dark brown lighter warm tone
2	75%		55%		Moderate brown light beige
3	80%		60%		Medium-dark brown golden tone
4	70%		50%		Subdued brown pale beige

SCG extracts produced stable earthy tones across all fabrics with Trial 1 yielding deeper shades and Trial 2 giving lighter cleaner colours, Trial 2 was selected for design work due to better motif clarity, uniformity and lower resource use aligning with earlier findings that coffee-based dyes offer reliable colour development and acceptable fastness for sustainable textile applications [26].

5.2 Effect of Alum Mordant on Colour Strength (K/S Values)

Table 6 - Effect of Alum Mordant on Colour Strength (K/S Value) of SCG-Dyed Fabrics

Fabric Type	K/S (Unmord-anted)	K/S (Alum Mordanted)	% Increase in Colour Strength
Sample-1	4.10	7.05	+71.9%
Sample-2	3.85	6.45	+67.5%
Sample-3	3.60	5.85	+62.5%
Sample-4	3.20	4.75	+48.4%

Table 6 shows that both fabric structure and alum significantly affect colour depth. Double Jersey achieved the highest K/S (7.05) due to its compact rib-knit structure [27]. Single Jersey showed moderately high uptake because of its open-loop geometry [28]. Cotton Crimp displayed mid-level absorption linked to increased capillarity [15 & 29]. Linen recorded the lowest K/S (4.75) owing to limited fibre swelling typical of flax weaves [16]. Across all fabrics, 5% alum improved colour strength by forming stable coordination bonds with cellulose and coffee-derived compounds, enhancing fastness [30].

5.3 Wash Fastness

Table 7 - Washing Fastness of SCG-Dyed Fabrics

Fabric Type	Alum Mordanted	Unmord-anted Control	Observation
Sample-1	4-5	3	Highest fixation due to open-knit structure
Sample-2	4	3	Dense structure limited penetration
Sample-3	4-5	3	Good fixation; moderate diffusion
Sample-4	4	3	Slight dye loss due to surface crimping

Table 7 shows that alum-treated fabrics achieved the highest wash fastness (Grade 4-5) outperforming untreated samples (Grade 3) due to stronger aluminum dye cellulose bonding [15 & 31].

5.4 Rub Fastness

Table 8 - Rubbing (Crocking) Fastness of SCG-Dyed Fabrics

Fabric Type	Dry (Alum)	Wet (Alum)	Control (Dry / Wet)	Observation
Sample -1	4-5	4	3 / 2–3	Excellent surface fixation
Sample -2	4	3	2–3 / 2	Limited internal fixation
Sample -3	4	3-4	3 / 2–3	Slight fibre stiffness caused minor crocking
Sample -4	4	3	2 / 2	Crimped surface increased abrasion loss

Table 8 shows that alum-treated fabrics performed well under frictional stress with dry rubbing ratings of 4-5 and slightly lower wet ratings of 3-4 due to fibre swelling and minor surface pigment transfer. Cotton Jersey showed the highest resistance followed by Linen, while Double Gauge and Cotton Crimp exhibited slightly higher colour transfer because of their compact or textured surfaces. These results align with reports that aluminium based mordants improve rubbing fastness by creating stronger dye fibre bonds [31].

5.5 Light Fastness

Table 9 - Light Fastness of SCG-Dyed Fabrics

Fabric Type	Alum Mord-anted	Unmord-anted Control	Observation
Sample-1	5	3	Excellent photo-stability
Sample-2	4-5	3	Slight surface fading
Sample-3	5	3	Strong Al³?–polyphenol stability
Sample-4	4-5	3	Good shade retention; minimal fading

Table 9 shows that alum-mordanted fabrics achieved light fastness ratings of 4-5, while untreated samples scored Grade 3, indicating noticeably greater fading. The improved stability results from aluminum ions forming durable bonds with the coloring compounds, reducing UV induced degradation. Cotton Jersey and Linen retained their shade most effectively, whereas slight fading in Double Gauge and Cotton Crimp was linked to tighter or irregular surfaces. These findings align with reports that alum enhances light fastness by strengthening dye fibre interactions confirming the suitability of SCG dyes for long-lasting sustainable textiles [31].

5.6 Colour Fastness to Perspiration

Table 10 – Colour Fastness to Perspiration

Table 10 shows that alum-treated SCG-dyed fabrics achieved perspiration fastness ratings of 4-5 in both acidic and alkaline conditions, indicating strong resistance to shade change and staining. This stability results from durable coordination bonds formed between aluminum ions and the dye's polyphenolic components. Slightly lower ratings in Samples 2 and 4 were linked to denser or textured structures that limited uniform mordant penetration and increased surface friction. These findings align with reports that aluminum treatment enhances perspiration fastness through stronger dye fibre bonding and that fabric density and surface characteristics influence colour retention [11 & 27].

5.7 Fabric Drape Evaluation

Drape performance (Table 7) showed only a slight 6-11% increase in Drape Coefficient after SCG alum dyeing indicating minor stiffening from dye mordant deposition while remaining within the typical industry range (45-55%). Single Jersey recorded the lowest DC (44.6%) due to its soft, elastic structure, whereas Linen showed the highest (55.8%) because of its firm plain weave. Double Gauge and Cotton Crimp displayed balanced drape suitable for semi-structured garments. These observations align with earlier reports that natural dyeing slightly increases stiffness without affecting wearability [4, 15 & 16].

Table 10 – Colour Fastness to Perspiration

Sample No.	Acidic: Colour Change	Acidic: Staining (Cotton/Wool)	Alkaline: Colour Change	Alkaline: Staining (Cotton/Wool)	Observation
Sample 1	4-5	4-5 / 4-5	4-5	4-5 / 4-5	Excellent fixation; no visible staining.
Sample 2	4	4 / 4	4	4 / 4	Slightly reduced fastness due to dense knit.
Sample 3	4-5	4-5 / 4-5	4-5	4-5 / 4-5	Very good stability; smooth surface aids resistance.
Sample 4	4	4 / 4	4	4 / 4	Minor surface transfer due to fabric texture.

Table 11 - Drape Coefficient of SCG-Dyed Fabrics as per Fabric Construction and Physical Properties

Fabric Sample	Structure & Key Features	GSM	Thickness (mm)	Hand Feel	Drape Coefficient (Before ? After)	% Change	Industrial Insight
Sample 1	Cotton, Single knit, lightweight, high stretch	120	0.65	Soft, elastic, very flexible	41.8 ? 44.6	+6.7%	Minor stiffening; still excellent drape. Ideal for soft apparel.
Sample 2	Cotton 1×1 Rib, compact, high density	150	0.85	Thick, semi-elastic, firm	47.2 ? 52.4	+11.0%	Increased DC due to tight structure; suitable for bulky outerwear.
Sample 3	Linen, Plain weave, medium weight, low stretch	150	0.72	Crisp, firm	50.5 ? 55.8	+10.5%	More rigid after dyeing/mordanting; good for shirts, tunics, trousers.
Sample 4	Cotton, Crimp weave, textured yarns	150	0.70	Soft, moderately flexible	45.0 ? 48.3	+7.3%	Crimp retained fluidity; suitable for dresses, capes.

5.8 Printing Processes

Figure 1: Printed Samples

Table 12 - Printing Testing Report of SCG Based Prints on Selected Fabrics

Parameter	Method	Cotton Crimp	100% Linen	Key Remarks
Visual Appearance	Visual	Good	Excellent	Sharper motifs on Linen (Fig. 1).
Print Uniformity	Grade 1-5	4	5	Linen more uniform due to smooth surface.
Colour Depth	Visual + ΔE	ΔE = 5.8	ΔE = 4.3	Deeper shade on Linen.
Dry Rubbing	ISO 105-X12	4-5	5	Good resistance on both.
Wet Rubbing	ISO 105-X12	4	4-5	Minor transfer on Cotton Crimp.
Washing Fastness	ISO 105-C06	4	4-5	Minimal fading at 40 °C.
Light Fastness	ISO 105-B02	3-4	4	Acceptable sunlight performance.
Hand Feel	Sensory	Soft	Very Soft	No stiffness after heat-set.
Eco-Aesthetic	Sensory	Rustic	Refined	Both showed desirable eco-look.

Following printing, Cotton Crimp and 100% Linen were evaluated for motif durability, surface quality and handle changes with comparative results summarised in Table 12.

5.9 Prototype Garments and Final Collection Development

Prototype garments were developed using a minimal-waste, eco-focused design process, with Cotton Crimp and Linen selected for their stable structure and strong response to SCG dyeing/printing. CAD-guided construction produced clean silhouettes and motifs, demonstrating the practical integration of coffee-waste dyes into contemporary apparel.

Figure 2: CAD Illustration Front & Back

Figure 3: Final Range

5.10 Consumer Perception Study

A consumer survey with 30 participants (18-25, 26-30, 31-35 years) rated the SCG-dyed garments on colour, design clarity, comfort and purchase intent using a 5-point scale, with mean scores (Table 13) indicating strong acceptance across all age groups.

Table 13 - Consumer Perception Analysis of SCG-Dyed Garments Across Different Age Groups

Age Group (Years)	No. of Respon-dents	Colour Appeal (1-5)	Design Clarity (1-5)	Comfort (1-5)	Purchase Intent (1-5)	Overall Mean Score
18-25	10	4.2	4.0	3.9	4.1	4.05
26-30	10	4.3	4.4	4.5	4.2	4.35
30-35	10	4.1	4.2	4.3	4.4	4.25

SCG dyes produced stable earthy shades across all fabrics, with colour depth governed by fabric density and extract concentration. Alum at 5% markedly improved K/S values and ensured strong wash, rub, light, and perspiration fastness (4–5). Drape increased only slightly and all fabrics remained within acceptable performance limits. Cotton Crimp and Linen performed best for printing and garment development, retaining clear motifs and soft handle. Consumer feedback (mean > 4.0) confirmed strong acceptance and market potential, highlighting SCG dyeing as an effective low-impact coloration alternative.

6. Conclusion

Spent coffee grounds provided an effective natural dye for cellulosic fabrics, producing stable earthy shades with acceptable fastness [12 & 27]. Alum was the most efficient, low-impact mordant, significantly enhancing colour strength and durability [15]. Consumer feedback showed strong acceptance of SCG dyed garments, especially among sustainability-oriented users, reflecting growing demand for eco-friendly apparel [18]. Overall, SCG-based dyeing offers a practical, adaptable and resource efficient alternative to synthetic dyes, with scope for broader application and future scale-up aligned with UN SDG 12.

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Comparative Study of Silk-Banana-Bamboo Fiber Blends for Sustainable Applications of the Traditional Saree

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Abstract:

The integration of sustainable fibres into traditional textiles offers potential to enhance both performance and cultural aesthetics. This study evaluates silk fabrics weft-blended with banana and bamboo fibres to determine their suitability for sustainable saree applications. Two fabric samples were developed and subjected to standardized tests assessing tensile strength, tearing strength, elongation, abrasion resistance, bursting strength, air permeability, and drapeability, with natural dyes applied to improve aesthetic qualities. The results showed that the silk–banana fabric demonstrated superior mechanical performance, including higher tensile and tearing strength, greater abrasion resistance up to 4000 cycles, and enhanced elongation and bursting strength due to its lignin-rich fibre structure. In contrast, the silk–bamboo fabric exhibited significantly higher air permeability resulting from its smoother fibre cross-section and open yarn matrix, making it more suitable for hot climatic conditions, though its lower durability and reduced elongation limited its potential for frequent handling. Drapeability analysis further indicated that the banana-blended fabric had a lower drape coefficient, producing a more elegant fall desirable in saree design. Overall, the study concludes that silk fabric blended with banana fibres provides a more balanced combination of strength, flexibility, comfort, and drape, making it a superior choice for sustainable and high-performance saree development.

Keywords: *Banana fiber, bamboo fiber, comfort and drape, ikat saree, silk filament*

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1. Introduction

The integration of sustainable fibers into traditional textiles is gaining momentum in response to increasing environmental concerns, resource scarcity, and demand for eco-conscious fashion. Sarees, as a significant representation of India's textile legacy, present a unique opportunity to blend sustainability with cultural expression. Silk filament yarn remains the material of choice for premium warp applications due to its high tensile strength, exceptional luster, smooth hand feel, and superior draping characteristics [1]. It also offers excellent dimensional stability and fabric resilience, which are essential in maintaining the structural performance of sarees during wear and wash cycles. However, growing environmental concerns necessitate exploring eco-friendly alternatives for the weft that maintain or enhance the quality of conventional blends.

Among the emerging sustainable fibers, bamboo and banana fibers have shown immense promise. Bamboo yarn is gaining attention due to its soft handle, breathability, biodegradability, and intrinsic antimicrobial properties attributed to the presence of bamboo making it ideal for next-to-skin applications [2]. It also possesses good moisture management capacity and UV resistance, making it particularly suitable for garments worn in tropical climates like India [3]. Banana fibers, on the other hand, are obtained from agricultural waste, making their extraction environmentally low-impact. These fibers exhibit high tenacity, low elongation, and excellent thermal resistance [4], with strength values comparable to jute but with better flexibility and luster attributes that align well with the aesthetics of saree fabrics [5]. However, research on woven fabrics using banana and bamboo fibers, especially in combination with silk filament yarns, is still limited, particularly with respect to performance parameters relevant to saree applications. Recent studies have attempted to evaluate various mechanical and comfort-related properties of natural-fiber-based woven fabrics. Researchers examined the mechanical properties of silk-based woven fabrics and found that silk provides high elongation and tensile strength while retaining an elegant drape [6]. The role of continuous filament silk yarns in achieving both strength and fluidity in draped garments has been well emphasized [7]. The aesthetic advantages of blending silk filament with natural weft yarns like linen and cotton, resulting in improved tactile response, visual texture, and user-perceived quality, have also been explored [8]. Studies on various traditional drape fabrics further established that drapability and air permeability are dominant factors influencing comfort in sarees, particularly in humid climates [9].

Air permeability, a key factor determining thermal comfort, has been widely studied in eco-fabrics [10, 21]. Loosely woven silk–cotton blends have been found to exhibit higher permeability, making them ideal for summer wear [10]. The abrasion resistance of blended fabrics has also been examined, showing that natural fiber combinations can be engineered to resist pilling and fiber rupture during wear [11]. Studies on handloom fabrics revealed that blending silk

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with sturdier weft yarns significantly enhances bursting strengthen important attribute in garments subject to folding and body tension, such as sarees [12].

Further research has focused on developing new blends involving banana and bamboo fibers. Woven blends from banana–bamboo fibers demonstrated good drapeability, acceptable tensile strength, and promising moisture management properties, indicating their suitability for apparel applications [13]. Eco-sarees created using banana–cotton blends showed user acceptance comparable to traditional fabrics, along with improved biodegradability and thermal behaviour [14]. The role of surface modifications, such as alkaline and enzymatic treatments, in improving fiber matrix adhesion, strength, and dye affinity of banana fibers has also been highlighted [15]. Additionally, composite yarns made from natural fibers with core-spun and plied structures have shown enhanced yarn strength and uniformity, reducing weft breakage during weaving [16].

A comprehensive review of breathable fabrics has linked fiber morphology and yarn spacing to air permeability, softness, and comfort factors vital in traditional attire such as sarees [17]. Studies evaluating comfort indices in eco-friendly woven fabrics have shown that natural blends can outperform polyester and viscose in softness and wearer satisfaction [18]. The need to balance mechanical strength with environmental responsibility in yarn engineering has also been emphasized [19]. Furthermore, integrating sustainable and organic fibers into India's mainstream textile economy has been proposed as a pathway to preserve cultural textiles while aligning with global sustainability standards, particularly through blending traditional silk with plant-based fibers [20].

This study thus fills a key research gap by analysing and comparing the mechanical (tensile, tear, bursting strength, abrasion) and comfort-related (air permeability, drapability) performance of woven fabrics created using silk filament in the warp with bamboo and banana yarns in the weft, targeted specifically for saree applications. By merging heritage silk weaving with sustainable innovation, this research offers an actionable path for eco-friendly, performance driven apparel in the Indian textile domain.

2. Methodology

2.1 Material

The fabrics developed in this study incorporated three natural yarns: silk filament, banana yarn, and bamboo yarn. The end per inch and picks per inch maintained in the samples were 64 x 54. Mulberry silk filament yarn was used in the warp direction for all samples, with a denier of 22D, chosen for its high luster, tensile strength, and drapability properties well-suited for saree applications. Two types of weft yarns were used: banana yarn with a count of 20s Ne, known for its coarse texture, high tenacity, and biodegradability; and bamboo yarn with a count of 30s Ne, valued for its breathability, softness, and eco-friendliness. All yarns were processed to remove the natural impurities and then dyed using natural dyes.

2.2 Method

Two sets of woven fabric samples were developed for this study using silk filament yarn (22D) in the warp direction, combined with two different weft yarns: banana yarn (20s Ne) and bamboo yarn (30s Ne). All fabrics were woven on a handloom using a plain weave structure. The fabric construction parameters such as ends per inch (EPI-64) and picks per inch (PPI-54) were kept consistent across both samples to ensure comparability. The woven fabrics were then conditioned under standard atmospheric conditions (65 ± 2% relative humidity and 27 ± 2°C) for 24 hours before testing.

A series of tests were conducted to evaluate the mechanical and comfort-related properties of the fabrics. Tensile strength was measured using a universal testing machine according to ASTM D5035, while tear strength was evaluated using the Elmendorf tear tester following ASTM D1424. Air permeability was tested in accordance with ASTM D737 to determine the breathability of the fabrics. Drapability was assessed using a drape meter based on BS 5058, capturing the fabric's ability to conform to body contours. Abrasion resistance was measured using the Martindale abrasion tester (as per ASTM D4966) to assess surface durability, and bursting strength was evaluated using the hydraulic bursting strength tester according to ISO 13938-1. All tests were carried out in triplicate to ensure consistency and statistical reliability. The results were analyzed to determine the comparative performance of silk–bamboo and silk–banana fabric combinations for their potential use in saree applications.

3. Results and Discussion

3.1 Tearing Strength

The tearing strength analysis conducted on two fabric samples, Sample 1: Silk warp with banana weft (blended) dyed using natural dyes, and Sample 2: Silk warp with bamboo weft (blended) also dyed using natural dyes reveals clear differences in performance, particularly in the weft direction shown in Table No. 1. In the warp direction, where silk yarn is consistently used across both samples, the tearing strength values are comparable. Sample 1 records an average tearing strength of 1600 g.f, while Sample 2 shows a slightly lower average of 1549 g.f, indicating that the variation in warp strength is minimal and likely influenced by the interaction between warp and the respective weft yarns. However, the weft direction reveals a significant disparity. Sample 1, which incorporates banana fiber in the weft, achieves a substantially higher average tearing strength of 1293 g.f compared to only 858 g.f in Sample 2, which uses bamboo fiber. This indicates that banana fibers, possibly due to their better fiber cohesion, tensile behaviour, and elasticity, contribute to superior resistance against tearing forces compared to bamboo. The lower performance of bamboo in the weft could be attributed to its inherent stiffness or lower elongation properties, which make it more prone to tearing under stress.

Table 1: Tearing strength results of woven fabrics made using the combination of silk with banana and bamboo yarn

Sr. No.	Sample 1 - Silk warp, Banana weft (g.f)		Sample 2 - Silk warp, Bamboo weft (g.f)	
	Warp	Weft	Warp	Weft
1	1536	1280	1600	960
2	1600	1344	1664	640
3	1600	1280	1280	960
4	1664	1280	1600	1088
5	1600	1280	1600	640
Average	**1600**	**1293**	**1549**	**858**

Consequently, the silk-banana blend fabric demonstrates greater structural integrity and resistance to tearing forces, particularly in the weft direction. This suggests that it may be more suitable for applications requiring durability and resilience, such as fitted garments or textile products subjected to frequent movement or mechanical stress. In contrast, the silk-bamboo blend, with its lower weft strength, might be more appropriate for draped or less stressed applications where tearing resistance is not a primary requirement. Overall, Sample 1 outperforms Sample 2 in tearing strength and may offer better longevity and performance in end uses demanding higher mechanical durability.

The statistical comparison presented in Table 2 shows that the warp tearing strengths of both fabrics were statistically similar, as indicated by a non-significant p-value ($p > 0.05$) in the independent t-test. However, a significant difference ($p < 0.05$) was observed in the weft direction, where the banana-weft fabric exhibited considerably higher tearing strength than the bamboo-weft fabric. The two-way ANOVA further confirmed that both the fabric type and tearing direction had statistically significant main effects on tearing performance, together with a significant interaction effect ($p < 0.01$). This interaction suggests that the influence of fibre material was dependent on the direction of tearing, thereby indicating that banana fibre contributes more effectively to weft-wise tearing resistance compared to bamboo fibre.

3.2 Tensile Strength

The tensile strength properties of the two developed fabric samples, Sample 1 (silk warp with banana weft, blended and dyed using natural dyes) and Sample 2 (silk warp with bamboo weft, blended) were evaluated in both warp and weft directions. The results indicated in Table No.3 show notable differences in mechanical behaviour influenced by the type of weft yarn used. In the warp direction, both samples employed silk yarn; however, Sample 1 exhibited a significantly higher average tensile strength of 81.32 kg.f compared to 36.6 kg.f in Sample 2. This substantial difference suggests that the banana-blended weft in Sample 1 facilitated better load distribution and interaction with the silk warp yarns, thereby enhancing the fabric's tensile performance. Reduction in tensile strength of the silk–bamboo woven fabric can be mainly attributed to the intrinsic mechanical limitations of bamboo yarn, which is generally finer, softer and structurally less compact compared to banana fibre yarn. Bamboo fibres contain a higher proportion of hemicellulose and exhibit smoother, more flexible fibrillar surfaces that reduce inter-fibre friction and yarn cohesion, resulting in lower load-bearing capability during tensile loading. Additionally, bamboo yarns are typically less crystalline and lower in linear density, which leads to reduced tensile modulus and inferior breaking load when woven in the weft. In contrast, banana fibres possess higher cellulose orientation, coarser fibrillary morphology, and a stiffer microstructure, which enhances stress-transfer and enables higher resistance to deformation. Elongation values further supported this observation: although Sample 2 showed a greater elongation of 41.48 mm relative to 35.16 mm in Sample 1, the tensile strength was considerably lower. This indicates that while the bamboo weft contributed to increased extensibility, it did not reinforce the structure as effectively as banana fibers in terms of load resistance.

In the weft direction, the performance trends differed. Sample 2 recorded a higher average tensile strength of 36.44 kg.f, as opposed to 26.36 kg.f in Sample 1. This suggests that bamboo fibers offered improved resistance to tensile loads

Table 2: Statistical comparison of Tearing strength values between the two woven fabrics

Parameter	Direction	Sample-1 Mean (g.f)	Sample-2 Mean (g.f)	Statistical test	p-value	Significance
Tearing strength	Warp	1600	1549	Independent t-test	0.507	NS
Tearing strength	Weft	1293	858	Independent t-test	0.009	*
Main effect – Fabric Type	–	–	–	Two-way ANOVA	0.000739	**
Main effect – Direction	–	–	–	Two-way ANOVA	2.36 × 10?7	**
Interaction (Fabric × Direction)	–	–	–	Two-way ANOVA	0.00468	**

Note: NS = Not significant ($p > 0.05$), * = significant at $p < 0.05$,

Table 3: Tensile strength results of woven fabrics made using the combination of silk with banana and bamboo yarn

Sr. No.	Sample 1 - silk warp, banana weft				Sample 2 - silk warp, weft bamboo yarn			
	Warp direction		Weft direction		Warp direction		Weft direction	
	Load (kg.f)	elongation (mm)	Load (kg.f)	elongation (mm)	Load (kg.f)	elongation (mm)	Load (kg.f)	elongation (mm)
1	81.0	37.4	24.9	28.3	37.6	45.9	36.9	28.3
2	77.5	32.1	27.5	30.2	37.3	43.0	36.8	23.6
3	87.6	38.5	26.1	31.4	35.0	35.9	36.2	22.0
4	78.9	32.9	25.5	28.9	38.2	44.0	36.5	22.4
5	81.6	34.9	27.8	30.9	34.9	38.6	35.8	22.6
Avg.	**81.3**	**35.2**	**24.9**	**28.3**	**36.6**	**41.5**	**36.4**	**23.8**

when aligned in the weft direction. However, the elongation behaviour once again revealed a trade-off: Sample 2 demonstrated lower extensibility (23.78 mm) compared to Sample 1 (29.94 mm), highlighting the stiffer and less deformable nature of bamboo yarns under tensile stress. Overall, the results emphasize that Sample 1 (silk-banana blend) is mechanically superior in the warp direction, offering a robust balance between tensile strength and elongation, which may enhance fabric durability under longitudinal stress. Conversely, Sample 2 (silk-bamboo blend) performs better in the weft direction in terms of tensile resistance, albeit with reduced flexibility. These findings underscore the critical role of weft yarn composition in determining directional mechanical properties and suggest that the banana-blended fabric may be more suitable for applications demanding both strength and flexibility, while the bamboo-blended variant could be considered for uses prioritizing tensile integrity with minimal deformation.

Table 4: Two–Way ANOVA on Tensile Strength (Warp & Weft × Yarn type)

Source	F-value	p-value
Yarn type	302.06	$p < 0.0001$
Direction	773.50	$p < 0.0001$
Interaction	757.89	$p < 0.0001$

Two-way ANOVA was performed considering yarn type (banana and bamboo) and test direction (warp and weft) as independent factors, and tensile load as the dependent variable. The results shown in the Table 4 indicated that the yarn type had a statistically significant effect on the tensile strength ($F = 302.06$, $p < 0.0001$), revealing that fabrics with banana weft exhibited significantly higher tensile load compared to the bamboo weft samples. Test direction also showed a strong significant effect ($F = 773.50$, $p < 0.0001$), with warp direction demonstrating superior tensile strength relative to the weft, which is expected due to mulberry silk warp dominance. Importantly, a highly significant interaction between yarn type and direction was observed ($F = 757.89$, $p < 0.0001$), indicating that the reduction in tensile strength occurring in bamboo-based samples was more pronounced in the weft direction compared to warp, confirming that bamboo yarn contributes less load-bearing ability than banana yarn when used as weft material.

3.3 Air Permeability

Air permeability is a critical property in textile materials, particularly for fabrics intended for apparel, technical, or comfort-focused applications. It reflects the ability of a fabric to allow air to pass through it, which directly influences breathability, thermal regulation, and wearer comfort. For the current study, evaluating the air permeability of the two developed fabric samples, Sample 1 (silk warp with banana weft, naturally dyed) and Sample 2 (silk warp with bamboo weft, blended) was essential to assess their suitability for applications where ventilation and comfort are paramount, such as summer wear or performance textiles. The results were shown in Table No. 5.

The test results, measured in both litres per hour (LPH) and $cm^3/sec/cm^2$, indicate that Sample 2 demonstrated higher air permeability compared to Sample 1. Sample 1 exhibited an average air permeability of 2520 LPH (equivalent to 699.804 $cm^3/sec/cm^2$), whereas Sample 2 recorded a higher average of 2830 LPH (equivalent to 785.891 $cm^3/sec/cm^2$). This notable increase in Sample 2 suggests that the bamboo-blended weft structure permits a greater volume of air to pass through the fabric matrix. This improved permeability in Sample 2 may be attributed to the structural characteristics of bamboo fibers, which are known for their smoother surface, rounder cross-section, and potentially looser packing within the yarn matrix, thereby allowing for more inter-yarn spaces. In contrast, banana fibers, although coarser and offering better mechanical interlocking, may create a denser weave with reduced porosity, as observed in Sample 1. Furthermore, bamboo yarns might produce less crimp or bulkiness when blended with silk, promoting a more open fabric structure and higher airflow.

Table 5: Air permeability test results of woven fabrics made using the combination of silk with banana and bamboo yarn

Sr. No.	Sample 1 - Silk warp, Banana weft		Sample 2 - Silk warp, weft Bamboo yarn	
	LPH	$cm^3/sec/cm^2$	LPH	$cm^3/sec/cm^2$
1	2400	666.48	2800	777.56
2	2500	694.25	2900	805.33
3	2700	749.79	2900	805.33
4	2200	610.94	2800	777.56
5	2500	694.25	2900	805.33
6	2500	694.25	2800	777.56
7	2600	722.02	2700	749.79
8	2500	694.25	2900	805.33
9	2600	722.02	2800	777.56
10	2700	749.79	2800	777.56
Average	**2520**	**699.80**	**2830**	**785.89**

While higher air permeability is advantageous for breathability and comfort, it may also imply lower wind resistance and possibly reduced insulation properties, depending on the end-use. Therefore, the application potential of Sample 2 may lean toward lightweight, breathable garments, especially for warm and humid climates. Sample 1, with its relatively lower permeability, might offer slightly better thermal insulation and wind resistance, making it suitable for moderate-weather apparel or layered clothing.

The statistical analysis of air permeability revealed a significant difference between the two woven samples were shown in Table 6. The bamboo-weft fabric exhibited higher air permeability values in both LPH and $cm^3/s/cm^2$ measurements ($p < 0.05$), indicating superior breathability compared with banana-weft fabric. These differences can be attributed to the finer structure and porous nature of bamboo fibres, which enhance airflow through the fabric. The results suggest that the use of bamboo yarn in the weft direction considerably improves the air permeability characteristics of the silk-based woven structure, making it more suitable for comfort-oriented textile applications such as saree fabrics.

3.4 Drapability

Drape is one of the most critical performance parameters in sarees, particularly in Ikat sarees, where the fabric's visual appeal, form, and comfort are heavily influenced by its ability to fall and flow gracefully. Traditionally, Ikat sarees employ silk yarns in both warp and weft to ensure richness in texture and sheen. However, in the present study, the conventional silk weft was strategically replaced with banana and bamboo yarns to explore the feasibility of developing more comfort-oriented and sustainable alternatives without compromising drape quality an essential characteristic in saree aesthetics. To evaluate the draping behaviour of the two developed fabric samples, the Mean Drape Coefficient (DC) was measured on both front and back sides and the results were shown in Table No.7. Sample 1, composed of silk warp and banana weft (naturally dyed), exhibited significantly lower drape coefficients 22.44% (front) and 19.79% (back) indicating a softer, more pliable fabric with excellent drape characteristics. In contrast, Sample 2, composed of silk warp and bamboo weft (blended), showed higher values of 33.66% (front) and 28.32% (back), reflecting a comparatively stiffer and less flexible structure.

Table 7: Drapability test results of woven fabrics made using the combination of silk with banana and bamboo yarn

Type	Sample 1 - Silk warp, Banana weft (%)	Sample 2 - Silk warp, Bamboo weft (%)
Front	22.44	33.66
Back	19.79	28.32

These results suggest that the banana fiber blend used in Sample 1 contributes positively to fabric flexibility, possibly due to its softer texture and finer structural characteristics. On the other hand, bamboo yarns, while smooth and strong, tend to add more stiffness to the fabric when used in certain blends, which is evident in the higher drape coefficients of Sample 2. The natural dyeing process, especially in Sample 1, may have further enhanced the softness and flow ability of the fabric by altering surface cohesion. Given the cultural expectations and functionality of Ikat sarees, which require a balanced combination of aesthetic drape and tactile comfort, Sample 1 demonstrates superior performance. It provides a viable alternative to full silk construction while promoting comfort, breathability, and sustainability. Sample 2, although slightly stiffer, may still hold potential for structured garment styles or could be improved through softening finishes to better suit saree applications.

Table 6: Statistical comparison of air permeability results between banana-weft and bamboo-weft fabrics

Parameter	Unit	Sample-1 Mean	Sample-2 Mean	Statistical test	p-value	Significance
Air permeability	LPH	2520	2830	Independent t-test	0.0012	*
Air permeability	$cm^3/s/cm^2$	699.80	785.89	Independent t-test	0.0015	*

*Note: * indicates significant at $p < 0.05$.*

3.5 Abrasion

The abrasions cum pilling test results are critical in evaluating the suitability of the developed fabrics for their intended application in Ikat sarees. Table No. 8 shows that Sample 1, comprising silk warp and banana-blended weft yarns, exhibited superior abrasion resistance by withstanding up to 4000 cycles before showing signs of pilling and surface wear. In contrast, Sample 2, made with silk warp and bamboo-blended weft, failed after 3000 cycles, with observable damage including warp yarn breakage. This indicates that the banana blend contributes to enhanced mechanical durability and better cohesion under stress, which is essential for sarees that undergo frequent folding, draping, and friction during wear. Although pilling was noted in Sample 1, it remained a surface-level phenomenon that did not compromise the fabric's structural integrity. Given the functional demands of Ikat sarees, particularly in terms of longevity and resistance to daily wear, Sample 1 demonstrates greater potential for practical application due to its higher resistance to abrasion and overall fabric stability.

Table 8: Abrasion test results of woven fabrics made using the combination of silk with banana and bamboo yarn

Abrasion cum Pilling	
Sample-1	After 4000 cycles pills & abrasion observed
Sample-2	After 3000 cycles abrasion & warp yarn cut

3.6 Bursting Strength

The bursting strength results in Table 9 showed a distinct difference between the two blended fabric samples. Sample 1 (silk warp with banana weft) recorded higher bursting strength values, ranging from 397.17 to 525.64 kPa, with an average of 460.33 kPa. This enhanced performance is mainly attributed to the lignin-rich and structurally rigid nature of banana fibres, which strengthens yarn cohesion and improves the fabric's ability to withstand multi-directional stresses. In contrast, Sample 2 (silk warp with bamboo weft) exhibited lower bursting strength values, ranging from 267.72 to 332.45 kPa, with an average of 304.40 kPa. The reduced resistance in this sample is associated with the smoother fibre surface and lower tenacity of bamboo fibres, resulting in weaker inter-fibre bonding and reduced load-bearing capacity. The clear difference in average bursting strength indicates that the banana-blended fabric offers superior durability and structural stability, making it more suitable for garments that undergo frequent handling and pressure, such as sarees.

From a practical standpoint, this property has direct implications for the final application in Ikat sarees. These traditional garments are subjected to constant mechanical manipulation through pleating, tucking, draping, and movement during wear which exerts strain on the fabric in multiple directions. A fabric with higher bursting strength is less prone to localized failures such as tearing or puncturing, especially in stress-prone zones like the waist, shoulder, and pleats. Additionally, sarees often undergo repeated washing and ironing, which further demands a durable fabric structure. Therefore, the higher bursting strength observed in Sample 1 indicates its greater suitability for use in Ikat sarees, ensuring better wear life, user comfort, and functional reliability without compromising on the intricate aesthetics characteristic of this textile tradition.

Table 9: Bursting Strength test results of woven fabrics made using the combination of silk with banana and bamboo yarn

Sr. No.	Sample 1 - Silk warp, Banana weft (kPa)	Sample 2 - Silk warp, Bamboo weft (kPa)
1	525.64	321.66
2	461.89	267.72
3	465.82	289.3
4	397.17	310.87
5	451.11	332.45
Average	460.326	304.4

The bursting strength results demonstrated a statistically significant difference between the two woven samples which is shown in Table 10. The banana-weft fabric exhibited considerably higher bursting resistance (460.33 kPa) compared with the bamboo-weft fabric (304.40 kPa), and the independent t-test confirmed this difference as statistically significant ($p < 0.05$). This suggests that the coarser and relatively stronger banana fibres are more effective in sustaining multidirectional stress during hydrostatic loading, whereas the finer bamboo fibres result in lower bursting resistance. These findings highlight the structural advantage of banana fibre reinforcement in woven fabrics where dimensional stability and hydrostatic strength are required.

4. Conclusions

This study compares two silk-based woven fabrics Sample 1 (silk warp with banana fibre weft) and Sample 2 (silk warp with bamboo fibre weft) to assess their suitability for sustainable saree applications, particularly in Ikat weaving. Results show that the weft fibre type strongly affects mechanical and comfort properties. Sample 1 exhibited superior tensile, tearing, abrasion, and bursting strength, enduring up to 4000 abrasion cycles, indicating greater durability for frequent handling. In contrast, Sample 2

Table 10: Statistical comparison of bursting strength between banana-weft and bamboo-weft woven fabrics

Parameter	Unit	Sample-1 Mean	Sample-2 Mean	Test used	p-value	Significance
Bursting strength	kPa	460.33	304.40	Independent t-test	0.0036	*

showed higher air permeability and breathability due to bamboo's smooth structure, offering comfort in warm climates but lower durability. Sample 1 also demonstrated better drapeability, producing a softer and more elegant fabric fall. Overall, the silk–banana blend achieved a balanced combination of strength, flexibility, and aesthetic appeal, making it a promising and sustainable choice for high-performance sarees suitable for both traditional and modern applications.

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Circular Approach to Filtration Media Design using Recycled Textile Waste

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Abstract:

Large quantities of used cooking oil are generated in households and food service establishments. Improper disposal causes water contamination and resource loss [1]. Oil reuse is possible after effective filtration. Most existing filter and sorbent media rely on virgin synthetic polymers and create secondary solid waste [2]. This review examines the use of recycled textile waste as nonwoven filtration media for kitchen oil purification and oil sorption applications. Recycled cotton, polyester, and blended textile fibres are processed into nonwoven structures using needle-punching and melt-blowing techniques [3, 4]. These structures provide high porosity, interconnected pore networks, and controlled permeability. Such characteristics support the removal of suspended food residues, carbonaceous particles, and polymerised oil fractions. Blending natural fibres with recycled polyester improves oil affinity and enhances retention behaviour due to combined capillary action and oleophilic response [5]. Observations from earlier studies show that fibre diameter, web density, and surface energy strongly influence filtration efficiency and pressure drop. The reviewed evidence indicates that recycled nonwoven filters support circular economy objectives by converting textile waste into functional filtration materials [6]. Performance variation across studies reflects differences in waste fibre sources and processing routes. Limited long-term durability data and thermal ageing assessments restrict direct industrial adoption. Further investigation on multilayer assemblies, biodegradable binders, and repeated use under kitchen conditions remains necessary.

Keywords: *Adsorption capacity, Biodegradable binder, Circular economy, Eco-friendly filtration media, Fiber morphology, Filtration efficiency, Green kitchen initiatives*

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1. Introduction

In both household and commercial kitchens, UCO - Used Cooking Oil is a major waste stream. Frequent changes of oil are costly and improper dumping leads to serious pollution in water + soil. The oil can be used again post filter but many conventional filter papers and or synthetic meshes often have such poor durability and are not environmentally friendly [7]. Therefore, developing sustainable, reusable, and efficient oil filtration media is crucial for eco-sensible kitchen management.

Non-woven fabrics show great advantages as filter material for its huge surface area, adjustable pore size and low cost for production [8]. It has been used in liquid filtration applications worldwide but still under exploration for use in kitchen oil filtration. Traditional non-woven filter media is mainly made from virgin polypropylene or polyester fibers, which hurt the environment when they are discarded [9]. On the contrary recycled non-woven textiles now made of rPET or waste cotton fabrics can be recycled into filter mats through mechanical recycling, melt-blowing, or electrospinning processes, providing almost identical filtration efficiency in a much greener way [10, 11].

The research experiments have certificated with the help of recycled fiber based non-woven filters that the suspended food residues, polymerised fats, carbon particles from UCO can be removed effectively. This way the oil clarity improves and useful life is elongated [12]. Also, addition of natural fibers in recycled matrix betters the oil affinity which also helps in capturing more impurities and that results in the enhanced filtration [13]. These advancements help in managing kitchen waste sustainably and contribute to the circular economy by converting waste textile into the product with a value [14].

This review paper accumulates current findings on recycled non-woven textile using oil filtration, evaluates performance parameters like permeability, reusability and retention efficiency and recommendations for potential upgrades for future eco-friendly residential & industrial kitchen filtration systems withstanding [15].

1.1 Problem Statement

- Existing process for spill cleanup relies heavily on single-use polypropylene sorbents and costs/impacts include:
- Environmental – Total non-biodegradables contributing to plastic waste problem.
- Economic – Over time replacement leads to cost issues.
- Use of Resources – Obligation to use virgin synthetic fibers leading to petroleum based raw material consideration.
- Limited Scope – Most sorbents are mean to be used for large-scale spill clean-up, without much consideration of kitchen spill or small-scale spill issue.

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As a result, there is a research gap with regard to functional reusable sorbents made from recycled fibers that will function in the kitchen and within marine spill recovery.

1.2 *Significance of the Study*

- The project is a new solution as it is to develop new needle-punched nonwoven oil wipes; using recycled cotton and polyester fibers from used textiles.
- Cotton fibers have high absorption capacity and provide quick and effective oil uptake.
- Polyester fibers provide strength, durability and oleophilic characteristics and as a result, will selectively absorb the oils and be water resistant.
- Needle-punching is a method of fabrication that will provide a nonwoven fabric that will be porous and durable, does not use any chemical binders.
- Recycled textile waste will keep used materials in the circular economy, limit materials ending up in a landfill, and reduce cost of materials.

1.3 *Proposed Methodology*

1.3.1 Fabrication of Recycled Non-Woven Filter Media

Recycled textile waste such as polyester (rPET), cotton, and blended fabrics were used as raw materials for preparing non-woven filter media. The collected textile waste was first cleaned to remove dirt, oil residues, and contaminants, followed by drying at ambient conditions. The cleaned materials were then mechanically shredded into fibers of suitable length.

Non-woven mats were fabricated using either needle-punching or melt-blowing techniques. In the needle-punching process, the fibers were randomly oriented and mechanically bonded to form a stable porous structure. For hybrid structures, natural fibers (cotton or jute) were blended with rPET fibers in different weight ratios before web formation. The thickness and density of the non-woven mats were controlled by adjusting fiber loading and processing parameters. In some cases, mild thermal bonding was applied to improve structural integrity.

1.3.2 Characterization and Testing of Filter Media

Morphological Analysis

The surface morphology and fiber distribution of the fabricated non-woven filters were examined using optical microscopy or scanning electron microscopy (SEM). Fiber diameter, pore structure, and uniformity were analyzed to understand their influence on filtration performance.

Physical Properties

Porosity and thickness of the filter media were measured using standard gravimetric and thickness gauge methods. Air or oil permeability was evaluated to assess flow behavior through the filter mat.

Oil Filtration Performance

Waste cooking oil was filtered using the prepared non-woven mats under gravity or low-pressure conditions. The filtration efficiency was evaluated by comparing the clarity, color, and impurity content of oil before and after filtration. The removal of suspended particles and carbonaceous residues was visually observed and, where possible, quantified.

Pressure Drop and Reusability

Pressure drop across the filter media during oil flow was measured to assess ease of filtration. Reusability was tested by cleaning the filter after use and repeating filtration cycles to evaluate performance retention.

Wettability Analysis

Contact angle measurements were conducted to study the wettability of the filter surface, especially for hybrid non-woven structures. Improved wettability was correlated with enhanced oil absorption and impurity removal.

2. Literature Review

2.1 Oil Sorbents and Their Importance

Oil sorbents are products that absorb or adsorb oil in a selective manner from water and other surfaces. They are essential to oil spill remediation both at small domestic scales, or large marine scale. The effectiveness of a sorbent can depend on, but is not limited to, the following properties: absorbency, hydrophobicity, oleophilicity, strength, and reusability. While there are a number of sorbent materials available, virgin polypropylene fibers (commonly used in sorbent booms) are by far the most common. Due to their oil attracting and water repelling features, non-biodegradable sorbent materials not only raise questions about waste and disposal, but impact the environment and ecosystem as well. Although there are a number of commercially available sorbents, they predominantly represent single use sorbents where there is no ability to reuse or recycle outside of the recycling facility.

2.2 Cotton-based Sorbents

Cotton is composed of cellulose-based natural fiber material and is highly absorbent owing to the fibers' hydrophilic structure and inherent capillary action. Cotton sorbents are capable of absorbing substantial amounts of oil; however, they tend to have low mechanical strength and will often degrade quickly when reused. Yet, cotton does have potential when it is used as a blend with synthetic fibers to provide a certain durability.

2.3 Polyester-based Sorbents

Polyester fibers are oleophilic and hydrophobic, making them ideally suited for oil absorption uses. Polyester sorbents have high tensile strength, chemical resistance, and can retain performance in harsh conditions. The main downside of polyester sorbents is that they are generally expensive, and they are non-biodegradable. When using recycled polyester fibers, the environmental footprint is less, but they will not compete with natural fibers on the absorbency.

2.4 Nonwoven textiles in Oil Pollution Containment

Nonwovens, specifically needle punched nonwovens, are a popular textile for studies on filtration and absorption due to their high porosity and surface area, as well as their strength. As needle-punching mechanically interlocks the fibers, and no chemical binder is utilized, fabric formed via needle-punching has the potential to be eco-friendly durable fabrics. It has been demonstrated through studies that nonwoven materials can exhibit a dramatically higher oil absorption efficiency, than woven textiles due to the open structural architecture and bulk of the fabric.

2.5 Recycled Textiles as Sustainable Materials

Textile waste is proving to be a pertinent global issue, with millions of tons thrown away annually, not mentioning incineration options. By recycling waste fibers into new products, we can continue to close the loop on the textile circular economy, while still reducing the burden on landfills. As covered in previous studies, mixture of recycled natural and synthetic fiber has the potential to balance an absorbent and durable sorbent material, thereby allowing for the construction of eco-friendly sorbents.

3. Objectives

3.1 General Objective

The general objective of this project is to design, fabricate, and test eco-friendly, reusable oil wipes made from needle-punched nonwoven material from reclaimed cotton and polyester fibers, and to demonstrate their effective use for cleaning oil from kitchen environments and recovering oil from marine spills.

3.2 Specific Objectives

3.2.1 Fabricate Eco-Friendly Oil Wipes

- Bi-products of both post-consumer waste and industrial waste from textiles will serve as raw material sources by recycling textile fibers.
- Cotton fibers will be used to absorb oils and polyester fibers to ensure strength, durability and oleophilicity.
- The needle-punched nonwoven method bonds the fibers in the fabric only mechanically and does not use chemical additives to bond the fibers, meaning the wipes will be production with an environmentally safe method.
- To determine and ascertain the optimal blending ratio of each fiber (e.g. 50:50, 60:40, 40:60) and ultimately produce the best performing product.

3.2.2 Performance Testing and Evaluation

- Measure the absorbency (in grams of oil absorbed per gram of fabric) of the wipes with both edible cooking oils (kitchen use) and crude oil simulants (marine use).
- Measure the oil retention capacity after contamination by measuring the amount of oil retained by wipe after the drip and centrifuge tests.
- Determine repeatability and their performance retention by subjecting the wipes to repeated wash cycles (minimum of 10 to 15 wash cycles).
- Determine mechanical parameters (e.g. tensile strength and bursting strength) to ensure it can withstand repeated use.
- To measure saltwater resistance by testing wipes under saltwater condition to simulate marine environments.
- To measure selectivity by demonstrating the wipes ability to absorb oil, while repelling water.

4. Comparative Assessment

- To compare the performance of the required wipes to commercially available polypropylene sorbents on the market.
- To assess differences in cost, reusability, efficiency and environmental footprint.
- To clarify the pros and cons of using recycled fiber nonwoven wipes.

4.1 Application development

- To identify and confirm real-world applications including:
- Kitchen space - the quick and effective clean-up of spilled cooking oil in homes, restaurants and food industries.
- Marine environment - recovery of crude oil slicks from salt water when spills occur.
- Industrial maintenance - the cleaning of machinery, automotive shops, and other environments prone to oil leaks.
- To demonstrate the ability to use the product in more than one way as a sorbent will help justify commercial viability.

4.*2 Sustainability and the Environment*

- To illustrate how recycled fibres reduce landfill use and the amount of textiles waste.
- To contribute to a circular economy, where waste textiles are used to make functional and high performance products.
- To find a sustainable alternative to synthesized, single-use sorbents, with decreased carbon footprint.
- To raise awareness of eco-friendly sorbent technologies in domestic and industrial markets.

4.3 Expected Outcomes from these Objectives

The objectives stated above will result in a project that will:

- Create a high performance and sustainable product, which can be reused.

- Consistently show efficient oil absorption (10 - 15 g/g of fabric).
- Continue to show this high performance, through up to 10-15 washes.
- Provide a cost alternative when compared to polypropylene pads.
- Have dual-application potential - home, and large-scale marine spill.

5. Materials and Methods

5.1 Materials

I. Raw Materials

- Recycled Cotton Fibres

  Sourced from post-consumer and industrial textile waste.

  The most absorbent of the three with cellulose structure which allowed for absorbency by design.

- Recycled Polyester Fibres (PET)

  Obtained from used PET plastic bottles and discarded polyester textile waste.

  Added strength and durability to the function of the sorbent pads and the primary oleophilic component.

II. Equipment and Machines

- Fiber Opening & Cleaning Machine – used to open/recycle the fibers and clean them.
- Blending Machine – used to mix cotton and polyester per the required ratios.
- Carding Machine – used to align the fibers to create a uniform web.
- Needle Punch Nonwoven Machine – used to mechanically bond fibers together to create a porous nonwoven fabric.
- Cutting Tools – used to create the nonwoven fabric into the final product, (wipes).

III. Testing Materials

- Cooking Oils (sunflower oil, palm oil, etc.) – to test against in the kitchen environment.
- Crude Oil Simulant – to test against using a 'marine' oil spill situation.
- Saltwater Solution (3.5% NaCl) – to test against simulated marine condition.

5.2 Overall Methodology

The methodology will have three main components:

- Fabrication of nonwoven wipes
- Testing and evaluation
- Comparative Analysis to commercial sorbents

Collection of Waste Textiles
(Consumer & industrial textile waste)
↓
Sorting of Materials
(Cotton-based and polyester-based textiles)
↓
Removal of Contaminants
(Buttons, zippers, labels, foreign materials)
↓
Fiber Preparation
(Shredding → opening → cleaning of fibers)
↓
Fiber Blending
(Cotton/Polyester blends: 50:50, 60:40, 40:60)
↓
Web Formation
(Carding of fibers into thin web)
↓
Layer Stacking
(Multiple web layers to achieve desired thickness)
↓
Needle-Punching
(Mechanical entanglement using barbed needles)
↓
Porous Nonwoven Fabric Formation
(Chemically binder-free structure)
↓
Cutting and Finishing
(Standard wipe size, edge trimming)
↓
Reusable Nonwoven Oil Wipe
↓
Performance Evaluation
(Oil absorption capacity, oil retention, reusability)
↓
Comparative Analysis
(Comparison with commercial polypropylene sorbents)
↓
End

Stage 1 involves the fabrication of nonwoven oil wipes from recycled textile waste. Consumer and industrial textile wastes are first collected and manually sorted into cotton-based and polyester-based categories. Foreign materials such as buttons, zippers, and labels are removed to avoid processing interference. The sorted textiles are shredded into small pieces, followed by fibre opening and cleaning to obtain process able fibres.
Cotton and polyester fibres are then blended in defined weight ratios of 50:50, 60:40, and 40:60 to study the influence of blend composition on oil absorbency and durability. The blended fibres are carded to form a thin web, and multiple web layers are stacked to achieve the required thickness.

The layered web is mechanically bonded using needle-punching, where repeated penetration of barbed needles entangles fibres in multiple directions and forms a porous nonwoven structure without chemical binders. The resulting fabric is cut into standard wipe dimensions, typically 20 cm × 20 cm, and edge trimming is carried out to reduce fibre shedding. The fabricated wipes are then evaluated against commercial polypropylene sorbents based on oil absorption capacity, oil retention, and reusability.

5.3 Experimental Approach

Three sets of nonwoven oil wipes are prepared using cotton–polyester blend ratios of 50:50, 60:40, and 40:60. Each performance test is conducted in triplicate to ensure consistency and to reduce experimental variability. Measured data are recorded and processed using basic statistical descriptors, including mean values and standard deviation, to allow comparison between samples. The performance of the fabricated wipes is evaluated against internationally accepted oil sorbent benchmarks, with reference to ASTM F726, which specifies standard procedures for assessing oil absorption and retention behaviour.

6. Result and Discussion

6.1 Oil Absorption Capacity

Nonwoven wipes fabricated from recycled cotton–polyester blends are expected to show oil absorption capacities in the range of 10–15 g of oil per gram of fabric. These values fall within or exceed the absorption range reported for commercial polypropylene sorbents, typically 8–12 g/g. Cotton fibres contribute rapid oil uptake through capillary action within the fibre network. Polyester fibres provide oleophilic behaviour and improve selective interaction with oil phases. The needle-punched nonwoven structure generates a porous architecture with high surface area, which supports oil penetration, storage, and retention within the fabric matrix.

6.2 Oil Retention Capacity (ORC)

The developed nonwoven wipes are expected to retain approximately 80–90% of the absorbed oil after drip and centrifugation tests. This level of retention supports stable handling during use. Mechanical entanglement created during needle-punching restricts fibre displacement and limits oil release from the structure. Polyester fibres contribute hydrophobic behaviour, which improves oil holding capacity and reduces leakage when the wipe is exposed to water.

6.3 Reusability and Durability

Reusability represents a key functional advantage over conventional polypropylene sorbents. The wipes are expected to retain 70–80% of their initial oil absorption capacity after 10–15 washing cycles. Mechanical strength testing is anticipated to show limited loss in tensile integrity and structural cohesion after repeated use. Fibre entanglement within the nonwoven matrix supports dimensional stability and resistance to tearing. Repeated use reduces material replacement frequency and lowers long-term operational cost.

6.4 Saltwater Resistance

Performance under saltwater conditions is expected to remain stable during simulated marine spill testing. Cotton fibres may initially interact with water, but the presence of polyester limits excessive water uptake. Hydrophobic response from the polyester component maintains oil selectivity and supports floating behaviour. Fibre blending is expected to balance absorbency and resistance, enabling use in both domestic oil cleanup and marine spill recovery scenarios.

6.5 Selectivity for Oil over Water

The wipes are expected to achieve oil selectivity above 90%, indicating preferential oil absorption with minimal water uptake. High selectivity is critical for marine applications, where buoyancy and oil capture efficiency determine recovery effectiveness. Cotton-only sorbents tend to absorb both oil and water, which reduces functional efficiency. The cotton–polyester blend improves selectivity by combining capillary absorption with oleophilic surface interaction.

6.6 Cost and Sustainability

Repeated use of the developed wipes is expected to reduce overall cost compared to single-use polypropylene sorbents. The use of recycled fibres diverts textile waste from landfill and lowers demand for virgin polymer production. Reduced material turnover contributes to lower solid waste generation. Environmental benefit is anticipated through reduced resource consumption, although quantitative life cycle assessment is required to confirm relative carbon emission reduction.

6.7 Limitations of the Study

The present study is subject to limitations related to material variability, testing scale, and performance scope. The properties of recycled nonwoven textile fibres used as filtration media depend strongly on their source, previous use, and recycling route. Variations in fibre length, fineness, and surface contamination influence pore structure, absorption behaviour, and mechanical durability. These variations were not quantified in a systematic manner across different batches of recycled materials.

Several studies report oil absorption and retention values for recycled cotton–polyester nonwoven sorbents that fall within the range of commercial polypropylene pads. Direct quantitative comparison under identical testing conditions remains limited. Most reported data originate from laboratory-scale evaluations with differences in oil type, loading method, filtration duration, and reuse protocol. As a result, performance consistency and long-term durability relative to virgin polypropylene sorbents cannot be fully established.

The study emphasizes circular economy benefits through textile waste reuse and reduced dependence on single-use synthetic sorbents. A formal life cycle assessment is not included. Quantitative data on carbon footprint, water footprint, and energy demand for recycled cotton–polyester nonwoven wipes are not compared with commercial polypropylene sorbents. End-of-life aspects are addressed at a descriptive level, with focus on reusability and waste diversion. Disposal pathways such as recycling, incineration, and landfill impact are not evaluated using a structured framework. Environmental trade-offs linked to fibre recycling, processing energy, repeated washing, and final disposal remain unquantified. As a result, the environmental advantage is indicated but not demonstrated through LCA-based metrics.

The evaluation focused primarily on the removal of suspended particulate matter and carbonaceous residues from used cooking oil. Dissolved degradation products and chemical contaminants were not assessed. Long-term thermal ageing, fouling behaviour, and extended reusability beyond the experimental timeframe were also not examined. In addition, large-scale performance under continuous kitchen or restaurant operating conditions was not investigated. These constraints restrict direct translation of laboratory findings to industrial implementation and indicate the need for further standardized and application-oriented studies.

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Synthesis and Environmental Evaluation of Hybrid Al_2O_3–CuO Nanofluids for Minimum Quantity Lubrication

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Abstract:

The increased need to join forces on sustainable manufacturing of the environment has enhanced investigations of biodegradable nanofluids to develop further machining methodology like Minimum Quantity Lubrication (MQL). This paper has produced a hybrid nanofluid made of Aluminum Oxide (Al2O3) and Copper Oxide (CuO) nanoparticles in a two-step process by referring to the magnetic stirring and ultrasonic methods, where 1% oleic acid was employed as a dispersing agent and a coconut oil. To assess the compatibility with the environment, BOD, Chemical Oxygen Demand (COD), and the ratio between the two were determined by experiment using standard procedures. The hypothesis tested was the variation of the Al2O3 concentration (0.50, 0.75 and 1.00 vol.%) with equal doses of CuO (0.25 vol.%) to test the three hybrids. The outcomes show that, all the formulations have a BOD/COD ratio of more than 0.5, which confirms their biodegradability. Among them, Hybrid B (0.75% Al2O3 + 0.25% CuO) showed the best balance between biodegradability and formulation performance with BOD of 105 mg/L, COD of 180 mg/L and a BOD/COD ratio of 0.57, which signified that it was highly biodegradable and able to disperse the nanoparticles used. The results prove that the Al2O3-CuO hybrid nanofluids in coconut oil are a promising eco-friendly cutting fluid as an alternative to the traditional mineral-based cutting fluids in a sustainable MQL machining process.

Keywords: *Biodegradability, BOD/COD Ratio, Coconut Oil, Hybrid Nanofluids, Oleic Acid Surfactant, Two-Step Synthesis*

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1. Introduction

In recent years, nanofluids, defined as engineered colloidal suspensions of nanoparticles in base fluids, have received significant scrutiny in the scholarly community due to their enhanced thermo-physical qualities and their application potential in heat transfer, tribology, and sustainable manufacturing processes [1]. Minimum Quantity Lubrication (MQL) is one application that shows a lot of promise; it is a machining process that requires a very low amount of cutting-fluid in order to reduce friction and heat, and extend tool life. However, instability in dispersion, agglomeration of particles and sedimentation are the problems on the way of the use of nanofluids in MQL systems as these phenomena may affect the performance of the fluids producing inconsistent delivery [2].

To overcome these limitations, Hybrid nanofluids i.e. suspensions which include more than two types of nanoparticles to form a composition, have been promoted as a mitigating approach, since the synergetic action of various particle properties can jointly increase lubricating and thermal properties [3]. The Aluminum Oxide (Al2O3) is well utilized in terms of tribological hardness and wear-resistance, whereas the Copper Oxide (CuO) has high thermal conductivity [4]. When added to a biodegradable base fluid like coconut oil and have the same stabilized with a surfactant involving the *Oleic Acid* 1% individual components combine to have both environmental sustainability and excellent machining capabilities [5, 6].

Ensuring stability of such hybrid nanofluids is invaluable before they can be deployed in the field. One parameter that has become conventionally acceptable, a property of electrokinetics used frequently in dispersion stability is called Zeta Potential [7-9]. A large absolute zeta potential ±30 mV indicates the opposite where the attraction between nanoparticles is vigorously repelled thus preventing aggregation and hence the maintenance of the uniform distribution of nanoparticles at a given time. Zeta potential analysis is of specific significance in the case of MQL operations where the effective lubrication and cooling depends on the consistency of fluid flow and activity of nanoparticles [10].

Although some works have been done on the performance of single-component nanofluids, there is a huge research gap concerning the systematic synthesis and stability evaluation of hybrid nanofluids incorporating Al2O3 and CuO in vegetable oil based systems. his study addresses this gap by focusing on the synthesis of a coconut oil-based hybrid

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nanofluid, and the dispersion stability of the latter exclusively measured based on its zeta potential. The goal is to find out the best concentration of Al2O3 that gives the maximum colloidal stability in combination with constant concentration of CuO and SDS [11].

The stability of the prepared nanofluids was evaluated using zeta potential analysis, which is a widely accepted electrokinetic method for assessing colloidal stability. A detailed explanation has now been added in the Introduction and Future Scope sections. It is clarified that nanofluids exhibiting absolute zeta potential values greater than ±30 mV indicates good dispersion stability, which is essential for consistent performance in MQL applications.

1.1 Objectives of the Study

a) To make the Al2O3 CuO hybrid nanofluids with a virgin coconut oil as a biodegradable base fluid and test the hybrids with regards to environmentally friendly properties in terms of Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD) and BOD/COD ratio.

b) To determine an efficient eco-friendly hybrid nanofluid formulation that can be used in Minimum Quantity Lubrication (MQL) machining through the examination of how the concentration of Al2O3 affects the biodegradability and formulation performance.

2. Materials and Methods

2.1. Materials

In study, virgin coconut oil serves as the base fluid in which the nanofluids were prepared. It was chosen based on its natural source, good biodegradability, thermal stability and self- lubricating ability which makes it a suitable tool to use in sustainable machining. Aluminum Oxide (Al2O3) and Copper Oxide (CuO) nanoparticles were considered as nanoparticle of choice to be used in the hybrid formulation. The properties that were utilized in the use of Aluminum Oxide are high hardness, chemical stability and provision of improved wear resistance at the cutting interface. Copper Oxide was chosen on the basis of high thermal conductivity that helps to provide an efficient heat dissipation process in the cutting zone. A surfactant, *Oleic Acid* 1% improved the dispersion of the nanoparticles and hindered their agglomeration. *Oleic Acid* enhances stability due to its effects of lowering the surface tension, fine dispersion of nanoparticles in the coconut oil media [12-15].

2.2. Nanofluid Synthesis Procedure

The synthesis of nanofluids was carried out using the two-step method, which is effective for achieving uniform dispersion of nanoparticles in base fluids. This process involved the separate preparation of individual nanofluids using Aluminum Oxide (Al_2O_3) and Copper Oxide (CuO), followed by their combination to create a hybrid nanofluid.

2.3. Procedure Synthesis of Nanofluids

The production of nanofluids has been completed according to the two-step procedure that is applicable in generating uniform nanoparticle dispersion of base fluids. This reaction was done by preparing single Aluminum Oxide (Al_2O_3) copper Oxide (CuO) nanofluids and combining them to form a hybrid nanofluid.

Figure 1: Nanopowders

a) Synthesis of Al2O3 Nano fluid

The Al2O3 nanofluid was prepared by weighing precisely 0.75 grams of Aluminum Oxide nanoparticles (average size 2050 nm) into 100 mL virgin coconut oil and introducing them gradually in the oil. To improve the dispersal of the nanoparticles, 1% by volume of Oleic Acid was added into the mixture. The applied suspension was magnetically stirred, and after 2 hours of uniform mixing, it was further ultrasonicated (60 min) in order to disintegrate the agglomerates of the suspensions and obtain a stable dispersion of the particles.

Figure 2: Synthesis process of Al_2O_3 nanofluid using coconut oil and Oleic Acid

b) CuO Nanofluid preparation:

In the same manner, in the case of CuO nanofluid, 0.25 g of Copper Oxide nanoparticles (particle size 30 50 nm) was added to 100 mL of the virgin coconut oil and 1% *Oleic Acid* surfactant. The mixture was magnetically stirred and ultrasonicated, after which the mixture was sonicated at 60 minutes. This step made the CuO particles in the base fluid to be evenly distributed.

c) Synthesis of Al2O3-CuO Nanofluid Hybrid:

The formation of the hybrid nanofluid was conducted by exposing 0.75 grams of Al2O3 and 0.25 grams of CuO nanoparticles to virgin coconut oil at the same time and mixing them with 100 mL of the oil and 1% *Oleic Acid* was added to this mixture to facilitate dispersion. The mixed suspension was magnetically stirred during 2 hours to homogenize and 60 minutes of ultrasonication. This produced a stable hybrid nanofluid with the nanoparticles highly dispersed which can be used in Minimum Quantity lubrication (MQL) machining processes.

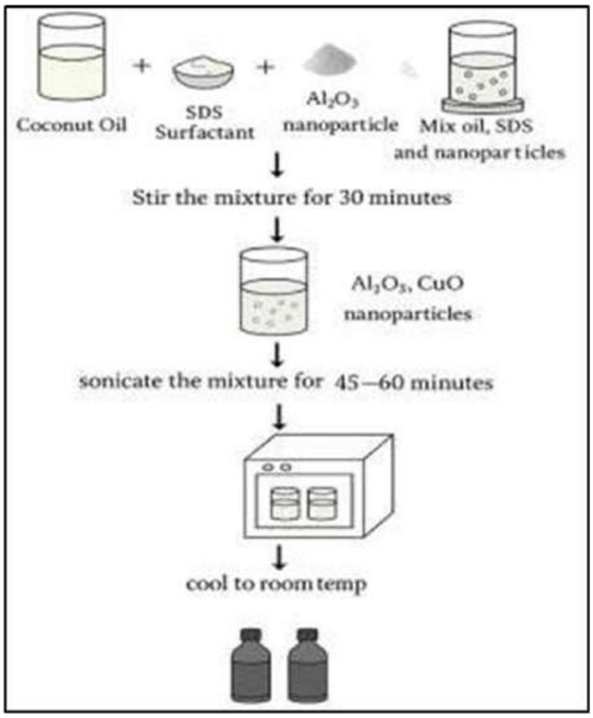

Figure 3: Synthesis process of hybrid Nanofluid

Figure 4: Preparation of Al_2O_3–CuO hybrid nanofluid (0.75% Al_2O_3 + 0.25% CuO)

3. Results and Discussion

In the current study, the biodegradability of nanofluids prepared using virgin coconut oil as a base fluid of natural origin, whose biodegradation property has been extensively reported, was assessed. The amount of CuO (0.25 vol. %) and SDS surfactant (1.0 vol. %) was maintained constant whereas the concentration of aluminium oxide (Al2O3) nanoparticle was varied i.e. 0.50%, 0.75%, and 1.00 % in order to see the effect it had on biodegradability.

As analytical methods, biochemical oxygen demand (BOD) and chemical oxygen demand (COD) tests, which wide reputation as environmental impact assessment tools, were used. Findings indicated that the difference in the values of BOD & COD grew by using more Al2O3 nano-particles, which proves the decline in the biodegradability of hybrid nanofluids.

The BOD/COD ratios recorded in the three formulas of the hybrid nanofluid used were more than 0.5 each, thus proving that they are biodegradable as per the environmental regulations. Of these formulas, Hybrid A had the highest BOD/COD ratio (0.58) and was followed by Hybrid B (0.57) and Hybrid C (0.55).

However, although Hybrid A recorded the highest BOD/COD ratio numerically, Hybrid B was considered to be optimal due to the moderately good balance of biodegradability, nanoparticle dispersion, and machining performance. The relative decrease of the ratio in Hybrid C can be explained by the increase of Al2O3 concentration (1.0 vol. %), which can reduce the percentage of organic, biodegradable content of the fluid.

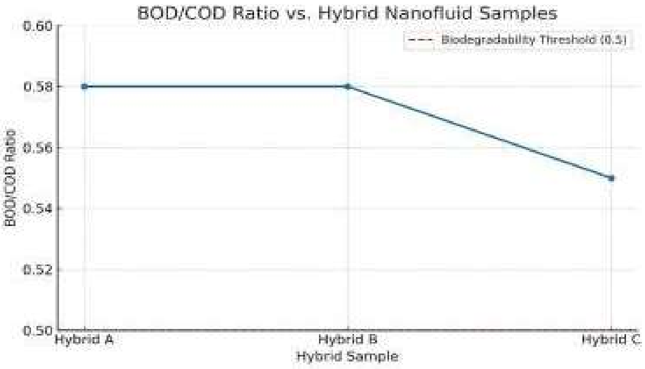

Figure 5: Plot of BOD/COD Ratio vs. Al_2O_3 concentration (Hybrid A, B, C)

The results confirm the use of Al2O3-CuO composite nanofluids in coconut oil as environmentally-sustainable replacements to mineral-based cutting fluids. There are two best combinations, Hybrid B (0.75 % Al2O3+ 0.25 % CuO)

Table 1: Biodegradability of Hybrid Nanofluids

Hybrid Sample	Base Fluid	Al2O3 (vol.%)	CuO (vol.%)	Oleic Acid (vol.%)	BOD (mg/L)	COD (mg/L)	BOD/ COD Ratio	Biodegradability
Hybrid A	Coconut Oil	0.50	0.25	1.00	108	185	0.58	Readily biodegradable
Hybrid B	Coconut Oil	0.75	0.25	1.00	105	180	0.57	Highly biodegradable
Hybrid C	Coconut Oil	1.00	0.25	1.00	98	178	0.55	Biodegradable,slightly lower

which is the optimal balance in terms of green chemistry, thermal stability and efficiency in machining under minimum-quantity- lubrication (MQL) environment.

4. Conclusion

The paper has achieved the findings on the synthesis and evaluation of biodegradability and of Aluminum Oxide (Al2O3)-Copper Oxide (CuO) hybrid nanofluids with virgin coconut oil as a base fluid and *Oleic Acid* 1% as a surfactant. The concentration of Al2O3 was altered and kept the amount of CuO and *Oleic Acid* the same to achieve three nanofluid samples (Hybrid A, B, and C) and the analysis was conducted to check the environmental compatibility using the test of BOD/COD ratio.

The BOD/COD ratios in all the samples were higher than 0.5, which proves their biodegradability and their ability to substitute conventional cutting fluids and be a more environmentally friendly product. Of them, Hybrid A (0.50% Al2O3) ranked the highest in biodegradability (BOD /COD=0.58), Hybrid B (0.75% Al2O3) was the chosen composite, which balanced biodegradability (0.57), the dispersion stability of the nanoparticle, and estimated performance in the machining process. Hybrid C (1.00% Al2O3) exhibited lesser biodegradability (0.55), as compared to the other two hybrids, probably because of augmented nanoparticle populace that lowered the organic substance.

The Al2O3- CuO / coconut oil based nanofluid thus developed, especially Hybrid B is an actual eco-friendly alternative in Minimum Quantity Lubrication (MQL) operations in the manufacturing process thus supporting the objective of sustainable manufacturing by being eco-friendly and inducing efficient lubrication.

5. Future Scope

The current paper serves as a strong basis to formulate biodegradable hybrid nanofluids that can be applied through Minimum Quantity Lubrication (MQL) in the process of CNC turning processes. To make this more prominent, the future research directions may be as follows:

i. Advanced Characterization of Nanoparticle Interaction: Zeta potential measurements should be extended to assess long-term stability of nanofluids varying environmental factors such as temperature and vibration. Further, FTIR & UV-Vis spectroscopy can be used to track chemical bonding and stability between nanoparticles, surfactant, and base fluid, both over time and after machining.

ii. Comprehensive Thermal & Oxidative Analysis: Thermogravimetric Analysis (TGA) can be further utilized to examine the thermal degradation and oxidation behavior of nanofluids during continuous or high-temperature machining cycles,

iii. Elemental & Microstructural Mapping using EDS and SEM can reveal elemental analysis and morphology

iv. Response Surface Methodology (RSM) can be expanded to optimization for machining outputs such as surface roughness, MRR and environmental sustainability.

6. Conflicts of Interest

The authors declare no conflicts of interest about the publication of this research paper.

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Next-Generation Weaving: Transforming the Indian Textile - In the Age of Industry 5.0

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Abstract:

Background: *The Indian textile industry, which is one of the oldest and most labor-intensive sectors in the world, is challenging and transforming with the introduction of Industry 5.0. The new industrial paradigm insists on a human-machine partnership, it also focuses on sustainability and resilient supply chains. The sector which is already facing problems of environmental degradation, lack of skills, and global competition, sees Industry 5.0 as the modern and strategic way of transforming operations while improving the workers' and the organization's morale and even effectiveness.*

Methods: *This descriptive study is carried out primarily by reviewing secondary data such as scholarly articles, industry reports, and government publications extensively. The study applies a thematic analysis method to investigate the impact of Industry 5.0 on the Indian textile industry, giving particular attention to the areas of technology integration, human-centered results, and sustainability.*

Results: *The study demonstrates that the turning point towards Industry 5.0 technologies allows for a combination of operational efficiency, mass customization, and environmental sustainability in the textiles sector. Also, the pairing of collaborative robots and artificial intelligence with human creativity leads to better workforce engagement, workplace spirituality, and psychological capital. On the other hand, the high implementation costs, lack of infrastructure, and limited digital skills among employees are some of the challenges that still prevent the technology from being adopted broadly.*

Conclusion: *The results indicate that Industry 5.0 can be a game changer for the Indian textile industry as it will bring about extinction through the use of technology. However, proper implementation through gradual assets allocation and reskilling of the workforce along with more tailorable laws will be needed. The industrial sector should not only focus on human but also on being environmentally friendly during the whole process as it will guarantee the textile industry's long-term competitiveness and inclusive growth.*

Keywords: *Artificial Intelligence, Industry 5.0, IoT, Robotics, Sustainability, Textile Sector.*

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1. Introduction

The global industrial landscape has witnessed rapid transformations across successive phases of industrialization; from mechanization in Industry 1.0 to automation in Industry 4.0 [1-4]. Each phase has introduced new levels of efficiency, productivity, and technological advancement [5]. However, the fourth industrial revolution, while advancing smart automation and data integration, has been critiqued for its overemphasis on technology and lack of focus on human-centric values [6]. In response, Industry 5.0 has emerged as a novel paradigm that emphasizes the synergy between human intelligence and advanced technologies, aiming to build sustainable, resilient, and human-cantered industrial systems [7].

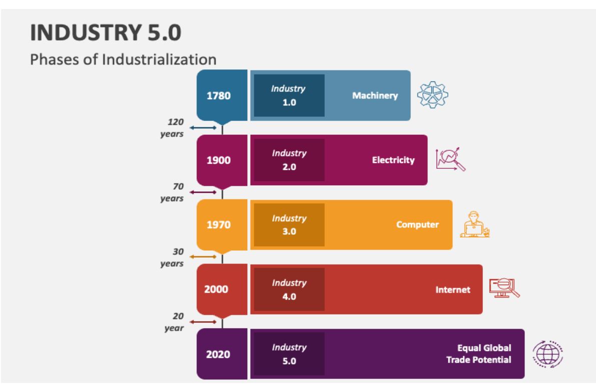

Figure 1- Phases of Industrialization

Industry 5.0 is characterized by collaborative robotics (cobots), artificial intelligence (AI), Internet of Things (IoT), and big data analytics, technologies that are no longer viewed as mere tools of automation but as partners in co-creation with human workers [8]. This shift has critical implications for labour markets, sustainability goals, and manufacturing practices, particularly in sectors such as textiles that have historically relied on labour-intensive processes and artisanal knowledge [4]. (Ref. Fig. 1 & Table 1).

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Table 1- Industry 4.0 Versus Industry 5.0

Aspect	Industry 4.0	Industry 5.0
Approach	Automation and Digitalization	Human–Machine Innovation
Efficiency and Automation	Robots and automated systems execute repetitive and precise tasks	Humans are assisted by cobots in creative and decision-making tasks
Big Data and Internet of Things (IoT)	Real-time data sharing through connected devices	Real-time data sharing through connected devices
Artificial Intelligence	Algorithms and processes that predicts failures	Algorithms and processes that predicts failures
Robot-Human Collaboration	Not applicable	Humans work alongside collaborative robots
Focus on People	Not applicable	Worker experience and well-being are enhanced
Sustainability	Not applicable	Environmentally friendly industrial practices are followed
Significance	Increased efficiency, cost reduction, improved decision-making	Improved quality of work life, production adaptability, attraction of talent
Challenges	High initial investment, infrastructure adaptation, cybersecurity concerns	Integration of advanced technology, continuous training, human–machine synergy

"(Source: https://inspenet.com/en/articulo/industry-5-0-vs-industry-4-0-benefits)"

India's textile industry, one of the oldest and most labour-intensive sectors in the world, contributes significantly to the nation's GDP, employment, and export revenues [9]. Yet, the sector faces mounting challenges including environmental degradation, rising production costs, global competition, and an urgent need for sustainable practices [10]. Moreover, textile clusters in cities such as Tirupur, Surat, and Ludhiana continue to rely on outdated machinery and conventional production methods, rendering them less competitive in the global market [11]. Against this backdrop, Industry 5.0 presents an opportunity to integrate technological innovation with India's rich textile heritage, blending precision manufacturing with human creativity and environmental responsibility [4].

As the Indian textile industry explores pathways to modernization, the transition toward Industry 5.0 is not only technological but also deeply organizational and cultural [12]. The implementation of Industry 5.0 requires investments in infrastructure, workforce reskilling, digital literacy, and ethical frameworks to ensure that human values remain central to industrial development [13]. Furthermore, for developing economies like India, the transformation must be inclusive, addressing the needs of small and medium enterprises (SMEs) that form the backbone of the textile sector but often lack the resources to adopt high-end technologies [8]. (Ref. Fig. 2).

This study aims to examine the implications of Industry 5.0 in the Indian textile industry by identifying its key characteristics, exploring its potential benefits, and addressing the barriers to its adoption [14]. By situating Industry 5.0 within the specific socio-economic and technological context of Indian textile manufacturing, the paper seeks to offer strategic insights for sustainable industrial transformation [4].

Figure 2- Industry 5.0 on Textile Sector

This study aims to examine the implications of Industry 5.0 in the Indian textile industry by identifying its key characteristics, exploring its potential benefits, and addressing the barriers to its adoption [14]. By situating Industry 5.0 within the specific socio-economic and technological context of Indian textile manufacturing, the paper seeks to offer strategic insights for sustainable industrial transformation [4].

2. Literature Review

The emergence of Industry 5.0 marks a paradigm shift from automation-driven production to a more human-centric, sustainable, and resilient industrial model [15]. Several scholars have explored its conceptual foundations, sector-specific applications, and implementation challenges, particularly in developing economies [15].

2.1 Conceptual Framework of Industry 5.0

Industry 5.0 builds upon the digital transformation of Industry 4.0 by integrating collaborative robotics (cobots), artificial intelligence (AI), and the Internet of Things (IoT) into a framework that centres on human–machine interaction, creativity, and ethical industrial practices [16, 17 & 14]. According to [18], the transition to Industry 5.0 offers three core values: human reintegration into production processes, enhanced corporate resilience, and environmental stewardship [19]. Their Delphi-based study identified 33 technological capabilities that underpin this transition, including human-centric automation, data-driven personalization, and waste minimization in the clothing sector [20-23 & 19].

Through a systematic review of 58 articles from 2012 to 2022, proposed a theoretical production model for Industry 5.0 within textile SMEs [7]. Their findings emphasize that although interest in sustainable, resilient, and human-focused models has grown, there remains a significant lack of practical implementation and clarity around the essential components required for operationalizing Industry 5.0, especially in small and resource-constrained enterprises [8].

2.2 Technological Evolution and Indian Textile Sector

The Indian textile industry has a rich historical legacy but remains largely dependent on traditional and manual production processes [5]. Research literature [10] highlights the disjunction between global technological advancements and India's textile hubs, noting that despite India's contribution to the global market, its adoption of advanced technologies is fragmented and slow. The study argues that aligning technological upgrades with the country's economic goals and industrial policy is essential for maintaining global competitiveness [19].

Furthermore, [8] contend that SMEs in India, which constitute the majority of textile enterprises, face structural barriers in transitioning to Industry 5.0. These include high capital requirements, insufficient infrastructure, and limited access to upskilling opportunities for employees [10]. The authors warn that without targeted policy and financial support, SMEs may lag behind in adopting new technologies, thereby widening the productivity and innovation gap with larger firms [6].

2.3 Human-Centricity and Workforce Transformation

The core differentiator of Industry 5.0 lies in its emphasis on human-centricity, reintegrating the workforce into collaborative and decision-making roles alongside intelligent machines. Industry 5.0 moves beyond mere efficiency and productivity [14], reaffirming the role of industry in advancing societal well-being and sustainability. In the context of the textile industry, this entails re-skilling workers, promoting workplace spirituality, and fostering psychological capital to ensure a smooth transition and enhanced work satisfaction [5].

However, the transition also brings psychological and organizational challenges [5]. A study by [8] identifies employee resistance, fear of job loss, and low digital literacy as key hindrances to embracing human–machine collaboration. Therefore, fostering trust, transparency, and participatory change management practices are critical to the success of Industry 5.0. (Ref. Table 2).

Table 2 – Impact of Industry 5.0 on Profitability

Factors	Impact on Profits
AI and Automation in 5.0	Product cost cut down by 15–20%
Energy-Efficient Techniques and Methods	Energy consumption lowered by 10–15%
Circular Economy	Raw material costs saved by 5–10%
Mass Customization	Sales increased by 10–15%

"(Source: https://www.fashionatingworld.com/new1-2/industry-5-0-weaving-a-new-future-for-indian-textiles)"

2.4 Identified Gaps and Research Opportunity

While existing literature offers a robust theoretical base for Industry 5.0, empirical studies focusing specifically on the Indian textile sector remain limited. Few studies systematically assess how human-centric technologies can improve organizational sustainability, employee well-being, and industrial resilience in the Indian context. There is also a noticeable gap in research addressing the interplay between technological adoption and workplace outcomes such as psychological capital, work stress, and workforce adaptability [9].

This study seeks to address these gaps by exploring the strategic implications of Industry 5.0 for Indian textile manufacturing, with a focus on the barriers, enablers, and transformative outcomes relevant to SMEs and policy stakeholders.

3. Objectives of the Study

Building upon existing literature and practical challenges in the Indian textile sector, this study is positioned to understand the multifaceted implications of Industry 5.0, particularly its convergence with human-centric innovation, sustainability, and workforce transformation. The key objectives of this research are:

i. To delineate the core characteristics of Industry 5.0 and its relevance to the Indian textile manufacturing sector.

ii. To analyse the influence of Industry v5.0 on production efficiency, labour dynamics, and environmental sustainability.

iii. To explore the benefits and constraints associated with implementing Industry 5.0 technologies in Indian textile enterprises, especially small and medium-sized enterprises (SMEs).

iv. To examine the role of human–machine collaboration in enhancing workplace well-being, with a focus on psychological capital and workplace spirituality.

v. To provide actionable insights and strategic recommendations for policymakers and industrial leaders aiming to transition toward Industry 5.0–enabled textile manufacturing.

These objectives aim to bridge the existing knowledge gap by combining technological innovation with human-centric outcomes, thereby contributing to sustainable industrial advancement in emerging economies like India.

4. Research Methodology

This research adopts a descriptive and exploratory design, drawing upon secondary data from peer-reviewed journal articles, industrial whitepapers, policy documents, and reputable digital repositories. The rationale for selecting a qualitative-descriptive method lies in its ability to explore nuanced dimensions of a relatively under-researched phenomenon; Industry 5.0 in the Indian textile context; through interpretive synthesis and thematic exploration [15]. The study primarily sources insights from recent publications between 2019 and 2025, including those indexed in Scopus, Web of Science, and databases like ScienceDirect and SpringerLink. Thematic analysis is employed to categorize findings under key domains such as: technological applications, workforce transformation, sustainability, and adoption challenges. Sources such as PwC (2024), [14], and studies by [18, 8], and [7] provide a comprehensive empirical foundation for the discussion. This method is particularly appropriate for synthesizing evolving industrial paradigms where real-time field data may be limited but where policy and scholarly interpretations offer rich insights.

5. Advantages of Industry 5.0 in the Textile Industry

5.1 Human-Centric Manufacturing

Industry 5.0 repositions human workers at the core of industrial processes, combining artisanal skill with intelligent automation. The use of collaborative robots (cobots) allows for creative co-production, where machines handle repetitive tasks while humans oversee design, customization, and decision-making [14, 5]. This synergy promotes not only higher output quality but also worker satisfaction and engagement.

5.2 Mass Customization

Consumer demand has shifted from mass production to personalization. Industry 5.0 leverages AI and data analytics to facilitate mass customization in textile design, enabling producers to tailor fabric types, colours, and fits at scale [7]. This customization improves market responsiveness and consumer loyalty.

5.3 Environmental Sustainability and Green Practices

Industry 5.0 facilitates the integration of circular economy principles into manufacturing. Techniques like waterless dyeing, smart energy grids, and waste tracking using IoT reduce environmental footprints while complying with global ESG mandates [12, 11].

5.4 Global Competitiveness

By adopting cutting-edge technologies such as 3D weaving, robotics, and blockchain-enabled supply chains, Indian textile firms can compete more effectively with global players like China and Bangladesh [19]. Industry 5.0 acts as a differentiator in terms of both quality and sustainability metrics.

5.5 Workforce Empowerment and Skill Development

Rather than rendering labour obsolete, Industry 5.0 encourages re-skilling and up-skilling. Workers become collaborators in the production process, enhancing their sense of agency and reducing fear of redundancy [8, 5].

5.6 Enhanced Efficiency and Quality Control

Predictive analytics and smart monitoring allow firms to detect defects early, optimize production cycles, and reduce downtime. These capabilities lead to better quality assurance and reduced operational costs [6]. (Ref. Fig. 3).

Figure 3 - Advantages of Industry 5.0 for Textile Industry

6. Bottlenecks to Adopting Industry 5.0 in Indian Textile Sector

6.1 High Capital Investment

Advanced technologies such as cobots, IoT-enabled looms, and AI systems demand significant capital outlay, posing a challenge for SMEs that dominate the Indian textile landscape [8].

6.2 Skill Gap and Digital Illiteracy

There is a substantial gap in the technical expertise required to operate and maintain smart machines. Most Indian textile workers lack formal training in emerging technologies [7].

6.3 Resistance to Technological Change

In traditional textile hubs like Surat and Tirupur, entrenched mindsets and fear of job displacement create resistance to adopting new technologies [10].

6.4 Infrastructure and Connectivity Limitations

Many textile clusters suffer from unreliable internet access, power fluctuations, and logistical bottlenecks, each of which hampers the smooth implementation of Industry 5.0 [11].

6.5 Limited Financial Access for SMEs

SMEs, which comprise nearly 80% of the textile sector, often struggle to secure financing for digital transformation initiatives. Government schemes are either insufficient or poorly targeted [18].

6.6 Data Privacy and Cybersecurity

As Industry 5.0 increases digital dependency, it also heightens vulnerability to cyber threats. The lack of robust cybersecurity frameworks in Indian firms is a pressing concern [12].

6.7 Global Competitive Pressure

While India is transitioning from Industry 4.0 to 5.0, other nations like China are already reaping the benefits of smart, sustainable manufacturing. The gap in readiness may widen if India does not accelerate its transformation [24].

7. Results and Discussion

This study reveals that the integration of Industry 5.0 into the Indian textile sector is not merely a technological upgrade but a paradigm shifts toward sustainable, inclusive, and human-cantered industrialization. The findings suggest that firms implementing Industry 5.0 technologies have the potential to enhance operational efficiency, achieve product differentiation, and reduce environmental impact. Simultaneously, psychological outcomes such as increased workplace spirituality and enhanced psychological capital can foster employee resilience and reduce occupational stress.

Nonetheless, successful integration hinges on resolving systemic challenges including workforce preparedness, infrastructural inadequacies, and financial constraints, particularly within SMEs. Interventions such as the Government of India's MITRA Scheme (Mega Integrated Textile Region and Apparel) could play a catalytic role in facilitating infrastructure upgrades and workforce training [9]. A multi-stakeholder approach involving industry, academia, and government is essential to ensure a smooth transition.

8. Conclusion

Industry 5.0 presents a strategic opportunity for the Indian textile industry to modernize, compete globally, and transition toward more sustainable and inclusive business models. However, the sector remains constrained by capital limitations, digital illiteracy, outdated infrastructure, and organizational inertia. Overcoming these challenges requires targeted policy support, robust infrastructure development, and industry-wide skill enhancement programs.

For Indian manufacturers to fully leverage the potential of Industry 5.0, strategic focus must be placed on fostering innovation ecosystems, enabling access to finance for SMEs, and embedding human-centric principles into industrial design and operations. Future research could focus on empirical assessments of psychological capital and workplace spirituality in Industry 5.0-enabled firms, thereby further integrating technological and human development paradigms.

8.1 Limitations and Future Research Directions

While this study offers valuable insights into the transformative potential of Industry 5.0 within the Indian textile sector, it is not without limitations. First, the study is based primarily on secondary data and conceptual synthesis, which, while methodologically sound for exploratory purposes, limits empirical generalizability. The lack of field-based primary data restricts our ability to validate the practical implementation of Industry 5.0 technologies across different organizational contexts, particularly SMEs.

Second, the human-centric dimensions explored, such as workplace spirituality, psychological capital, and work-related stress, are conceptually integrated into the discussion, but not empirically measured. Future research should consider conducting quantitative or mixed-method studies to examine how these variables are influenced by specific Industry 5.0 interventions in textile manufacturing.

Third, the sectoral focus of this study is primarily limited to Indian textile clusters. While this offers contextual depth, it may not capture inter-sectoral or international variations in Industry 5.0 readiness, adoption, or outcomes. Comparative studies across manufacturing domains or cross-country analyses could enrich future findings.

Future research directions:

- Empirical validation of the proposed advantages of Industry 5.0 using structured surveys or case studies.
- Investigating the mediating role of psychological capital in the relationship between human–machine collaboration and employee well-being.
- Longitudinal studies tracking the impact of Industry 5.0 adoption on sustainability metrics, operational efficiency, and employee productivity.
- Policy analysis to assess the effectiveness of government schemes (e.g., MITRA) in accelerating Industry 5.0 adoption in SMEs.

Such directions can contribute to the development of a robust, evidence-based framework for implementing Industry 5.0, one that simultaneously enhances economic competitiveness, environmental stewardship, and human development in India's manufacturing ecosystem.

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Role of Textile-Based Fruit Covering Bags in Fruit Protection and Quality Improvement – A Review

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Abstract:

To produce high-quality fruits, constant monitoring and care are necessary. Constant care can be done in several ways. Generally, protective layers of textile-based fruit bagging stand out among the several methods. In this review paper, different types of fruit bags are reviewed and compared in terms of different qualities along with the results of fruit quality. In addition, it can reduce pest infestations, notably fruit flies, and minimize pesticide residues. It may help to regulate the harvesting process.

Keywords: *Agro-Textile, fruit bagging, Physical and Mechanical properties, Textile material*

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1. Introduction

Many good agricultural practices (GAP) are gaining popularity globally to produce fruits [1, 2]. The fruits can achieve the desired colour, texture, and flavour by the fruit bag's regulated atmosphere. Fruit bags maximize the ripening process. Fruit crops include apples, pears, peaches, citrus fruits, mangoes, grapes, guavas, Papaya and so on, and get benefited greatly from this method. Because of superior strength, durability, elongation, and other qualities, synthetic fibres are chosen over natural fibres as fruit bag materials. As fruit bags commonly utilized materials include nylon, polyester, polyethylene, and polypropylene [3]. In addition to improving their appearance, bagging is a physical protective method that alters the microenvironment of fruit development and lowers the likelihood of fruit cracking. They also help in shielding the fruits from fruit fly attacks and stop moths from laying eggs. Plastic bags (Nonwoven and Film), paper sacks, or cloth bags (Woven) can be used for this purpose. The bagging technique, was first utilized in Japan in the 20th century for pears and grapes. Some farmers made basic paper sacks by folding and stapling old newspapers together rather than buying bags which were helpful to improve some fruit qualities [4]. Fruit protective bags should be long-lasting, effective, and appropriate for use in fruit cultivation. Their mechanical qualities are essential. ISO Standards (e.g., ISO 874, ISO 6660) are used to measure these attributes to assess their resilience to environmental influences, handling stress, and possible harm and measuring fruit quality attribute [5].

1.1 Objectives of study

To review and classify textile-based fruit covering bags and to evaluate its physical and mechanical properties

i. To assess the impact of textile-based fruit bagging on fruit quality,

ii. To compare the performance and suitability of various bagging materials for different fruit crops and cultivation conditions, based on reported literature.

Some quality requirements of fruit bags are listed below:

Here some quality requirements of fruit bags related to air, water, and light permeability, along with their functional importance in improving fruit quality are given.

- Air Permeability: Air permeability is the measure of how easily air can pass through a material. It's often measured in terms of the volume of air passing through a specific area in a given time ($cm^3/cm^2/s$). [6] It ensures adequate oxygen for the fruit, and suppresses mold growth. It allows fruit respiration and prevents condensation. Ideal range for bag is 10 to 700 $cm^3/cm^2/s$.
- Water Permeability: It is the rate at which moisture vapor passes through a material ($g/m^2/day$). It helps to maintain fruit hydration without trapping excess moisture. Controls fruit humidity and prevent spoilage. Water Permeability range for fruit bag are 5 to 800 $g/m^2/day$. [7]
- Light Transmission: Light transmission allows filtered sunlight to reach the fruit. Fruit bags regulate photosynthesis inside the Bag. It helps maintain normal physiological activity during development. Adequate light exposure promotes uniform and natural skin colour, improving market value. Light transmission range is 5 % to 90 %. Depends on type of bags. [7]

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Table 1: Comparative studies on fruit bagging materials and their influence on fruit quality

Fruits	Recommended Bag Type	Effect Observed	Reference
Litchi	Cellophane or Fabric Bags	Enhanced color improvement	Hu et al., 2001
Peach	Orange & Black Bags	Better skin color	Hu et al., 2001
Date Palm	Black or Blue Polyethylene Bags	Enhanced skin color	Awad, 2007
Apple	Paper Bags	Improved color and protection	Dong et al., 2007
Peach	Transparent Polypropylene Micro-Perforated Bags	Better ripening and color	Coelho et al., 2008
Pear	White-Coated Bags	Improved fruit quality	Lin et al., 2008
Peach	White-Coated Bags	Color improvement	Kim et al., 2008b
Mango	Brown Paper Bags	Reduced fruit fly infestation	Sarker et al., 2009
Guava	Nylon Bags	Protection against fruit fly	Morera-Montoya, 2010
Mango	Brown/Black Paper Bags	Better color improvement	Ding & Syakirah, 2010
Apple	Spun-Bound Light-Yellow Fabric Bags	Enhanced color and quality	Sharma et al., 2013
Papaya	non-woven or spun-bound fabric bags	Could improve color and protect against sunburn	PubMed NCBI 2013
Banana	Polypropylene (PP) Non-Woven Bags	Color uniformity and insect control. Fruit maturity, enhanced weight, texture, visual appeal, and functional attributes significantly reduced fruit drop and provided complete control of fruit fly, anthracnose, and bird damage	PubMed NCBI 2013

2. Bagging Material

Fruits may be significantly impacted by the type and material of the fruit bag. A bag designed for one fruit might not be suitable for another. The choice of material has been the subject of numerous investigations, with conflicting findings. The list of research studies shown in Table 1. provides strong evidence for the effectiveness of different bagging materials in improving fruit color, quality, and protection from pests [8, 9].

Different types of Bagging Materials are reviewed in short and presented in the following segments.

2.1 Paper Bags

Paper is a very easily available commodity it shows high water absorption due to its cellulosic composition [10]. Cellulosic composition of paper bags makes them eco-friendly, biodegradable, and breathable [11]. However, due to short chain length of cellulose paper bag usually show inferior mechanical stability. Farmers even use plain waste newspaper to create fruit specific protective layers by stapling the same. And it is the oldest and greatest option for growers since it is ecologically friendly, insect and bird-proof, antibacterial, light-transmitting, and increases plant yield [12].

Figure 1: Paper Bag (image source: https://www.amazon.in/Fruit-Protection-Growth-Covers)

2.2 Plastic Bags

Most available material other than paper are plastic bags usually they are made from Polyethylene, Polypropylene, polyester. Due to higher molecular weight and inherent hydrophobic nature of these polymers, the resultant plastic bags are mechanically very stable, biostable, and poor water and air permeability [13].

Figure 2: Plastic Bag (www.indiamart.com)

2.3 Non-Woven Fruit Bags

To improve water and air permeability of afford plastic bags, without harming their inherent mechanical properties, non-woven structured made from PP, PE, and PET are used to create non-woven-based plastic fruit bags [14]. They are mostly white, odourless, and soft. Usually, 5 to 10 Denier filaments are used for nonwoven synthetic. Due to their higher molecular weight in comparison to cellulosic bags they provide better mechanical stability. PP, PE, and PET show inherent water resistance, which helps to protect fruits from overexposure to water. However, due to the porous construction of nonwoven, they show better light transmission, air and moisture permeability, than the nonporous counterparts. Thus, they are capable to control microenvironment of fruits in terms of low-level temp and moisture variation [15]. The non-woven fabric bags are more effective in prevention of pests, diseases, isolation from pesticides, and insect eggs. It also helps in preventing the spread of germs, infection, and fruit damage. They provide physical barriers to birds, bats, and other animals from harming the fruits. They act as a barrier between air and waterborne harmful substances [16]. Young fruits can develop and grow nicely. Ultimately, fruits become juicier, waxy peel, juicy, and tenderness of the flesh. [17]

Figure 3: Nonwoven Bag (Image source: https://jqnonwoven.en.made-in-china.com/)

2.4 Woven and Knitted Fruit Bags

Other than than fibrous form textile material yarn is also used to create fruit bags. Usually woven and knitted structures are used to create such bags. Woven textile material is very popular in agro textile, specifically used as mulch mats, shade cloths etc. [18]. Very few mansions and reference has been found which narrates woven fruit bags. One such woven fruit bag forming material is jute. Though the commercial availability of such jute-based woven fruit bags is not pronounced.

Figure 4: Woven and Knitted fruit Bag (image source: https://pdfs.semanticscholar.org/)

3. Textile-Based Fruit Bagging: Influence of Timing and Material Selection

Following Fruit bagging has been shown to improve fruit quality when applied at suitable stages of fruit development using appropriate materials. The start time of bagging and the type of bag used play a crucial role in determining the final fruit quality. [19]

Table 2: The effects of different types of bagging on Fruit Quality

Fruits	Bagging start	Types of bags	Effect	Ref.
Mango	30 days prior to harvest	Black polybag, transparent polybag, brown paper	Higher total soluble sugars in it with better fruit quality	Sarkar et al., 2009
Apple	40–50 days prior to harvest	standard Kraft paper	reduction in lenticel	Sharma et al., 2013
Guava	30 days after pollination	nylon nets, non-woven polypropylene, butter paper, and brown paper	advanced fruit maturity, improved fruit weight, texture, visual appeal, quality, and functional attributes	Sharma et al., 2013
Litchi	15 and 30 days after full	cellophane or fabric	better fruit color/shape appearance	Ali et al., 2021
Grape	after fruit set	non-woven UV stabilized polypropylene of different colors	Good yield	Debnath and Mitra, 2008

4. Characteristics of Fruit Bags

Weather elements like temperature, sunlight, rainfall, wind, humidity, and storms play vital role in determining fruit quality. Optimal conditions promote better size, sweetness, color, and shelf life. Extremes or Imbalances can cause physical damage, diseases and reduced market value. Proper climate management and protective measures are essential for maintaining high fruit quality. Fruit bagging is the process to enhance fruit quality with protective layers. [21] It also helps to preserve them from biological and environmental hazards. The effectiveness of these bagging materials is mostly determined by their mechanical and physical characteristics, including air and moisture permeability, durability, and light transmission. [22].

4.1 Mechanical properties of different types of Fruit Bags

Some mechanical and structural qualities like tensile strength, tearing resistance, elongation at break, material thickness, GSM, UV resistance etc. help to protect from environmental influences and control the microenvironment of the fruit. These attributes are assessed by different standardized examinations to evaluate their resilience against environmental influences handling stress and possible harm. The statistical mechanical characteristics evaluated in fruit bags are listed below [23, 24].

physical and mechanical stability of different types of fruit bags are represented in table 3 and table 4. Polyethylene bags excel in tear resistance, UV resistance, and in light weight. They are durable but potentially less breathable. Nonwoven bags have high burst strength and moderate tear resistance. Thus, they can be a balanced choice. Paper bags perform the worst in tear and burst strength. They are least durable choice with moderate breathability. [25]

Following Table 3 and. 4 show a comparative representation of commercially available fruit bag materials and its mechanical Properties.

Following Table 5 and. 6 show a comparative representation of commercially available fruit bag materials and its Physical Properties.

Table: 3 Mechanical properties of commercially available fruit bag materials

Material	Tensile Strength	Elongation	Tear Resistance	Permeability
Polyethylene (PE)	Moderate	High	Moderate	Low (non-perforated)
Polypropylene (PP)	High	Moderate	High	Low (non-perforated)
Mesh (nylon/plastic)	Low	High	Low	High (breathable)
Jute/Cloth Bags	Low-Moderate	Low	High	High (breathable)
Polyethylene (PE)	Moderate	High	Moderate	Low (non-perforated)

Table 4: Comparative analysis of Fruit Bags Mechanical Properties

Property	Paper Bags	Non-Woven Bags	Polypropylene Bags (Non-porous plastic bags)
Tensile Strength	10–20 MPa	20–50 MPa	15–40 MPa
Elongation at Break	2–4%	20–50%	100–400%
Tear Resistance	50–200 N/m	200–500 N/m	300–800 N/m
Burst Strength	150–400 kPa	500–1000 kPa	800–2000 kPa
UV Resistance	Low	Moderate	High
Water Vapor Permeability	20–50 $g/m^2/day$	10–30 $g/m^2/day$	0.5–5 $g/m^2/day$
Weight (gsm)	30–80	50–150	-
Thickness (microns)	-	-	20–100

Table 5: Different Bagging material with Physical Properties

Properties	Paper Bags	Plastic Bags (Polypropylene)	Nonwoven Fruit Bags (PP/PLA etc.)
Air Permeability ($cm^3/cm^2/s$)	Moderate to High (100–250)	Moderate to High (200–700)	Moderate to High (<10)
Water Permeability ($g/m^2/day$)	Low (hydrophilic but limited) (<50)	Low (hydrophilic but limited) (100–1000)	Low (hydrophilic but limited) <5
Light Transmission (%)	Low (hydrophilic but limited) (0–5%)	Very Low (opaque) (20 -60 %)	Very Low (opaque) (70–90%)

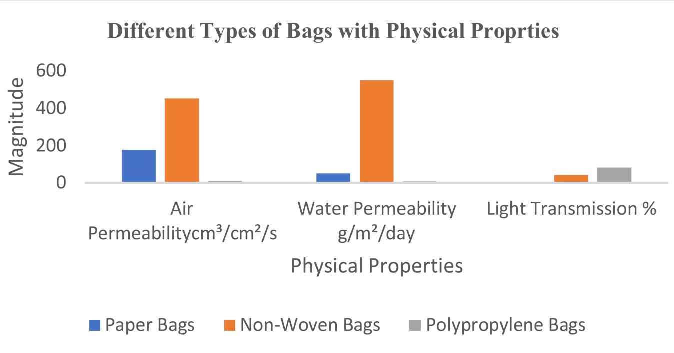

Figure 5: Different Bagging material with Physical Properties

Depending upon data represented in Table 5, permeability performance of different types of fruit bags is represented graphically in fig. 5. Non-woven bags exhibit the highest air and water permeability with moderate light transmission, making them suitable for fruits which required ventilation. Paper bags offer minimal light and water permeability. They are ideal for shading. Polypropylene bags provide maximum light transmission and act as strong moisture and air barrier. They are suitable for water-sensitive fruits.

4.2 Effect of Different Types of Fruit Bags on the Quality of Fruits

Different types of fruit bags have different performance profile. Thus, their performance in terms of control over fruit's microenvironment is variable with respect to type of the bags and fruits. Following table 6 presents a comparative analysis of the effectiveness of three types of fruit bagging materials paper bags, nonwoven bags, and plastic bags in protecting fruits and resultant fruit quality [26].

Table 6: Comparative Effectiveness of Fruit Bagging Materials on Quality and Protection Parameters

Parameters	Paper Bags	Nonwoven Bags	Plastic Bags
Protective Performance			
Pest Infestation Reduction (% control)	60–75%	85–95%	70–80%
Disease Incidence Reduction (%)	50–65%	80–90%	60–75%
Chemical Spray Reduction (%)	40–60%	70–90%	30–50%
Fruit Quality			
Self-Life Extension (days)	+3–5 days	+6–10 days	+2–4 days
Ripening Uniformity (% fruits evenly ripened)	70–80%	85–95%	60–75%
Fruit Surface Quality Improvement (% clean fruits)	75–85%	90–95%	65–75%
Average Fruit Size Increase (%)	5–10%	10–15%	3–8%
Sunburn Damage Reduction (%)	60–70%	80–90%	50–60%

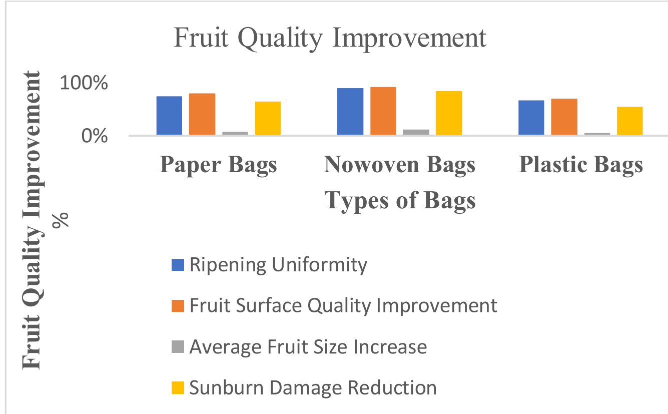

Figure 6: Effect of Fruit Bag Types on Fruit Quality Parameters

It visually highlights how nonwoven bags consistently outperform others, especially in pest/disease control, shelf life, and fruit surface quality. Paper bags are biodegradable and moderately effective across categories. Plastic bags offer limited advantages and may create microenvironments that reduce overall fruit quality. Nonwoven bags clearly enhance all key fruit quality traits compared to paper and plastic options. [27]

5. Critical analysis of Fruit Bagging from the Farmer's Perspective

Although fruit bagging offers clear advantages in terms of improved fruit quality and reduced pest damage, its adoption by farmers is influenced by several practical and economic considerations. The initial cost of bagging materials, particularly non-woven and UV-stabilized textile bags, and the additional labour required for bag application and removal can increase production costs, making the practice less attractive for small and marginal farmers. Improper selection of bag type or incorrect timing of bagging may lead to excessive heat and moisture accumulation, adversely affecting fruit physiology and potentially reducing quality rather than enhancing it. [28] Reusability and disposal of synthetic bags pose environmental and logistical challenges, especially in regions lacking organized waste management systems. Furthermore, the benefits of bagging are crop- and location-specific; thus, uniform adoption without localized validation may not yield consistent economic returns. [29,30]. Therefore, while fruit bagging is a promising technology for quality enhancement, its successful implementation at the farm level requires careful material selection, cost–benefit analysis, farmer training, and the development of affordable, biodegradable textile alternatives to ensure long-term sustainability and widespread acceptance.

6. Conclusion

The present review highlights and statistical analysis shows critical role of textile-based fruit covering bags in improving fruit quality, minimizing pest and disease incidence, and enhancing the commercial value of fruit. Bagging acts as a microclimate regulator, safeguarding developing fruits from adverse environmental elements and biological threats, while influencing physiological parameters like color development, ripening, texture, and self-life.

Among the bagging materials studied Paper, Non-Woven, and Plastic Bags each demonstrates unique performance profiles:

- Paper bags, being biodegradable and cost-effective, offer moderate protection and are suitable for eco-conscious practices, although they lack durability and mechanical strength.
- Non-Woven bags emerged as the most balanced and effective option, offering superior pest and disease protection, enhanced fruit appearance, better regulation of temperature and humidity, and significantly extended shelf life. Their porous structure supports ventilation and moisture control, making them ideal for quality-sensitive and high-value fruits.
- Plastic bags, particularly polyethylene and polypropylene films, provide excellent mechanical strength and water resistance but are limited by low permeability. While they offer robust protection in wet or pest-heavy environments, improper usage can negatively impact fruit physiology due to heat and moisture build-up.

The findings suggest that non-woven bags are the best options for optimizing fruit quality, extending self-life, and minimizing pest damage. The selection of the appropriate bagging material should be based on specific fruit types, environmental conditions, and commercial objectives. Further research and innovations in bagging technologies could refine these materials to enhance sustainability, cost-effectiveness, and efficiency in fruit cultivation.

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Psychological Wellbeing and Job Performance in the Textile Industry

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Abstract:

Background:

The textile industry is inherently labour intensive, characterized by demanding production schedules, repetitive tasks, and strong dependence on human effort. These conditions place considerable psychological demands on employees, making their psychological wellbeing a crucial factor for sustaining productivity and organizational effectiveness. Although employee wellbeing has gained attention in management research, empirical evidence explaining how psychological wellbeing influences job performance particularly through behavioural mechanisms remains limited within the textile industry context.

Methods:

A quantitative research design was employed using primary data collected from 220 employees working in textile manufacturing units. Data were gathered through a structured questionnaire comprising validated measurement scales adapted from established literature to assess psychological wellbeing, work–life balance, organizational citizenship behaviour, and job performance. Descriptive statistics were used to summarize respondent characteristics, while correlation analysis examined relationships among variables.

Results:

The findings reveal a significant positive relationship between psychological wellbeing and job performance ($r = 0.48$, $p < 0.01$), indicating that employees with higher levels of psychological wellbeing demonstrate superior performance outcomes. Regression analysis further confirms that psychological wellbeing significantly predicts job performance ($\beta = 0.36$, $p < 0.01$). Mediation analysis shows that both work–life balance and organizational citizenship behaviour partially mediate this relationship, suggesting that psychologically healthy employees perform better not only directly but also through improved balance between work and personal life and increased engagement in discretionary, prosocial workplace behaviours.

Conclusion:

The study underscores the strategic importance of psychological wellbeing as a key performance driver in the textile industry. By empirically demonstrating the mediating roles of work–life balance and organizational citizenship behaviour, the research contributes to textile management and human resource literature. The findings suggest that textile organizations should adopt wellbeing-focused human resource practices to foster sustainable employee performance and long-term organizational success.

Keywords: *Job Performance, Organizational Citizenship Behaviors, Psychological Wellbeing, Textile Industry, Work–Life Balance*

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1. Introduction

The textile industry plays a vital role in economic development and employment generation, particularly in developing economies. Despite rapid technological advancements, the industry remains highly labor-intensive, requiring sustained human involvement across the textile value chain. Employees in textile organizations often face demanding work conditions, including long working hours, strict production targets, shift work, and repetitive tasks. These conditions can adversely affect psychological wellbeing, which in turn influences job performance and organizational effectiveness.

Psychological wellbeing refers to an individual's mental health, emotional resilience, and capacity to manage stress and workplace challenges. In recent years, organizations have increasingly recognized that employee performance is not solely determined by technical skills or machinery but is strongly influenced by psychological and behavioral factors. In the textile industry, where productivity and quality are closely linked to human effort, psychological wellbeing becomes a critical performance enabler.

Work–life balance is an important dimension of employee wellbeing, particularly in industries with rigid schedules and high workloads. Poor work–life balance can lead to fatigue, burnout, and reduced job satisfaction, ultimately affecting productivity. Employees who experience a healthy balance between work and personal life are more likely to remain motivated, focused, and committed to organizational goals. In the textile sector, achieving work–life balance can be challenging, making it a crucial area of investigation.

Organizational citizenship behavior represents discretionary

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employee behaviors that go beyond formal job requirements, such as helping colleagues, maintaining a positive work attitude, and supporting organizational initiatives. OCB is especially important in textile operations where teamwork, coordination, and cooperation directly impact production efficiency and quality. Employees with higher psychological wellbeing are more likely to demonstrate such positive behaviors, thereby contributing to improved organizational performance.

Although prior studies have examined psychological wellbeing, work–life balance, and job performance across various sectors, limited research has focused specifically on the textile industry. Moreover, the combined mediating role of work–life balance and organizational citizenship behavior in the relationship between psychological wellbeing and job performance remains underexplored. This study seeks to address this gap by empirically examining how psychological wellbeing enhances job performance in the textile industry through these two key mechanisms.

The objectives of this study are threefold: first, to assess the impact of psychological wellbeing on job performance in the textile industry; second, to examine the role of work–life balance as a mediating factor; and third, to analyze the influence of organizational citizenship behavior on the wellbeing–performance relationship. By integrating psychological and organizational perspectives, this research aims to provide valuable insights for improving workforce productivity and sustainability in the textile sector.

This study makes a significant contribution to the existing literature by empirically establishing psychological wellbeing as a critical performance enabler within the labor-intensive textile industry, a context that has received limited scholarly attention. By simultaneously examining the mediating roles of work–life balance and organizational citizenship behavior, the study advances existing wellbeing–performance frameworks beyond simple direct relationships and uncovers the behavioral mechanisms through which employee wellbeing translates into improved job performance. The findings enrich textile management and organizational behavior literature by providing sector-specific evidence that psychological and behavioral factors are as vital as technical efficiency in enhancing productivity. Additionally, the study offers actionable insights for textile managers by demonstrating that wellbeing-oriented human resource practices can foster better balance, discretionary work behaviors, and sustainable performance outcomes in demanding manufacturing environments.

Although psychological wellbeing has been widely examined across service and knowledge-based sectors, empirical evidence within labor-intensive manufacturing industries, particularly the textile industry, remains limited. Existing studies often examine wellbeing and job performance as a direct relationship, overlooking the underlying behavioral mechanisms through which wellbeing influences performance outcomes. Moreover, the combined mediating roles of work–life balance and organizational citizenship behavior have received inadequate attention in textile industry research, where workforce efficiency, coordination, and discretionary effort are critical for productivity. This lack of sector-specific empirical investigation highlights a significant research gap in understanding how psychological wellbeing translates into performance within textile manufacturing environments.

This study addresses the identified research gap by empirically examining psychological wellbeing as a performance enabler in the textile industry. By integrating work–life balance and organizational citizenship behavior as mediating mechanisms, the study extends existing wellbeing and performance frameworks to a textile management context. The findings contribute to textile management literature by providing evidence-based insights into how psychological and behavioral factors influence employee performance in labor-intensive textile operations. The study further offers practical implications for textile managers seeking to enhance productivity, workforce stability, and operational efficiency through wellbeing-oriented human resource strategies.

1. To examine the effect of psychological wellbeing on job performance in the textile industry.
2. To analyze the mediating role of work–life balance in the relationship between psychological wellbeing and job performance.
3. To examine the mediating role of organizational citizenship behaviour in the relationship between psychological wellbeing and job performance.

Psychological wellbeing has a significant positive influence on job performance in the textile industry.
Work–life balance mediates the relationship between psychological wellbeing and job performance in the textile industry.

Organizational citizenship behavior mediates the relationship between psychological wellbeing and job performance in the textile industry.

2. Methodology

Research Design

This study adopts a quantitative research design to examine the relationship between psychological wellbeing, work–life balance, organizational citizenship behavior, and job performance in the textile industry. A cross-sectional survey approach was employed to collect primary data from textile industry employees. The quantitative approach was considered appropriate as it allows statistical testing of hypothesized relationships and mediating effects among the study variables.

Population and Sample Size

The population of the study comprises employees working in various segments of the textile industry, including spinning, weaving, and garment manufacturing, and processing units. A total of 220 respondents were selected using a stratified random sampling technique to ensure adequate representation across different operational units and job roles.

The selected sample size is considered statistically adequate for regression and mediation analysis, as suggested by prior empirical studies in industrial and textile management research. A sample size exceeding 200 respondents provides sufficient statistical power to generate reliable and generalizable results.

Simple Questions

1. How many years of experience do you have in the textile industry?

o ☐ Less than 5 years
o ☐ 5–10 years
o ☐ 10–15 years
o ☐ More than 15 years

2. Does your organization provide support programs for employee wellbeing?

o ☐ Yes
o ☐ No

3. Are you satisfied with your current work schedule in the textile unit?

o ☐ Yes
o ☐ No

4. Do you feel motivated to perform beyond your formal job responsibilities?

o ☐ Yes
o ☐ No

5. Do you believe that mental wellbeing directly affects productivity in the textile industry?

o ☐ Yes
o ☐ No

Data Collection Instrument

Primary data were collected using a structured questionnaire designed based on established measurement scales from previous research.

The questionnaire consisted of four sections:
(I) Demographic profile,
(ii) Psychological wellbeing,
(iii) Work–life balance and organizational citizenship behavior, and
(iv) Job performance.

Psychological wellbeing was measured using items adapted from the Ryff (1989) psychological wellbeing scale, focusing on emotional stability and mental health at work. Organizational citizenship behaviour was measured using items adapted from Organ (1988), emphasizing voluntary helping behaviour and cooperation. Work–life balance and job performance items were adapted from relevant empirical studies in organizational and industrial psychology literature.

Measurement Scale

All questionnaire items were measured using a five-point Likert scale, ranging from
1 = Strongly Disagree to 5 = Strongly Agree.
The Likert scale was selected as it is widely used in behavioral and management research and allows respondents to express the intensity of their agreement with each statement.

Reliability Analysis

To assess the internal consistency of the measurement scales, Cronbach's alpha reliability analysis was conducted. The reliability coefficients for all constructs exceeded the recommended threshold of 0.70, indicating acceptable reliability.

Table 1: Reliability Statistics

Variable	Number of Items	Cronbach's Alpha
Psychological Wellbeing	3	0.82
Work–Life Balance	1	0.79
Organizational Citizenship Behaviour	1	0.81
Job Performance	1	0.84

Data Analysis Technique

Data analysis was carried out using statistical software. Descriptive statistics were used to summarize respondent characteristics and variable distributions. Pearson correlation analysis was employed to examine the relationships among psychological wellbeing, work–life balance, organizational citizenship behaviour, and job performance.

To test the proposed hypotheses, multiple regression analysis was conducted. Mediation effects of work–life balance and organizational citizenship behaviour were examined using a regression-based mediation approach, following established mediation testing procedures. Statistical significance was assessed at the 5% level.

3. Data Analysis

Descriptive Statistics

Descriptive statistics were computed to understand the central tendency and variability of the study variables. Mean scores indicate that respondents reported moderate to high levels of psychological wellbeing, work–life balance, organizational citizenship behaviour, and job performance.

Table 2: Descriptive Statistics

Variable	Mean	Standard Deviation
Psychological Wellbeing	3.88	0.62
Work–Life Balance	3.74	0.68
Organizational Citizenship Behaviour	3.95	0.59
Job Performance	3.82	0.64

Correlation Analysis

Pearson correlation analysis was conducted to examine the relationships among the study variables. The results indicate significant positive correlations between psychological wellbeing and job performance, work–life balance, and organizational citizenship behaviour.

Table 3: Correlation Matrix

Variable	1	2	3	4
1. Psychological Wellbeing	1			
2. Work–Life Balance	0.52**	1		
3. Organizational Citizenship Behaviour	0.48**	0.46**	1	
4. Job Performance	0.48**	0.44**	0.50**	1

Note: ***$p < 0.01$***

Regression Analysis

Multiple regression analysis was conducted to test the direct effect of psychological wellbeing on job performance. The results demonstrate that psychological wellbeing significantly predicts job performance in the textile industry.

Table 4: Regression Results

Predictor	β	t-value	p-value
Psychological Wellbeing	0.36	5.21	0.000

$R^2 = 0.23$

Mediation Analysis

To test the mediating roles of work–life balance and organizational citizenship behaviour, regression-based mediation analysis was conducted. The results indicate that both mediators partially explain the relationship between psychological wellbeing and job performance.

Table 5: Mediation Analysis Results

Path	β	t-value	p-value	Result
Wellbeing ? Job Performance	0.36	5.21	0.000	Significant
Wellbeing ? WLB	0.52	6.34	0.000	Significant
WLB ? Job Performance	0.29	4.18	0.000	Significant
Wellbeing ? OCB	0.48	5.89	0.000	Significant
OCB ? Job Performance	0.32	4.76	0.000	Significant

4. Results and Discussion

This section presents the results of the hypothesis testing and discusses the findings in the context of textile industry operations and workforce productivity. The discussion is structured hypothesis-wise to ensure clarity and alignment with the study objectives.

Effect of Psychological Wellbeing on Job Performance

The results of the regression analysis indicate that psychological wellbeing has a significant positive influence on job performance in the textile industry. As shown in Table 3, psychological wellbeing significantly predicts job performance ($\beta = 0.36$, $t = 5.21$, $p < 0.01$), thereby supporting.

This finding suggests that textile employees with higher levels of mental health and emotional stability are better able to meet production targets, maintain work quality, and sustain consistent performance levels. In labour-intensive textile operations, psychological wellbeing enhances employees' concentration, reduces fatigue-related errors, and improves adherence to production standards. These results are consistent with earlier studies that highlight the positive association between employee wellbeing and job performance in industrial settings (Wright & Bonett, 2007; Cropanzano & Wright, 2001).

From a textile management perspective, the findings emphasize that productivity is not solely driven by machinery or technical efficiency but is strongly influenced by employees' psychological capacity to manage work demands.

Mediating Role of Work–Life Balance

The mediation analysis results reveal that work–life balance partially mediates the relationship between psychological wellbeing and job performance, thereby supporting. As presented in Table 4, psychological wellbeing significantly influences work–life balance ($\beta = 0.52$, $p < 0.01$), and work–life balance, in turn, significantly affects job performance ($\beta = 0.29$, $p < 0.01$).

These findings indicate that psychologically healthy textile employees are more capable of managing the demands of work and personal life, which positively affects their work efficiency and commitment. In the textile industry, where extended working hours and shift-based operations are common, poor work–life balance often results in stress, absenteeism, and reduced productivity. Improved work–life balance enables employees to remain focused, motivated, and less prone to burnout, thereby enhancing overall performance.

The results align with previous research emphasizing the importance of work–life balance in improving employee outcomes and organizational effectiveness (Greenhaus & Allen, 2011). The partial mediation effect suggests that while wellbeing directly improves performance, its impact is also transmitted through employees' ability to balance work and non-work responsibilities.

Mediating Role of Organizational Citizenship Behaviour

The findings further demonstrate that organizational citizenship behaviour partially mediates the relationship between psychological wellbeing and job performance, supporting. As shown in Table 4, psychological wellbeing significantly predicts organizational citizenship behaviour ($\beta = 0.48$, $p < 0.01$), and organizational citizenship behaviour significantly influences job performance ($\beta = 0.32$, $p < 0.01$).

This result highlights that psychologically healthy textile employees are more likely to engage in discretionary behaviours such as helping colleagues, cooperating during peak production periods, and voluntarily supporting organizational goals. In textile manufacturing environments, such behaviours are critical for maintaining smooth workflow, reducing production delays, and ensuring quality consistency.

The findings are consistent with prior studies that link employee wellbeing to positive organizational behaviours and enhanced performance outcomes (Podsakoff et al., 2009). The partial mediation effect indicates that organizational citizenship behaviour serves as an important behavioural pathway through which psychological wellbeing enhances performance in textile operations.

Integrated Discussion and Textile Industry Implications

Taken together, the results confirm that psychological wellbeing functions as a key performance enabler in the textile industry, operating both directly and indirectly through work–life balance and organizational citizenship behaviour. The combined mediating effects underscore the importance of adopting a holistic approach to workforce management in textile organizations.

For textile managers, the findings suggest that investments in employee wellbeing initiatives can yield tangible productivity benefits. Improved psychological wellbeing reduces stress-related inefficiencies, enhances cooperation among workers, and supports sustained performance in demanding production environments. These results extend existing wellbeing and performance literature by providing textile-specific empirical evidence and reinforce the strategic value of human-centric management practices in labour-intensive industries.

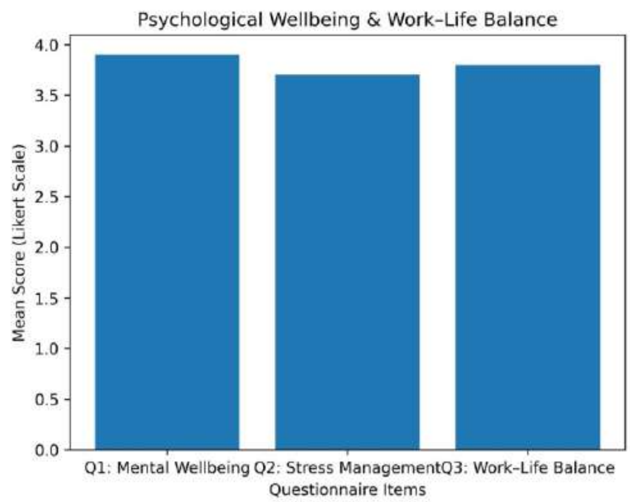

Figure 1: Psychological Wellbeing & Work–Life Balance

Figure 1: Table 7: Organizational Citizenship Behaviour & Job PerformancePsychological Wellbeing & Work–Life Balance

Item No.	Statement	1	2	3	4	5
Q4	I voluntarily help my colleagues when they need support	☐	☐	☐	☐	☐
Q5	I consistently perform my job efficiently and meet assigned targets	☐	☐	☐	☐	☐

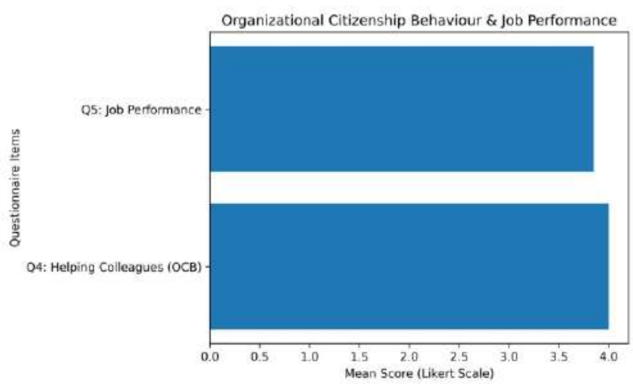

Figure 2: Organizational Citizenship Behaviour & Job

Psychological Wellbeing Initiatives in a Garment Manufacturing Unit

To illustrate the practical implications of psychological wellbeing initiatives in the textile industry, a medium-scale garment manufacturing unit located in South India was

Questionnaire

Table 6: Psychological Wellbeing & Work–Life Balance

Item No.	Statement	1	2	3	4	5
Q1	I feel mentally healthy and emotionally stable at my workplace					
Q2	I am able to manage work pressure and stress effectively					
Q3	My job allows me to maintain a healthy balance between work and personal life					

selected for this case study. The unit employed approximately 350 workers across production, quality control, and supervisory roles and primarily catered to export-oriented apparel markets. Despite adequate production infrastructure, the organization experienced operational challenges associated with human factors.

Prior to the intervention, the unit reported high absenteeism, inconsistent productivity levels, and increased defect rates in stitching and finishing processes. Employee feedback indicated elevated stress levels, fatigue, and reduced morale, primarily due to long working hours, repetitive tasks, and strict production deadlines. These challenges adversely affected workflow coordination and overall operational efficiency.

Recognizing the strategic importance of employee wellbeing, management implemented a structured psychological wellbeing intervention program. The initiatives included stress management workshops focusing on coping strategies and emotional regulation, flexible shift scheduling to improve work–life balance, and supervisor training aimed at enhancing supportive leadership behaviours and communication. These interventions were implemented over a six-month period to assess their impact on employee behaviour and performance outcomes.

Post-intervention analysis revealed notable improvements across key performance indicators. Absenteeism rates declined by approximately 15%, reflecting improved employee engagement and reduced work-related stress. Defect rates in garment production decreased by nearly 10%, indicating enhanced attention to quality and reduced fatigue-related errors. Furthermore, overall productivity improved by approximately 12%, as measured by output per worker and on-time order completion rates.

Employee feedback further indicated improved psychological wellbeing and work–life balance. Workers reported increased motivation, emotional stability, and willingness to support colleagues during peak production periods. These behavioural changes reflected higher levels of organizational citizenship behaviour, contributing to smoother workflow coordination and improved team cooperation.

The findings of this case study demonstrate that psychological wellbeing initiatives can function as effective performance enablers in the textile industry. By addressing mental health, behavioural, and work–life balance factors, textile organizations can achieve measurable improvements in productivity and quality without substantial technological investment. The case study underscores the value of integrating wellbeing-oriented strategies into textile management practices to achieve sustainable operational performance.

5. Conclusion

This study confirms that psychological wellbeing is a key driver of job performance in the labour-intensive textile industry. Employees with better mental health and emotional stability demonstrate higher efficiency, consistency, and adherence to production standards, directly influencing productivity and quality outcomes. The findings further show that work–life balance and organizational citizenship behaviour act as important pathways through which psychological wellbeing enhances performance. A healthy work–life balance reduces stress and absenteeism, while positive discretionary behaviours such as cooperation and helping colleagues support smooth workflow during demanding production periods. From a management perspective, employee wellbeing should be regarded not merely as a welfare concern but as a strategic performance tool.

Based on the study findings, the following practical recommendations are proposed for textile managers:

- Integrate structured psychological wellbeing programs, such as stress management and mental health awareness initiatives, into human resource policies.
- Implement flexible work scheduling practices to improve work–life balance, particularly in shift-based textile operations.
- Train supervisors and line managers in supportive leadership behaviours to enhance employee motivation and emotional wellbeing.
- Encourage organizational citizenship behaviour by fostering a collaborative work culture and recognizing voluntary employee contributions.
- Monitor wellbeing-related performance indicators, such as absenteeism, defect rates, and productivity levels, to assess the effectiveness of wellbeing initiatives.

Despite its contributions, the study has certain limitations. The cross-sectional research design limits the ability to examine long-term causal relationships. Future research may adopt longitudinal designs to assess the sustained impact of psychological wellbeing interventions on performance outcomes. Additionally, sector-specific comparative studies across different segments of the textile value chain, such as spinning, weaving, and garment manufacturing, may provide deeper insights into context-specific wellbeing strategies.

In conclusion, this study emphasizes that psychological wellbeing is a vital organizational resource in the textile industry. Textile organizations that proactively invest in employee mental health and supportive work environments are more likely to achieve sustainable productivity, improved workforce engagement, and long-term competitive advantage.

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

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Abstract:

This study systematically examines the structural and tactile properties of polyester-based blended fabrics, concentrating on polyester-silk (PS), polyester-cotton (PC), and polyester-wool (PW) in various blend ratios (50/50, 65/35, 80/20). The results show that PS blends, especially the 50/50 mix, have the most thread density, the least mass, and the best softness, as shown by the lowest bending length, flexural rigidity, and fabric feel factor. On the other hand, PC and PW blends, which have higher GSM and thickness, are stiffer and rougher, especially when they have more polyester in them. Drape coefficient analyses further show how flexible PS blends are, while PC and PW samples keep their shape better, making them better for formal and winter wear. The data show that adding more polyester usually makes fabrics stiffer and rougher. Adding silk, on the other hand, makes fabrics much softer and more drapey. These insights provide important guidance for choosing fabrics for different textile uses, stressing how important it is to optimize fiber blends for certain fabrics end uses.

Keywords: *Bending Length, curtain fabric, Drape Coefficient, Fabric Feel Factor, Flexural Rigidity*

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1. Introduction

Blended fabrics are now a key part of textile innovation because they let manufacturers combine the best qualities of different fibers to meet the needs of different consumers and applications. Polyester mixed with natural fibers like silk, cotton, and wool is one of the most studied and commercially important blends. These blends are meant to improve the properties of the fabric by finding the right balance between comfort, durability, looks, and cost. Polyester is strong, durable, and cheap, but it doesn't absorb moisture as well as natural fibers like cotton, silk, or wool [1, 2]. To make up for these flaws, polyester is often mixed with natural fibers. People like cotton because it breathes well and is comfortable, but it tends to wrinkle and doesn't last very long. One of the oldest and most studied ways to make fabric more stable, less likely to shrink, and stronger while still being comfortable is to mix cotton with polyester [3, 4]. Polyester-wool blends are also very popular in clothing and upholstery because they are more durable and hold their shape better. Wool adds warmth, bulk, and softness, while polyester adds strength and makes things easier to care for [5-8]. According previously research that the hand and drape of blended fabrics depend a lot on the blend ratio and fiber fineness. Higher polyester content, on the other hand, makes fabrics stiffer and less comfortable to touch. Silk has long been seen as the height of luxury and comfort. Now, it is more often mixed with polyester to make fabrics that combine silk's unique shine, softness, and smoothness with the strength and low cost of synthetic fibers [9-11]. Previous research has shown that even a small amount of silk can greatly improve the feel and look of blended fabrics, also said that adding silk to polyester-based blends makes them more flexible and drapable, which makes them great for high-end fashion and home décor [12, 13].

Although there has been a lot of research on the structural properties and performance of polyester-based blends, there aren't many studies that compare how different blend ratios affect performance, especially when comparing polyester-silk, polyester-cotton, and polyester-wool blends. Previous research has primarily concentrated on binary blends or particular end-use performance characteristics, including wear resistance, pilling, or colorfastness. There is an increasing demand for thorough analysis that combines structural attributes (including thread density, GSM, and thickness) with handle characteristics (such as bending length, flexural rigidity, drape coefficient, and fabric feel factor) across prevalent blend ratios.

This study seeks to address the research deficiency by methodically examining the structural and tactile characteristics of polyester blended with silk, cotton, and wool in varying proportions. This work aims to offer practical insights and recommendations for curtain fabric engineers in choosing the most appropriate materials for specific textile applications by building on prior research and utilizing a comprehensive comparative framework.

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.

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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.

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 Fabric particulars

The fabric's mass per unit area (g/m2), thickness (mm), linear density of yarn (denier), ends per inch (PPI), and picks per inch (PPI) will all be measured. Using an electronic weighing balance, the yarn linear density and fabric mass per unit area will be determined in accordance with ASTM D 1059- 01 and ASTM D 3776 M -09a standards, respectively.

2.2.2 Bending Length & Flexural Rigidity

Bending properties Samples are tested using the Shirley stiffness tester. A rectangular fabric strip measuring 25 cm by 2.5 cm is positioned on a horizontal platform so that it overhangs like a cantilever and bends dovtimarth. The fabric bending length, flexural rigidity, and bending modulus are calculated using the angle formed by the free end of the fabric with the horizontal.

2.2.3 Drape Coefficient

The combined influence of multiple elements, including stiffness, flexural rigidity, weight, thickness, etc., determines a fabric's drapability. One of the key elements in defining the drape quality of a fabric is its stiffness; for example, a soft fabric will drape in a ripple-forming manner closer to the body, whereas a stiff fabric will drape farther away. The geometrical dimensions of the fabric determine its stiffness. The drape coefficient is defined as the ratio of the area difference between the specimen and the supporting disk to the area difference between the supporting disk and the draped sample. Measured and compared are the areas of the

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

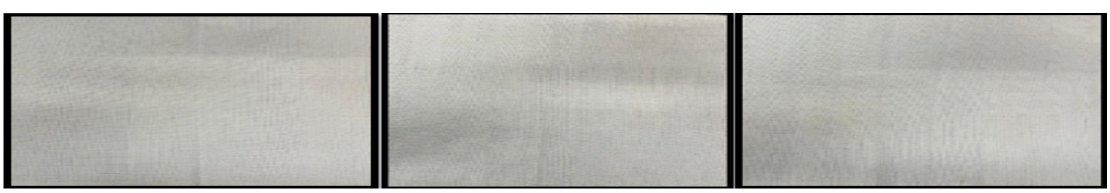

Figure 2: (a) Polyester/ Wool (80:20), (b) Polyester/ Wool (50:50), (c) Polyester/ Wool (65:35)

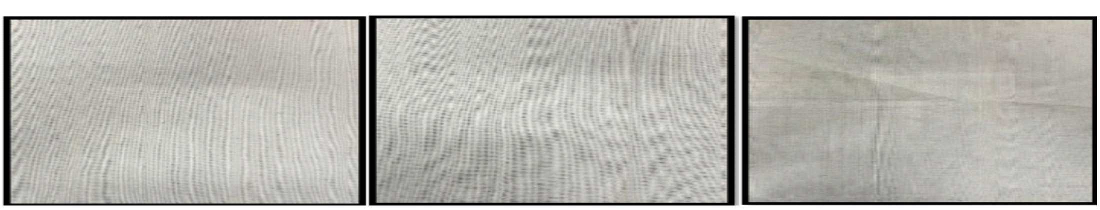

Figure 3: (a) Polyester/ Cotton (80:20), (b) Polyester/ Cotton (50:50), (c) Polyester

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

Table 4: Fabric handle property: Bending length and flexural rigidity

Sr. No.	Sample Code	Bending Length		Flexural Rigidity (mg.cm)	
		Warp wise (cm)	Weft wise (cm)	Warp wise (mg.cm)	Weft wise (mg.cm)
1	PS 50/50	0.75	0.55	39.69	15.12
2	PC 50/50	1.1	1	243.62	162.9
3	PW 50/50	1.3	1	373.62	185.3
4	PS 65/35	0.9	0.7	72.09	33.92
5	PC 65/35	1.3	1	290.92	187.4
6	PW 65/35	1.4	1.2	405.8	212.7
7	PS 80/20	1	0.8	105.6	54.06
8	PC 80/20	1.5	1.2	356.75	192.5
9	PW 80/20	1.6	1.3	484	275.1

shadow (As), the sample (Ad), and the supporting platform (A').

Drape coefficient (F) = (As – A') / (Ad- A') * 100%.

2.2.4 Fabric Feel Factor

The Presently there are few instruments available for evaluating fabric handle objectively, like Kawabata evaluation system for fabrics and Fabric feel tester. Here in this study fabric feel tester was used to obtain the objective evaluation about the fabric feel. Sample size of 24 cm diameter is used in the test. The fabric feel factor for the tested fabrics were obtained using the Equation i. When the feel factor value is low the fabric would be softer and at higher value it's vice versa i.e., fabric would be harsher.

Feel factor (f) = 26.58+ 20.65*PE – 0.436 * WE – 0.131* a + 5.064 * PR -0.361 * DR …. (i)

Where, PE- Peak Height of Extraction curve (Kg)

WE- Area under the curve for extraction curve (Kgmm)

A -Unload fabric across orifile for extraction curve

PR -Peak height for radial curve (kg)

DR-Peak distance for radial curve (mm)

3. Result & Discussions

Table 3 compares the structural properties of different polyester blends, with a focus on yarn density, fabric mass, and thickness. In the PS (polyester-silk) series, the thread density is higher. For example, PS 65/35 has 148 ends and 74 picks per inch. The fabric has a mass of 98 GSM and a thickness of 0.48 mm, which makes it light but dense. When the amount of polyester goes down, the thread density goes down too. For example, PS 50/50 has 120 ends and 72 picks, which means the GSM goes down slightly to 95. The PS 80/20 blend is less dense, but it has a higher GSM (106) and thickness (0.51 mm). In the PC (polyester-cotton) series, the thread density stays the same at 50 ends and 26 or 28 picks. This makes the GSM higher (up to 191) and the thickness greater (0.59 mm). The PW (polyester-wool) blends have the same structure as the PC blends, with GSMs between 185 and 192, which means the fabrics are strong and long-lasting.

3.1. Bending Length & Flexural Rigidity

The bending length analysis of polyester-based fabric blends reveals that polyester-silk (PS) fabrics are the most flexible and soft, with the lowest bending lengths in both warp and weft directions. The PS 50/50 and PS 65/35 blends, in particular, recorded values under 1.0 cm, showcasing their superior drapability and tactile comfort. This softness is attributed to silk's fine, smooth fibers, which reduce rigidity and enhance flow, making PS blends ideal for luxury garments and home furnishings where elegance and comfort are key. Polyester-cotton (PC) fabrics, on the other hand, display moderate bending lengths, with values increasing as polyester content rises. The 80/20 PC blend showed the highest stiffness, while the 50/50 and 65/35 blends provided a balance of softness and firmness, making them suitable for household textiles like curtains and upholstery. Polyester-wool (PW) fabrics were the stiffest, with the 80/20 blend exceeding 1.6 cm in bending length, reflecting wool's bulkier fibers. These fabrics offer excellent structure and form, making them ideal for winter wear and tailored garments. The results emphasize how fiber composition and blend ratios influence fabric performance and suitability for specific applications.

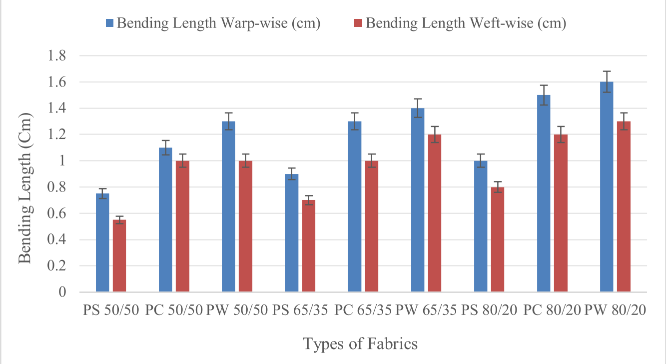

Figure 4: Bending length PC, PS, PW Blend Ratio (80/20, 50/50, 65/35)

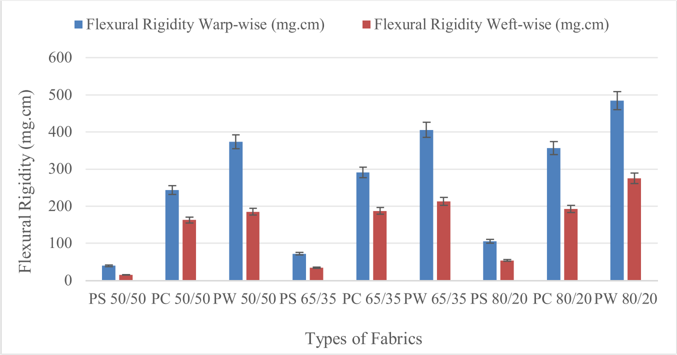

Figure 5: Flexural rigidity PC, PS, PW Blend Ratio (80/20, 50/50, 65/35)

Among the fabric blends studied, polyester-silk (PS) fabrics consistently showed the lowest flexural rigidity, indicating superior softness and flexibility. According to figure 5, PS 50/50 and PS 65/35 blends recorded particularly low rigidity in both the warp and weft directions, with even the PS 80/20 blend maintaining relatively low stiffness compared to polyester-cotton (PC) and polyester-wool (PW) blends. This softness is attributed to silk's fine, smooth texture, which reduces resistance to bending and enhances fluidity, comfort, and elegance. PS fabrics are therefore ideal for applications where drape and softness are essential, such as luxury garments and home décor. In contrast, polyester-cotton (PC) fabrics exhibited moderate flexural rigidity. These fabrics provided a balance between flexibility and firmness, with rigidity increasing as polyester content rose. The PC 80/20 blend, being the stiffest in this group, highlights polyester's role in enhancing durability, while cotton offers structure and breathability, making these fabrics well-suited for household textiles. Polyester-wool (PW) fabrics were the stiffest, with the PW 80/20 blend exceeding 480 mg.cm in the warp direction. Wool's bulkier fibers contribute to the fabric's rigidity, making PW blends ideal for structured applications such as winter wear and upholstery, where shape retention is prioritized over fluidity. These findings demonstrate how fiber composition and blend ratios influence fabric performance and suitability for different uses.

3.2. Drape Coefficient

The figure 6, illustrates the drape coefficient values of polyester-based fabric blends: polyester-silk (PS), polyester-cotton (PC), and polyester-wool (PW), at varying blend ratios (50/50, 65/35, and 80/20). The drape coefficient plays a key role in assessing how a fabric behaves in terms of fluidity and structure. A lower coefficient indicates a softer, more flowing fabric, while a higher value suggests greater stiffness. In the 50/50 blends, PS has the lowest drape coefficient (around 40%), indicating a soft, fluid drape, whereas PC is stiffer, with a coefficient near 60%. PW lies between these two at about 55%. As the polyester proportion increases, the drape generally becomes stiffer, except in the case of silk blends, which maintain softer characteristics. The 65/35 and 80/20 blends show similar trends, with PS remaining the softest. Notably, PC 80/20 shows a significant increase in drape stiffness (63%). These findings underscore that polyester-cotton blends offer greater structure and shape retention, making them ideal for formal wear, while polyester-silk blends remain more fluid and are better suited for garments requiring a softer fall [14-17].

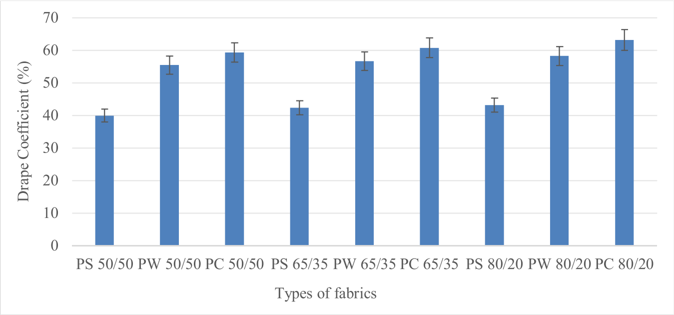

Figure 6: Drape Coefficient PC, PS, PW Blend Ratio (80/20, 50/50, 65/35)

Table 5: Fabric handle property: Drape coefficient and Fabric feel factor

Sr. No.	Sample Code	Drape Coefficient (%)	Fabric feel factor
1	PS 65/35	42.4	22.13
2	PS 50/50	40	19.42
3	PS 80/20	43.2	24.22
4	PC 65/35	60.8	32.12
5	PC 50/50	59.4	28.84
6	PC 80/20	63.2	34.21
7	PW 65/35	56.7	30.25
8	PW 50/50	55.5	28.13
9	PW 80/20	58.3	32.84

3.3. Fabric Feel Factor

The PS 50/50 blend (Polyester/Silk) has the lowest fabric feel factor (19.42) in the results table 5 & figure 7, which means it is the softest of all the samples tested. All PS (Polyester/Silk) blends tend to feel less good than PC (Polyester/Cotton) and

PW (Polyester/Wool) blends. This indicates that incorporating silk into the blend substantially improves fabric softness, corroborating prior research that silk fibers enhance smoothness and impart a more opulent texture.

In contrast, the PC 80/20 (34.21) and PW 80/20 (32.84) samples have the highest fabric feel factors, which means that these fabrics are much rougher to the touch. PC and PW blends have a higher percentage of polyester, which makes the fabrics stiffer. This is because polyester is naturally less soft than silk, cotton, or wool.

The 65/35 and 50/50 blends of PC and PW have intermediate values, which means they are moderately comfortable. As the amount of polyester in the blend goes up, the fabric feel factor usually goes up as well. This shows that more polyester means more harshness [18-20].

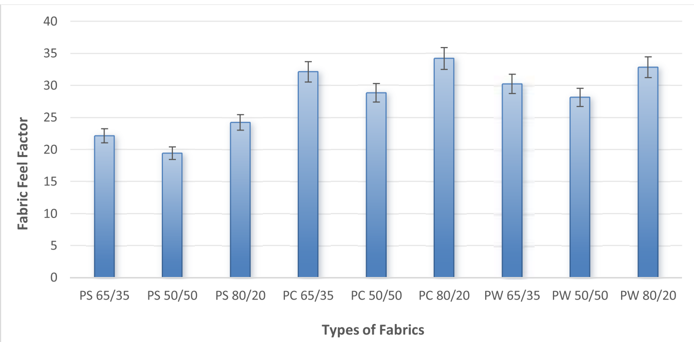

Figure 7: Fabric Feel Factor on PC, PS, PW Blend Ratio (80/20, 50/50, 65/35)

4. Conclusions

This comprehensive study of polyester-based blended fabrics highlights the pivotal role of fiber composition and blend ratios in determining the structural and tactile qualities of various fabrics. Polyester-silk (PS) combinations consistently showed better softness, flexibility, and drapability than other fabric blends that were tested. The 50/50 PS blend, in particular, stood out for its exceptionally low fabric feel factor (19.42), shortest bending lengths, and minimal flexural rigidity. These qualities make it perfect for high-end clothing and home furnishings, where comfort and style are very important. The fine and smooth texture of the silk fibers makes the fabric much less stiff and more fluid, giving it a luxurious feel. On the other hand, polyester-cotton (PC) and polyester-wool (PW) blends had a higher GSM (grams per square meter), were thicker, and were stiffer, especially when the polyester content was close to 80%. The higher polyester levels made the fabrics stiffer and rougher, as shown by their higher fabric feel factors (PC 80/20: 34.21; PW 80/20: 32.84). These blends are better for uses where structure, durability, and shape retention are important, like in curtain fabrics. Interestingly, intermediate blends like 65/35 and 50/50 of PC and PW struck a good balance between comfort and firmness, making them good choices for a wide range of household textiles.

The research further revealed that PS blends possess the lowest drape coefficient among the samples, reinforcing their potential in applications requiring a soft, flowing drape. Ultimately, the results show how important it is to choose the right blend ratio and fiber types to make fabrics that are best for certain uses. Adding silk to polyester blends makes them much softer and better at draping. On the other hand, adding more polyester makes them more durable and stiffer. These insights give the textile industry a solid base for fabric engineering and product development. This lets manufacturers make smart choices when designing curtain fabrics and other textile goods to meet performance needs.

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Revival of Tangaliya Dotted Weaving Patterns through Jamdani Weaving Technique using Sustainable Practices

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Abstract:

Tangaliya weaving, a 700-year-old indigenous textile craft from the Dagasia community in Surendranagar, Gujarat, is at risk as a consequence of modernization, mechanization, and declining artisan engagement. This research explores the revival of the age-old Tangaliya weaving through modern applications that enhance its adaptability while preserving its cultural significance.

By integrating traditional Jamdani weaving techniques of Bengal, the study introduces innovative design adaptations that make Tangaliya textiles more versatile for contemporary markets. These enhancements allow traditional Tangaliya weaving patterns to be reimagined without compromising their authenticity, making them relevant for fashion, home textiles, and luxury handloom segments. Additionally, the use of eco-friendly natural dyeing methods, such as indigo vat dyeing, and use of natural fibre yarns like cotton ensures sustainability while adding commercial value to the handcrafted textiles.

The present research also corroborates the importance of artisan empowerment in the revival process. By fostering collaborations with designers, digital marketplaces, and ethical fashion brands, the study suggests a sustainable business model that can create greater economic opportunities for the handloom weavers. Policy recommendations include fair trade practices, government support for indigenous crafts, and community-driven initiatives to sustain weaving traditions in a competitive market.

This study contributes to the broader discourse on indigenous textile revival by demonstrating how traditional crafts can thrive in modern applications. By balancing heritage preservation with innovation, Tangaliya weaving can be revitalized as a sustainable and commercially viable weaving art form, ensuring its continuity for future generations.

Keywords: *Eco-friendly textiles, Heritage preservation, Jamdani integration, Natural dyeing, Sustainability, Tangaliya weaving*

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1. Introduction

Indian handloom fabrics have a long and illustrious history that stretches back thousands of years, and they are deeply ingrained in the country's culture. These textiles, which are highly regarded for their intricate designs, vibrant colours, and exquisite craftsmanship, are a testament to India's skilled talent and rich cultural heritage. These handloom textiles are extremely prized, and essential for weddings, festivals, and other festive occasions. They are more than just textiles; they embody the cultural identity and heritage of the people who produce them.

Handloom weaving has a long history in India, with many regions having unique designs and techniques. All fabrics, from the intricate to the simple, from the colourful Kanchipuram sarees of Tamil Nadu to the Banarasi silks of Uttar Pradesh, from the Back-strap weaving of Manipur to the Tangaliya weaving of Gujarat, each has a history that captures the regional customs, beliefs, and lifestyles.

However, a number of causes, such as changes in the economy, society, and environment, are contributing to the gradual decline of these age-old traditional textile crafts. Traditional Indian textile trades are in decline due to a number of important factors which include:

i. Industrialization: The need for handcrafted textiles has decreased as a result of industrialization and mechanical production. Traditional craftspeople lose market share to mass-produced fabrics, which can provide less expensive substitutes for handcrafted textiles.

ii. Competition from synthetic fabrics: Synthetic fabrics have gained popularity due to their affordability and durability, posing a threat to the demand for traditional handloom textiles made from natural fibres.

iii. Transforming consumer inclinations: Developing consumer tastes and preferences, shaped by international fashion trends., have led to a shift away from traditional textiles towards Western-style clothing and modern fabrics.

In order to meet the demands of the market, many traditional textiles must be updated or supported by the next generation. Tangaliya Weaving is one of these traditional textiles.

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Tangaliya weaving is one of such handicrafts that require the hands (skills), head (intellect), and heart (involvement and passion) of artists.

This beautiful craft of dotted woven cloth was created originally by the Dangasia Community in the Surendranagar area of Gujarat. Because, Tangaliya weaving mimics knots or beads on fabric, it is also known as "Daana" weaving. Beautiful dotted motifs/patterns that are visible on both sides of the fabric are created by weaving colorful knots onto warps in this intriguing technique [1, 2]. Traditional Tangaliya products were made with cotton and wool yarns dyed with natural dyes. The contemporary products are, however, made of cotton, wool and even acrylic yarns dyed with synthetic dyes for wider and brighter colour range [3]. In the present study, focus has been made to use only the natural materials like 100% cotton yarns dyed with natural dyes like indigo to make the entire process chain eco-friendly and sustainable.

Needless to mention that Eco-friendly innovations are playing a transformative role in preserving and revitalizing traditional weaving practices. As awareness of environmental sustainability grows, artisans and communities are integrating eco-conscious methods into age-old weaving traditions without compromising authenticity or quality. Innovations such as the use of organic and naturally dyed fibres, biodegradable mordants, solar-powered looms, and water-efficient dyeing processes are making traditional textiles more sustainable. These advancements help reduce the ecological footprint of weaving, which historically relied on resource-intensive practices. Additionally, innovations like natural pest management for fibre crops and upcycling of textile waste into new yarns are further aligning traditional crafts with modern sustainability goals. Eco-friendly approaches not only appeal to a new generation of environmentally conscious consumers but also provide weavers with tools to access niche global markets, ensuring the economic viability of their craft. Importantly, such innovations are often developed in collaboration with the artisan communities themselves, allowing traditional knowledge systems to evolve organically while respecting cultural integrity. In this way, eco-friendly innovations are not merely technological upgrades rather they are a bridge, instead, connecting heritage craftsmanship with the demands of a greener future.

1.1 Tangaliya weaving

An ancient indigenous craft dating back approximately 700 years, Tangaliya weaving is practiced in the Saurashtra region. This art was formerly practiced in numerous villages in the districts of Ahmedabad and Rajkot, but it is currently mostly practiced in a small number of villages in the Surendranagar region. Although, many of the weavers in Bajana, Bhathariya, Dedadara, Sayla, Sudamada, and Vastadi have expanded their product lines in the present day for a variety of reasons, some of them still weave Tangaliya pieces [1-9]. Although the traditional Tangaliya technique uses natural materials, but it is not sustainable due to complicated nature of weaving dotted patterns, which are tedious and time-consuming process. The truth is that the market for textiles woven in Tangaliya is steadily declining. This craft is in decline, and many artisans have moved to other fields or begun weaving carpets, mats, rugs, and other items out of leftover textile materials. Furthermore, the vast majority of Tangaliya artists are against teaching their kids this age-old craft. As a result, the sustainability of such a priceless handicraft is in doubt and its future doesn't appear safe or secure. Therefore, this is the main reason of selecting this moribund traditional craft in this study in an attempt to rekindle it in a sustainable way.

1.2 Types of Tangaliya weaving

Four types of Tangaliya were made: Zalawadi used just white and maroon danas, while Halari and Bhadar used colorful danas. Tangaliya, also known as Ramraj, types included a border of woven zari and a black background with a maroon horizontal line. Vibrant hues including maroon, green, orange, yellow, pink, and white were used extensively in the Dana work. Charmalia, the second type of Tangaliya, was made of maroon warp yarn and black weft yarn, and it was mostly white with a few maroon danas. The Dhunslu, third type of Tangaliya, which features less dana work in maroon and white on a black background, is worn by older women. Lobdi: Another unique Tangaliya design style, however overall descriptions of it are less detailed than those of Ramraj or Charmalia [1-9].

1.3 Sustainability approach towards the dyeing

Sustainable dyeing techniques within the textile sector are progressively adopting natural dyeing to minimize the negative effects on the environment and human health caused by artificial/synthetic dyes. Natural dyes come from renewable materials like plants, minerals, and insects, with popular examples being indigo, madder, turmeric, and cochineal. Unlike synthetic dyes, which often release toxic chemicals into water systems and require intensive energy and resource use, natural dyes are biodegradable and generally produce minimal waste. In practical applications, sustainable natural dyeing involves several key strategies: careful and ethical sourcing of raw materials to ensure preservation of biodiversity; the use of non-toxic, biodegradable mordants like alum, myrobalan, or tannins instead of harmful heavy metals to fix dyes to fibers; and adopting low-energy techniques such as cold dyeing or utilizing solar heat to minimize energy consumption. Many practitioners also focus on closed-loop water systems and natural wastewater treatment methods to further limit ecological impact. Additionally, by reviving and adapting traditional dyeing techniques, artisans and industries not only protect cultural heritage but also foster local economies and craftsmanship. The integration of scientific research with traditional wisdom is helping to optimize natural dye processes for scalability, color fastness, and efficiency, making natural dyeing a viable solution for a more sustainable and ethical textile industry.

1.4 Jamdani weaving

Jamdani is a unique weaving method that skilfully blends artistic expression with traditional craftsmanship to create beautiful motifs on fragile substrates like silk, linen, or cotton muslin. These motifs can range from geometric and floral patterns to abstract designs. In the Bengal region, which includes parts of Eastern India and present-day Bangladesh, this art form has been practiced for thousands of years [4, 5].

The distinctive technique known as additional weft weaving is what distinguishes Jamdani weaving. Using this method, more weft threads are added to the base weave and expertly floated over the underlying framework without compromising its integrity. By weaving back and forth along the same path as the primary weft, these supplementary wefts allow the intricate designs to be painstakingly created right on the loom.

In keeping with the floral themes that frequently predominate in Jamdani designs, the term "Jamdani" is derived from Persian, where "jam" means flower and "dani" means vase. Overlaying the fragile and transparent fabric created by the main weft, the extra figuring weft which is generally of coarser counts than the ground weft threads create a complex array of patterns that seem to hover on the glossy surface of the material [5, 6].

It also used to make handkerchiefs and scarves. Geometric, botanical, and floral motifs are frequently seen in Jamdani textiles; many of these designs are thought to have been handed down through the generations. "Kalka" (paisley), "Butidar" (small flowers), "Fulwar" (flowers in straight rows), "Tersa" (diagonal patterns), "Jalar" (patterns that cover the entire sari), "Duria" (polka dots), "Charkona" (rectangular motifs), and "Panna Hajar" (a thousand emeralds) are a few of the most common motifs.

The motifs on Jamdani sarees are mostly floral and geometrical in nature, woven with extra weft by hand.

- In 'Butidar' Jamdani, the floral motifs are in the form of small flowers spread across the saree ground.
- In 'Tercha/Tersa' Jamdani, small flower motifs spread across the diagonal and are inclined.
- In 'Jalar/Jhalar/Jsalar' Jamdani, floral motifs along with leaves and peacocks cover the entire saree.
- In 'Duria' Jamdani, the motifs which resemble polka dots, spread across the saree jamin/field.
- In 'Phulwar' Jamdani, there are rows of flowers.'
- Toradar' Jamdani is that variety of 'Phulwar' Jamdani, in which floral motifs are bigger in size.
- In 'Belwari' Jamdani, on the other hand, there is a vibrant golden boarder which runs across the field.

In some cases, the term 'Paper Jamdani' is also used, where the weaver replicates any creative and artistic design previously drawn onto a paper by a skilled artist. The weaver replicates the same design pattern by keeping the paper drawing under the warp. This technique gives more room for innovation and experimentation [7-11].

Historically, only royal and aristocratic families could afford such opulent fabrics because to the intricate and delicate artistry of Jamdani weaving and its profound cultural significance. The traditional art of Jamdani weaving was added to UNESCO's list of Intangible Cultural Heritage in 2013 due to its cultural and historical significance [7]. Some of the traditional Jamdani motifs are shown in Figure 1.

(a) Diamond design *(b) Airbel* *(c) Konia*

(d) Harava *(e) Butidar* *(f) Jaldar*

Figure 1: Different traditional motifs of Jamdani saree [11, 12]

1.5 Texture: An Innovative Element in Creative Fields

Materials can be distinguished by their diverse surface textures, which facilitate the recognition of familiar substances upon subsequent visual or tactile encounters and enable the identification of unfamiliar textures [19- 21]. The perception of texture is influenced by the extent to which a surface is disrupted by its material composition [22, 23] and by its light reflectance properties [24]. In routine product design, such as for household items, texture innovation is often constrained by functional or practical requirements. For instance, dinnerware surfaces are typically smooth to facilitate use and cleaning. Conversely, in artwork and conceptual design, surface texture can be employed in novel and creative ways. Distinct surface textures can provide sensory stimulation and leave a lasting impression.

1.5.1 Surface Texture in Fashion and Textile Design

Texture, a fundamental element, describes both the visual appearance and tactile sensation of a material. It can be categorized into two main groups: visible appearance and performance [25]. For instance, the texture of children's clothing and accessories ought to be pleasant and soft, even on a baby's delicate skin. Here, texture relates to the designer's choice of appropriate product materials. However, fashion design produces visual appearances, and to improve the visual and aesthetic characteristics of garment design, as well as designers' innovative approaches to textile texture development.

Texture roughness in fashion design is influenced by the quality of the materials used and the way they are arranged or treated. In the case of the Bottega Veneta denim dress, textural variations are evident in the fabric as well as the overall garment. Nevertheless, the loops in the fabric of the dress appear considerably coarser when compared to the fabric itself. The varying dimensions of textural elements play a crucial role in establishing the level of roughness. Texture is also related to the weight or perceived weight of garments and textiles. The appearance of textile texture is shaped by both the thickness of the yarn and the dimensions of the stitches or the weave pattern. When creating new textures from fabric or innovative materials, it is essential to consider the size and weight of the materials used. Such methods can modify the look of a silhouette by altering the smoothness or coarseness of the material, as well as influencing its color through the way it interacts with light, whether by reflecting or absorbing it from the surface [24]. Even so, a clothing designer is not limited to using pre-made fabrics for their creations. Chemical, mechanical, or handcrafted processes, along with embroidery and embellishment, are useful techniques typically employed by designers to develop fabric textures. Embroidery and embellishment are long-standing techniques for enhancing the appearance of surfaces and fabrics in both classic and contemporary fashion. Figure 2 illustrates the specific categorization of surface textures according to fashion and textile design. [25]

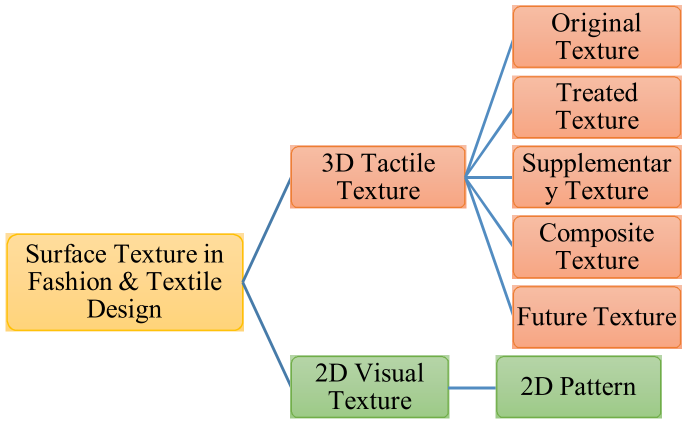

Figure 2: Broad classification of surface textures developed in fashion and textile design [25]

2. Review of literature

The Tangaliya weavings have been studied by a variety of scholars and designers. Below is a discussion of a few of them: Craft historians are still unaware of these 700-year-old crafts. Due to the competitive pressures of the dynamic changes in the worldwide market, the number of artisans employed in this procedure gradually decreased. The vast majority of the participating craftspeople are below the poverty level [1]. A total of 226 Tangaliya weavers from five villages were members of the Tangaliya Hastkala Association (Tangaliya Handicraft Association), which was established in Gandhinagar in 2007 with assistance from the National Institute of Fashion Technology (NIFT). In the years that followed, NIFT held workshops for design creation, quality assurance, and skill enhancement. Finally, GI registration status was granted to the Tangaliya Hastkala Association (THA) [10]. However, this craft gained recognition and identity when the artisans were assigned Geographic Indication Numbers (G.I. Aplication Numbers - 127). Although the majority of Tangaliya artists have begun weaving various other items including carpets, mats, rugs, Khadi, floor coverings, woolen shawls, cotton shawls, etc., only few of these were discovered during the field tour [2-6].

3. Research objectives:

The primary objectives of this study are as follows:

- Fusion of Tangaliya with Jamdani: modernizing the dwindling Tangaliya craft using Jamdani technique, an alternate weaving technique that is far more production-friendly than the conventional approach of making dotted woven textiles using Tangaliya.
- Use of natural fibre yarns and natural dyes to make the proposed production process (fusion of Tangaliya with Jamdani) sustainable.

The weavers of Bengal are now able to satisfy the growing demand for traditional textiles while preserving the handmade quality for which these fabrics are renowned for - thanks to the use of fly shuttle pit looms. The rich legacy of Bengal's handloom weaving is preserved because of the fusion of tradition and technology. By using the same technique, a new approach can be made to revive the old traditional craft of Tangaliya weaving of Gujarat also.

4. Methodology

4.1 Materials

The yarns used for this study were procured from the local market of Santipur and Phulia, West Bengal. The yarn types were mainly cotton, linen and viscose, the specifications of which are mentioned in Table 1. As regards dyes, natural indigo was extracted for dyeing the required weft yarns.

Table 1: Yarn Specification

Type of Yarn	Count (in English system)
Khadi Cotton	84 Ne
Mercerized Cotton	2/60 Ne
Linen	60 Ne
Linen	05 Ne
Slub Viscose	17 Ne

4.2 Dyeing of the weft yarns with Indigo: a sustainable dye

Dyeing with indigo, especially when sourced naturally, holds significant potential for promoting sustainability in the textile industry. Unlike synthetic indigo, which is produced using petrochemicals and often releases harmful by-products into the environment, natural indigo is extracted from plants like Indigofera tinctoria through fermentation a process that is inherently eco-friendlier. Natural indigo dyeing reduces dependency on non-renewable resources and supports regenerative agricultural practices, as indigo plants can improve soil health by fixing nitrogen. Figure 3 shows the dyeing of the weft yarn with Indigo. Sustainable indigo dyeing practices also emphasize the use of non-toxic reducing agents in the vat preparation, moving away from chemical reducers like sodium hydrosulphite toward alternatives such as fructose, banana pulp, or microbial fermentation methods. Furthermore, the environmental impact of the dyeing process can be reduced by using closed-loop water systems and practicing cautious wastewater treatment. Because of its rich cultural background and ability to work with conventional hand-dyeing methods, indigo is a great choice for environmentally concerned craftspeople and companies looking to protect their legacy while tackling contemporary environmental issues. When handled properly, from plant cultivation to dye application, indigo dyeing becomes a paradigm of sustainability for the future of fashion and craft as well as a celebration of historic textile traditions.

Figure 3: Dyeing of weft yarn using natural Indigo

4.3 Weaving

- Warping: For making warp sheet, off-white mercerized cotton yarn of 2/60 Ne count was used. The warp width was kept at 50 inch and the reed count was 72s Stockport.
- Yarn winding: Hand operated Charkha winding device was used for winding the yarns for both warp and weft, i.e., for transferring the yarns from hank form to bobbins or pirns.
- Drafting & Denting: 2 heald shafts using straight draft was used, and denting was 4 ends/dent for both the selvedge and 2 ends/dent for the body of the fabric.
- Weaving: In accordance with the designed pattern, the weaving was done in the Jamdani (extra weft figuring) style using Tangaliya motifs. Figure 4 shows the weaving Tangaliya motifs using Jamdani technique.

The loom specifications are furnished in Table 2 below.

Table 2: Loom Specification

Items	Description
Loom used	Handloom
Loom type	Fly shuttle pit loom
Reed count & type	72^s Stockport (Pitch-baulk reed)
No. of Heald shaft used	2 heald shafts with nylon healds (for plain ground weave)

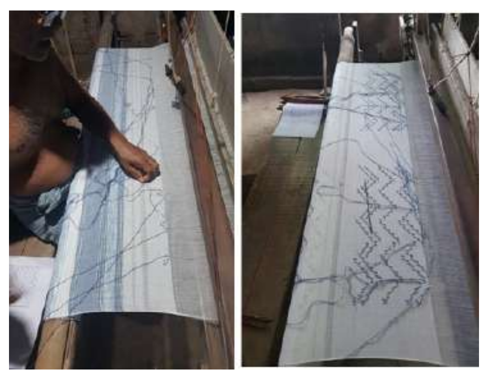

Figure 4: Weaving process: weaving Tangaliya motifs using Jamdani technique

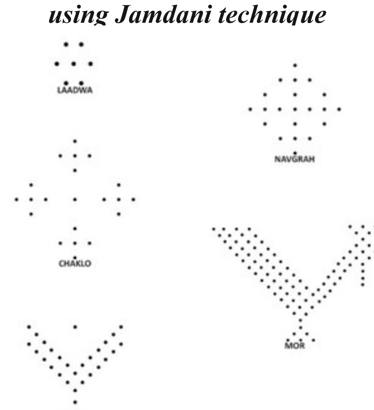

Figure 5: Traditional Tangaliya motifs

4.4 Design development

Traditional Motifs

Tangaliya motif created with a unique dana arrangement. Tangaliya motifs have a strong visual and geometric element to them. The Ladawa, an Indian confection, has historically been the fundamental motif of Tangaliya.

Tangaliya often employed peacocks, temples, trees, and various geometric shapes like squares, triangles, and circles as primary motifs These fundamental motifs are used to create various motifs, such as phandi, pag (the peacock's feet), ambo (mango ree), bajariya ni zhaadavi, chakalo, karoliyo, piyali ka zhaad, etc. Some of the motifs are shown in Figure 5.

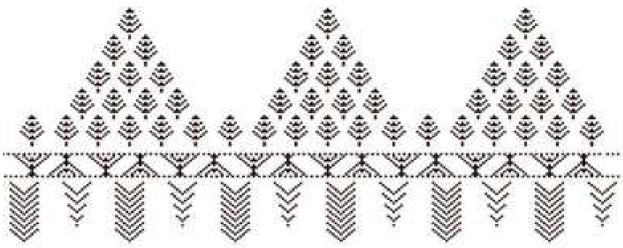

Figure 6: Design for Bedsheet

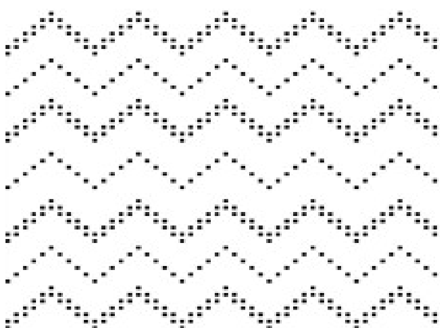

Figure 7: Design for Cushion

The design is developed from traditional Tangaliya motifs using Textile CAD software, ArahPaint6 Demo version. The designs which were modified and re-developed from traditional Tangaliya motifs are shown in Figure 6, 7, 8 & 9 below

5. Product development through sustainable approach

Home furnishing range has been developed through a greener approach by fusion of two traditional weaving techniques namely Tangaliya and Jamdani. Here, fusion implies creating Tangaliya's dotted patterns with Jamdani weaving technique. Jamdani's discontinuous weft reduces material consumption. The present approach also enhances biodegradability by focusing on natural yarns & natural dyes. Attempts have also been made to conserve water by implementing closed-loop dyeing systems. The final product range includes bedsheets, bedcovers, pillow covers, cushion covers, curtains both window and door, etc. Some of the product samples are shown in Figure 10. The collection contains Bedsheet, Pillow cover, Curtains, Side pillows.

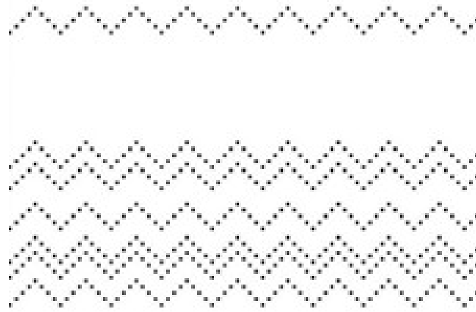

Figure 8: Design for Cushion

Figure 9: Design for Pillow cover

6. Finishing and Packaging

Traditional finishing methods for handloom products are deeply intertwined with cultural practices and local craftsmanship. These methods focus on enhancing the natural properties of the fabric, such as softness, sheen, and durability, while preserving the unique characteristics of handwoven textiles. By using natural materials and time-honoured techniques, these finishing processes contribute to the authenticity, beauty, and sustainability of handloom products. The fabric is soaked in water, often mixed with natural softening agents like Reatha (soapnut) or other herbal extracts. After soaking, the fabric is gently wrung out and dried. This process softens the fabric and enhances its natural lustre. After that traditional hand irons, often heated with charcoal, are used to press the fabric.

Figure 10: Home furnishing range developed by fusion of Tangaliya and Jamdani through sustainable approach

This method is particularly common in rural areas and adds a touch of traditional craftsmanship to the finished product.

7. Product Costing

Table 3 shows the costing of raw materials and labour charges whereas Table 4 shows the costing of prototype/product costing respectively. A collection has been made in this study. So, the product costing shown here is approximate.

Table 3: Costing of raw materials and labour charges for the developed samples

Expenses (Category/Process wise)	Amount (Rs.)
Warping charge	Rs. 700/-
Raw material cost	Rs. 1,547/-
Dyeing Cost	Rs. 1,000/-
Loom Setting charge	Rs. 500/-
Labour charge	Rs. 6,000/-
Misc charge	Rs. 500/-
Designer Cost	Rs. 3,000/-
Total costing/charges	Rs. 13,247/-

Table 4: Approximate costing of the final products

Item / Final Product made	Dimension	Amount (Rs.)
Bedcover	80 inch x 50 inch	Rs. 1,475/-
Bedsheet	80 inch x 50 inch	Rs. 1,475/-
Curtain (Set of 2)	76 inch x 50 inch	Rs. 2,500/-
Cushion cover (Set of 4)	16 inch x 16 inch	Rs. 735/-
Pillow cover (Set of 2)	26 inch x 20 inch	Rs. 735/-
Extra fabric	80 inch x 50 inch	Rs. 1,475/-

8. Conclusion

The preservation and revitalization of traditional crafts like Tangaliya weaving require a thoughtful blend of cultural respect, eco-friendly innovation, and market-driven strategies. Through the integration of sustainable practices such as natural indigo dyeing, use of organic fibres, and energy-efficient weaving methods, it may be possible to reduce the environmental impact while enhancing the economic viability of these age-old traditions. Eco-friendly interventions not only address modern sustainability concerns but also breathe new life into traditional crafts by making them relevant and attractive to contemporary, environmentally conscious consumers. This research highlights that by adopting innovations rooted in environmental responsibility and ethical production, craftspeople can secure a resilient future for their art, thereby empowering local communities and safeguarding cultural heritage. The evolution of Tangaliya weaving through sustainable design adaptations like Jamdani-inspired techniques demonstrates a successful model where tradition and innovation coexist, ensuring that these beautiful handwoven textiles continue to thrive in a modern, sustainable world.

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Effects of Weave Parameters of the Cotton Fabrics on their Colour Management in Reactive Dyeing

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Abstract:

The structural variations between the fabric to be dyed and the reference fabric, for which the dying recipe has been determined, are a major source of problems in dyehouses. In such a case, knowledge of the effects of weave parameters such as Crossing over Firmness Factor (CFF), Floating Yarn Factor (FYF) and Fabric Firmness Factor (FFF), and geometrical properties such as areal density, thickness and porosity of woven cotton fabrics on the colour efficiency is of great importance for 'right-first-time' dyeing. In this research 11 woven fabrics differing only in weave structures and having the common count and fabric sett was produced, dyed with reactive dyes, and the colour measurements were carried out with a spectral photometer. Weave parameters and geometrical properties do not have any evident effect on the colour shade, although a considerable change in colour yield was determined.

Concludes that although weave parameters and fabric geometry do not visibly affect the final colour shade, they have a measurable impact on colour yield. Understanding these influences is crucial for optimizing dyeing recipes and improving consistency in industrial textile dyeing processes.

Keywords: *CFF, colour yield, FYF, FFF, weave structure, reactive dyeing*

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1. Introduction

Existing dyeing processes are increasingly being centred on environmental, economic, and punctual delivery issues, coupled with enhanced quality demands and consumer expectations. Textile dyers have first-production profitability as their utmost target to enhance business success, but struggle with shade reproducibility and level dyeing. Reactive dyes make up one-third of the dyes used to produce cellulose fibers nowadays [1], because of improved characteristics like increased fastness qualities, more vivid color effects, and a larger colour palette. Because there is a vast variety of reactive dyes available, many dyeing procedures can be employed [1], and the exhaust dyeing procedure is used to apply more than 60% of reactive dyes [2].

A major challenge in the textile dyeing industry is the inconsistency in color shades of dyed fabrics, which leads to significant financial losses each year due to product rejections and the production of lower-grade materials. This shade variation is attributed to several factors, including differences in fiber quality, yarn properties, textile structure, and unsuitable processing conditions during both pretreatment and dyeing stages. Most contemporary research has concentrated on knitted fabrics, as they are easier to manage in small-scale settings. However, some studies have explored how the characteristics of cotton yarn influence the diversity of color shades in dyed materials. For instance, research examining the origins of dye ability variations from cotton fiber to finished fabric found that yarns made from various cotton bales displayed more shade differences associated to those sampled at other stages of yarn production [3]. Additionally, it was observed that yarns sourced from different spinning mills could cause over a significant variation in the opticalpresence of the dyed fabric. Despite these findings, the researchers did not provide statistical correlations among specific yarn or cotton properties and the resulting color measurements of the finished textiles, leaving a gap in understanding the exact causes of color inconsistencies in dyed fabrics [3].

Also, associated to fabric woven from single ply weft yarns, has been observed that woven fabric from double plied weft yarns is more reflective and more in terms of colour difference [4]. Three studies show that knitted cloth made by compact yarns possess greater colour strength, higher chroma, and lower lightness than the cloth produced by ring spun yarn [5-7]. But yet another study found the opposite tale [8], and further studies say there is no different shade variations between the yarns produced from different technics like compact and conventional spinning methods [9, 10].

The shade variation in weft yarn is called Barré in the dyed fabric. This issue frequently arises when the weft yarn's properties change throughout the woven fabric's length

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[11]..Fluid movement within textile materials is inherently complex due to their fibrous nature and irregular structural arrangement, which can also deform under certain conditions. Despite this complexity, analyzing how fluids pass through fabrics is essential for understanding various physical and mechanical characteristics. Textiles are composed of macroscopic elements like fibres and filaments, making them inherently porous materials with void spaces distributed throughout their structure [12].

The goal of this study is to explore the influence of changing parameters of structure of fabrici.e., Interlacing firmness by CFF value,Float length & distribution value by FYF, Comprehensive tightness by FFF, weave Factor (P1), and important fabric physical parameters like GSM, thickness, and porosityon color shade alteration in reactive dye-treated fabrics. The above mentioned prior investigations in this area have not yet investigated the interdependence between these particular weave parameters and the colour coordinates of industrially dyed fabrics. All these weaving factors and properties of fabrics are for the first time mathematically evaluated and compared with the resulting colour harvests in the present research work. The results of the detailed evaluation are presented with regard to their relevance to textile science as well as to industrial application.

2. Methods

2.1. Fabric samples

Various samples of fabric, the samevertical and horizontalyarn but varied in differentfabric structures, were woven on anpower loom. Plain weaves utilized were Gaberdene and 4 up 4 down balanced twill, 2 up 2 down pointed twill, 8 thread twilled hopsack, huck-a-back, crepe cord sateen, honeycomb, brighten honeycomb and pin head crepe. Plain weave displays more interlacements of yarn, Gaberdene creates surface ridges, sateen features large weft floats, and crepe weave gives texture. Table 2 lists all sample details and weave variations for easy comparison and complete comprehension.

2.2 Fabric Processing and Dyeing

After weaving, the cloth samples were bleached with peroxide at 1:10 M:L ratio, with 1.5% peroxide, 1.2% caustic soda, 0.5% wetting agent, 0.3% lubricant oil, and 0.2% sodium silicate as stabilizer. The bleaching was done for 45 minutes at 90°C according to VPT Exports Private Limited's standards (Tamilnadu, India). Secondly, room temperature open bath dyeing was also performed using reactive cold brand yellow (Colour 1) and blue (Colour 2) dyes, Figure 1.

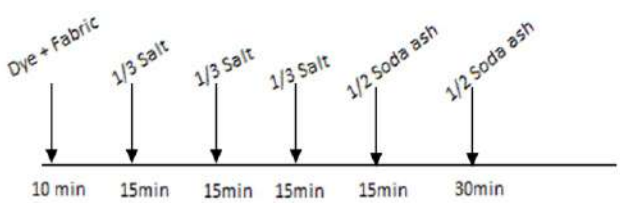

Figure 1 - Dyeing condition

Dyeing parameters are given in Table 1, which results in consistent, repeatable outcomes in bleaching and dyeing processes.

	Parameters	Stock Solution concentration	
M:L ratio	1:30	Dye	1%
Shade	1,2, and 2%	Salt	10%
Salt g/l	30	Soda ash	10%
M:L ratio	20		

2.3 Weave Factor

Weave factor (P1) measures interlacement between vertical and horizontal yarns, calculated from the matrix of the fabric structure [13, 14] established different factors of the weaves, P1 and P1, in their study; our research is based on P1 as described by them. The Floating Yarn Factor (FYF) is a degree of floats length in the fabric. FYF shows a strong connection to the weave factor and thus indicates its importance in assessing fabric structure in terms of yarn interlacements and float patterns [15].

2.4 Measurement of Porosity

Measurement of fabric porosity typically involves determining the ratio between the fabric bulk density and fibre density. Porosity, as a key structural characteristic, quantifies the open spaces within a fabric, directly influencing properties such as breathability and permeability to fluids or gases. The calculation is based on comparing the volume engaged by the solid fibres (fibre density) to the total bulk volume of the fabric (fabric bulk density), according to established equations1.

To measure fabric porosity:

Fabric Bulk Density: This is determined by measuring the mass and total volume (including voids) of a fabric sample.

Fibre Density: This refers to the mass per unit volume of the solid fibre material alone, typically obtained from manufacturer data or standard reference values.

Porosity Calculation: Porosity is then calculated using the formula:

$$\text{Porosity} = 1 - \frac{\text{Fabric Bulk Density}}{\text{Fibre Density}}$$

$$\text{Fabric bulk density } (g/cm^3) = \frac{\text{Gram per meter square}/10000}{\text{Thickness of fabric in cm}}$$

This direct method provides a straightforward and widely accepted approach to evaluating the porosity of textile materials1. Additional techniques, such as airflow, liquid penetration, or image analysis, may also be used for more detailed or non-destructive assessments.

2.5 Mass per 100 centimetre square and Thickness of the fabric

ASTM D3776and ASTM D1777 standards are used to measure the mass per 100 centimetre square and thickness of the fabric.

2.6 Colour yield determination (K/S Value)

Prior to colour yield determination, the dyed samples were conditioned. The readings were taken using Premier Spectrophotometer with the settings that prevented specular reflections and selected a large aperture, 10° standard observers, and D65illuminant level. The samples were doubled over two times for enhanced accuracy and minimization of error.

Colour strength was determined from reflectance over 400 to 700 nm wavelengths at 10-nm intervals within the observable range, using Equation 1. The process yielded reliable and standardized values for each sample of fabric, which have been expressed by K/S value [16, 17].

$$\frac{K}{S} = \frac{(1-R)2}{2R} \qquad (1)$$

Here, K = Absorption coefficient, (depending on the content of colorant)

S =Scattering coefficient, (depending on the structure of the dyed fabric).
R =Reflectance of the dyed sample.

For each wavelength, the value of colour yield was determined and then summed up. Increasing total value of colour yield reflects higher dye content, which in turn is directly related to enhanced color yield and deeper coloration of the fabric.

2.7. Weave structures parameters

2.7.1 Crossing-over Firmness Factor (CFF)

$$CFF = \frac{Number\ of\ cros\sin g\ \ overlines\ in\ the\ complete repeat}{Number\ of\ \mathrm{int}\ erlacement\ po\ \mathrm{int}\ in\ the\ complete repeat}$$

Ogawa first used the term CFF. The sole drawback was that it was not well understood to be further studied, to avoid this, Marino redefined the Crossing over Firmness Factor (CFF) [18], as under,

$$CFF = \frac{C}{I}$$

C= Crossing-over lines in the complete repeat
I= Interlacing points in the complete repeat

2.7.2 Floating Yarn Factor (FYF)

The floating yarn factor, shown visually in Figure 3, is a particular form of yarn structure. The definition for this factor was taken directly from the visual representation of the floating yarn in question, from which the weight of the same was derived. The visualization is what was needed to properly put each weight into context for how they were assigned to this particular yarn attribute.

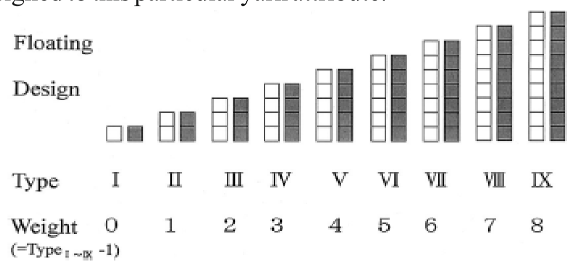

Figure 2 - Details of Floating Yarn Factor (FYF)

$$FYF = \frac{(Type_{I\sim IX} - 1) \times (Existing number of type_{I\sim IX} in the complete repeat)}{Number of\ \mathrm{int}\ erlacing po\ \mathrm{int}\ s in the complete repeat}$$

2.7.3 Firmness Factor of Fabric (FFF)

The calculation for this was performed using a specific formula developed by Milasius. This formula provides the precise method for determining the value in question. By applying Milasius's established mathematical relationship, the computation ensures accuracy and consistency in deriving the result [20, 21].

$$\varphi = \sqrt{\frac{12}{}}\ \frac{1}{P1} \sqrt{\frac{T_{av}}{\rho}}\ S_2^{\frac{1}{1+\frac{2}{3}\sqrt{\frac{T_1}{T_2}}}}\ S_1^{\frac{\frac{2}{3}\sqrt{\frac{T_1}{T_2}}}{1+\frac{2}{3}\sqrt{\frac{T_1}{T_2}}}}$$

Where $\rho = \frac{S_1\rho_1 + S_2\rho_2}{S_1 + S_2}$ and

$T_{av} = \frac{S_1T_1 + S_2T_2}{S_1 + S_2}$ T_1, T_2 and Here's a

In this context, T_{av} are formula used, where the verticalyarn count, horizontalyarn count, and average yarn count are all expressed in Texsystem of yarn numbering. P1 represents the Milasius weave factor, while ρ signifies the fiber density. Additionally, S_1 and S_2 denote the number of ends and picks per centimetre, respectively.

Table 2 - Fabric particular

Sr. No.	Fabric particular	GSM	Thickness (cm)	Porosity (%)	CFF	FYF	FFF	Yarn Count	Weave factor	Ends / cm	Picks /cm
1	Plain	97.58	0.034	80.639	2	0	0.49	19.08 tex	1	22	23
2	2/2 Twill	98.64	0.042	84.192	1	1	0.4		1.265	23	25
3	4/4 Twill	91.34	0.048	87.207	0.5	1.5	0.28		1.789	23	24
4	2/2 Pointed Twill	94.72	0.044	85.648	1	1	0.39		1.265	23	23
5	8 Thread Twilled Hopsack	93.68	0.045	86.244	1	1	0.38		1.321	23	24
6	8 Thread weft sateen	91.24	0.047	87.167	0.5	1.5	0.27		1.789	22	22
7	8 Thread honey comb	98.02	0.046	85.917	1.19	0.81	0.37		1.253	23	20
8	8 Thread brighten honey comb	102.8	0.057	87.977	1.5	0.5	0.44		1.109	22	23
9	8 Thread Huck – a- Back	96.26	0.053	88.674	1.25	0.75	0.4		1.188	22	22
10	8 Thread crepe cord	96.84	0.057	88.674	1.5	0.5	0.44		1.109	23	23
11	8 Thread Pin head crepe	91.78	0.053	88.368	1.13	0.88	0.38		1.249	22	22

3. Results and Discussions

The K/S Value of different shade and weaves are given in the table 3.

Table 3 - K/S Values for Colour 1 and 2 with Different Shade

Reactive cold brand yellow										
S. No	Fabric Particulars	COLOUR 1 1 %			COLOUR 1 2 %			COLOUR 1 3 %		
		RR	CC	RC	RR	CC	RC	RR	CC	RC
1	Plain	3.947	3.382	3.496	4.838	4.045	4.197	5.365	5.084	5.409
2	2/2 Twill	4.358	2.883	4.115	4.709	3.844	4.109	4.226	3.566	4.784
3	4/4 Twill	4.467	4.308	3.821	4.695	4.262	4.062	4.832	5.132	4.334
4	2/2 Pointed twill	3.067	3.426	3.221	4.282	4.596	4.058	4.89	5.251	4.824
5	8 Thread twilled hopsack	4.343	3.772	4.289	4.946	4.152	3.52	6.073	5.052	5.032
6	8 Thread weft sateen	3.271	3.391	3.891	3.947	3.452	4.396	5.088	5.053	6.33
7	8 Thread honey comb	3.827	3.90	4.67	4.418	3.576	4.186	5.974	5.939	5.925
8	8 Thread brighton honey comb	3.961	3.684	4.04	4.272	3.516	3.972	6.786	5.566	5.15
9	8 Thread huck-a-back	4.117	3.366	3.738	4.729	3.734	3.668	7.019	5.688	6.345
10	8 Thread crepe cord	4.636	3.892	4.589	4.531	4.047	5.041	6.861	5.053	6.2
11	8 Thread pin head crepe	4.064	3.384	3.902	4.505	3.915	4.192	6.435	5.853	6.796
Reactive cold brand blue										
		COLOUR 2 1 %			COLOUR 2 2 %			COLOUR 2 3 %		
		RR	CC	RC	RR	CC	RC	RR	CC	RC
1	Plain	22.59	22.067	20.128	27.92	25.25	31.024	28.594	30.318	33.168
2	2/2 Twill	20.25	19.333	21.311	25.25	28.41	27.691	39.417	37.979	35.59
3	4/4 Twill	24.72	22.544	21.62	30.33	40.71	33.362	42.411	39.162	35.592
4	2/2 Pointed twill	21.57	21.232	25.036	32.53	31.003	35.712	42.832	34.844	44.709
5	8 Thread twilled hopsack	22.06	22.065	26.754	28.12	46.27	35.895	37.999	36.641	38.069
6	8 Thread weft sateen	23.41	22.216	22.435	28.67	26.43	31.188	37.957	38.759	40.654
7	8 Thread honey comb	21.54	20.604	21.753	35.09	31.68	34.777	36.267	37.734	37.004
8	8 Thread brighton honey comb	22.82	22.375	24.116	30.92	29.81	33.972	43.446	34.961	39.777
9	8 Thread huck-a-back	22.91	21.187	23.82	28.74	26.75	35.499	41.865	34.141	40.806
10	8 Thread crepe cord	20.42	23.012	22.858	29.28	31.42	37.789	32.398	43.605	39.708
11	8 Thread pin head crepe	22.34	19.08	22.847	31.21	31.004	31.378	42.676	36.306	51.456

Correlation between K/S value and Fabric properties

The correlation between K/S values (a measure of dye uptake) and fabric structural parameters was analyzed for two reactive dye shades (Colour 1 and Colour 2) across three fabric combinations of ring spun yarns, compact spun yarns and ring spun yarn with compact spun yarn (Table 3).

3.1 Effect on Thickness and Porosity

For both dye shades, thickness and porosity exhibited strong positive correlations with K/S values (Colour 1: r = 0.878–0.925; Colour 2: r = 0.829–0.908). These results (Figures 12–15) suggest that thicker fabrics with greater porosity facilitate improved dye penetration and retention. The further studiesobserved that enhanced dye diffusion in textiles with increased capillary spaces [22].Among all samples, the Compact/Compact fabric consistently showed the highest correlation between porosity and dye uptake (r = 0.947 for Colour 1, r = 0.912 for Colour 2), indicating that compact yarns contribute to a more uniform and accessible pore network, which is beneficial for dye absorption.

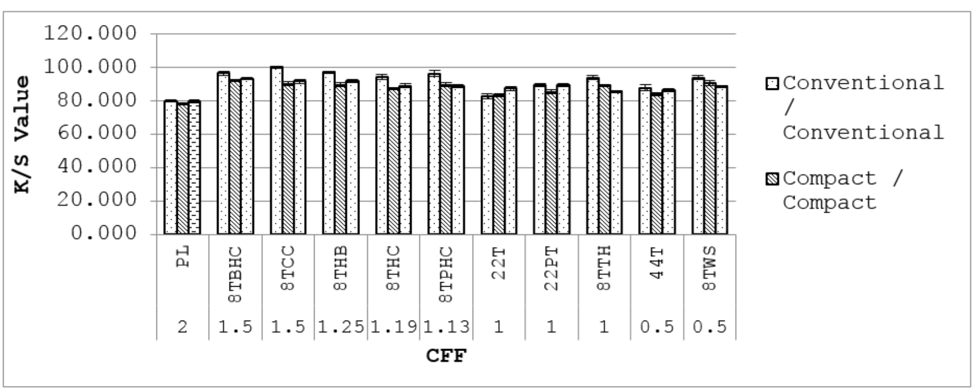

Figure 3 - Relationship between Dye Uptake and CFF (Colour 1)

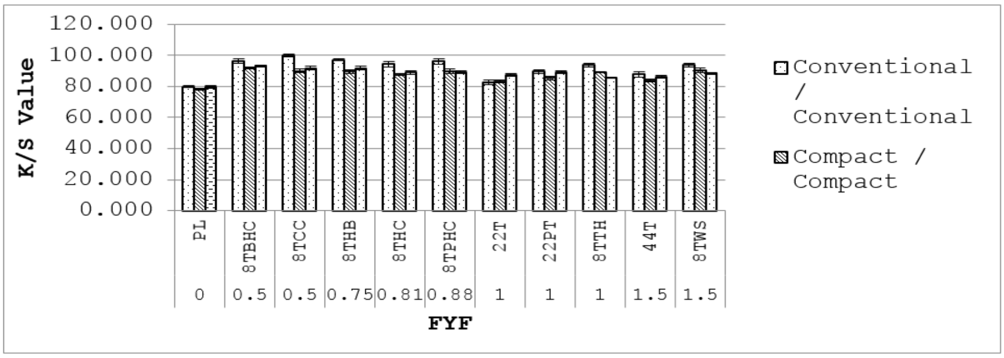

Figure4- Relationship between Dye Uptake and FYF (Colour 1)

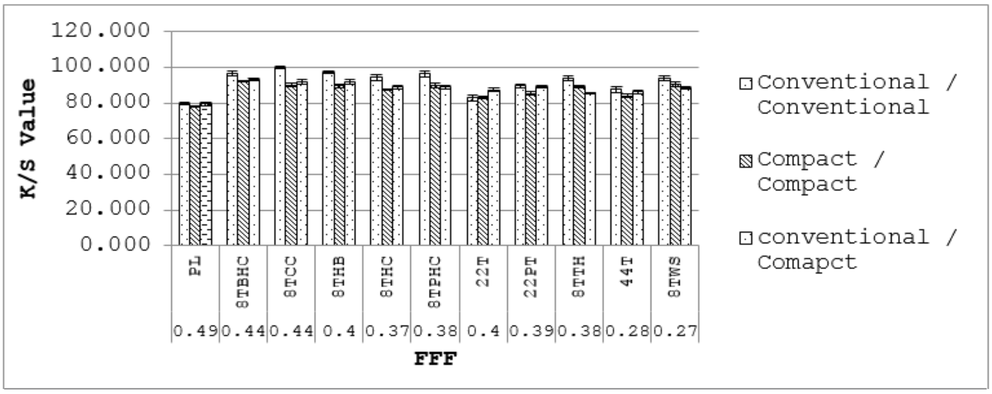

Figure 5- Relationship between Dye Uptake and FFF (Colour 1)

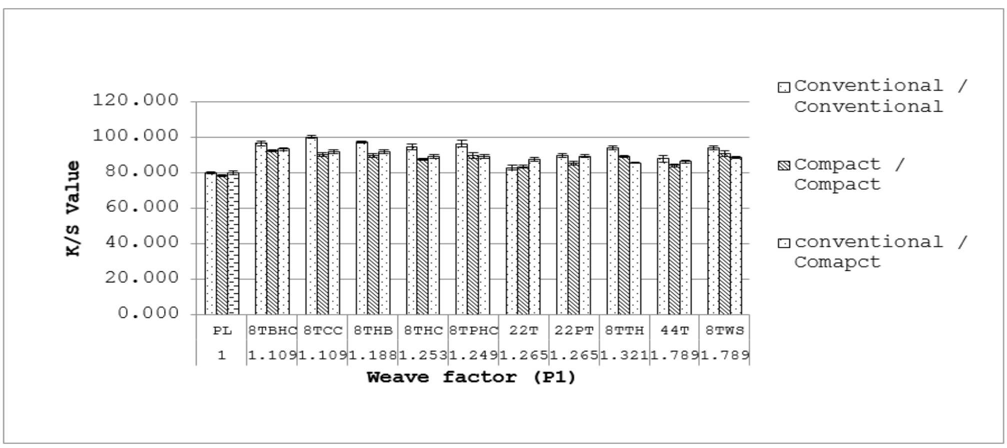

Figure 6- Relationship between Dye Uptake and Weave factor (P1) (Colour 1)

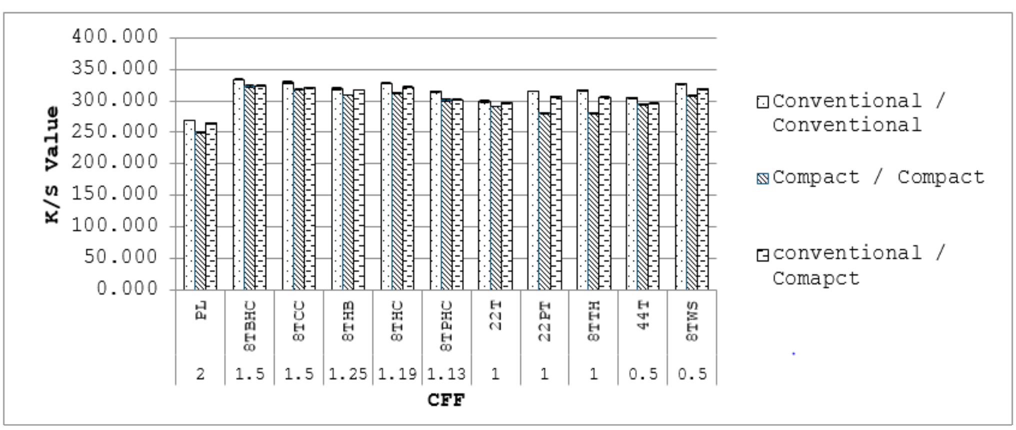

Figure 7- Relationship between Dye Uptake and CFF (Colour 2)

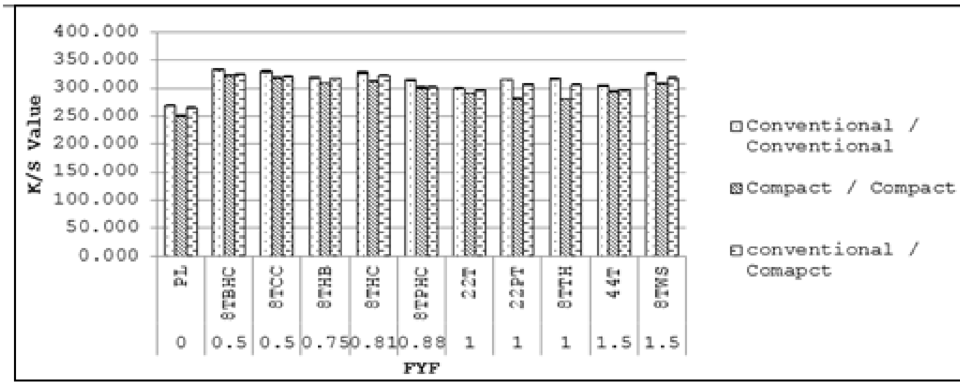

Figure 8- Relationship between Dye Uptake and FYF (Colour 2)

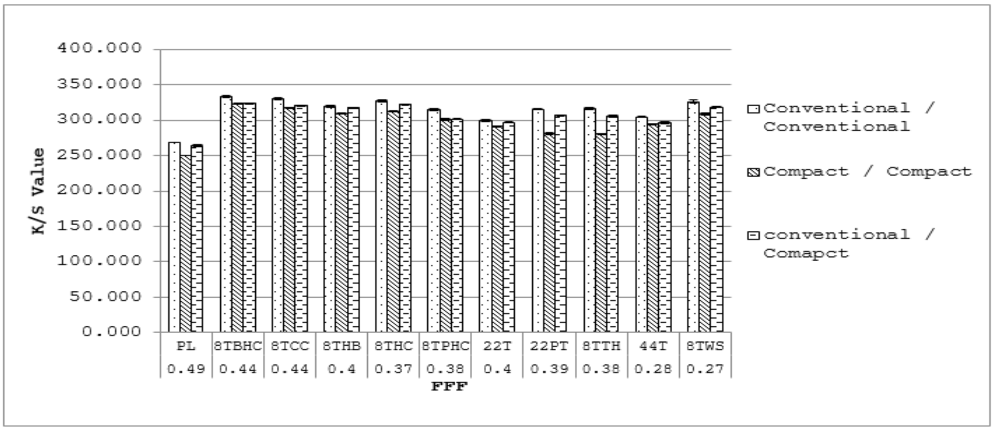

Figure 9- Relationship between Dye Uptake and FFF (Colour 2)

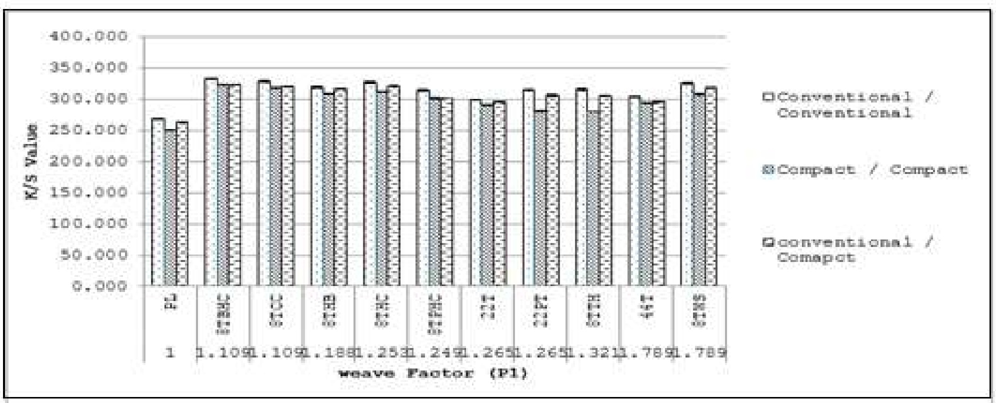

Figure 10- Relationship between Dye Uptake and Weave factor (P1) (Colour 2)

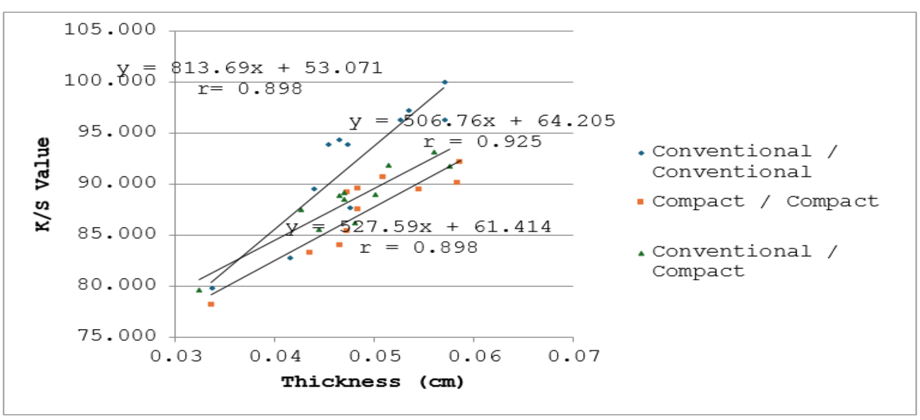

Figure 11- Relationship between Dye Uptake and Thickness (Colour 1)

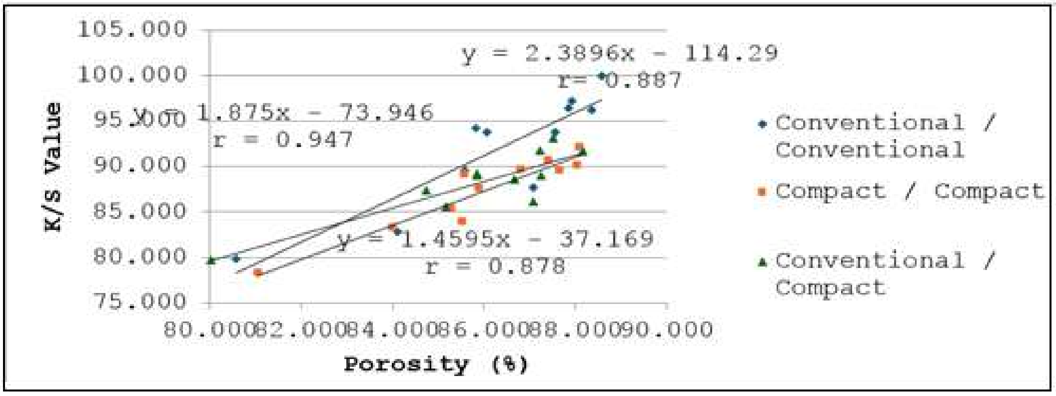

Figure 12- Relationship between Dye Uptake and Porosity (Colour 1)

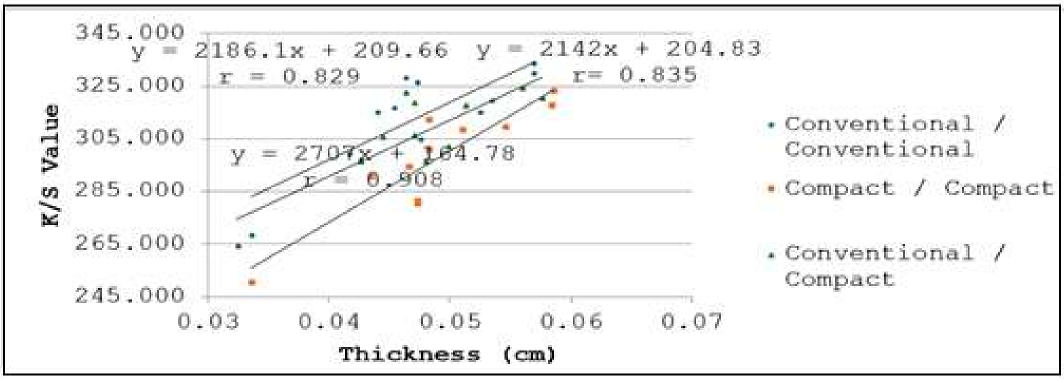

Figure 13- Relationship between Dye Uptake and Thickness (Colour 2)

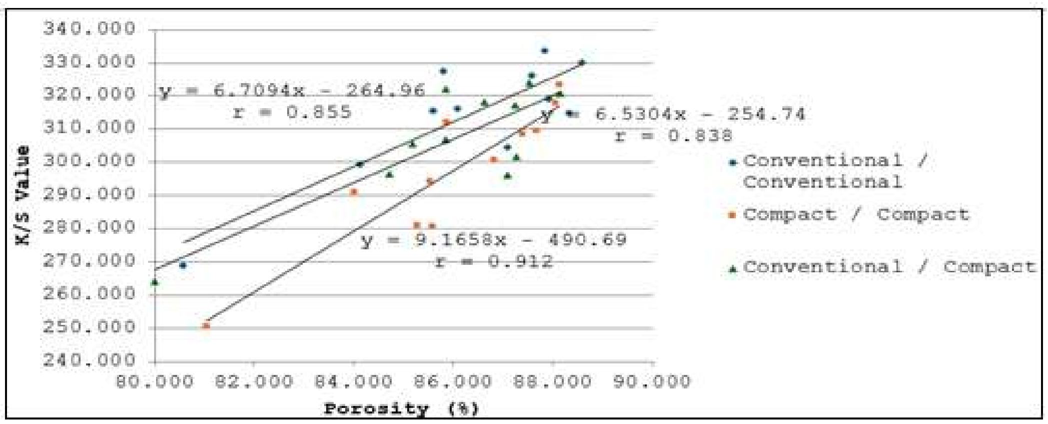

Figure 14- Relationship between Dye Uptake and Porosity (Colour 2)

3.2 Effect of weave parameters on K/S Value

Crossing Over Firmness Factor exhibited a negative correlation with dye uptake across both shades (Colour 1: -0.088 to -0.240; Colour 2: -0.232 to -0.316). This implies that as crimp increases, the availability of fibre surface for dye binding decreases (Figures 4 and 9).

Floating Yarn Factorshowed weak positive correlations (0.090 to 0.316), suggesting that longer floats may enhance dye uptake slightly by reducing interlacements (Figures 5 and 10). This trend was also noticed in the further studies [23], where reduced interlacement frequency promoted dye penetration.

Fabric Firmness Factor had consistent negative correlations (-0.084 to -0.301), confirming that firmer fabrics resist dye diffusion, possibly due to tighter packing and lower fabric mobility during dyeing (Figures 6 and 11).

3.3 Effect of weave Factor on K/S Value

The connection between K/S values and Weave Factor (P1) was generally weak (Colour 1: -0.049 to 0.110; Colour 2: 0.135 to 0.157), indicating that weave configuration alone does not significantly influence dye uptake in the absence of accompanying changes in porosity or thickness (Figures 7 and 11). This is consistent with further findings [24], where geometrical variables were secondary to fibre surface accessibility.

4. Conclusion

The present study highlights the significance of fabric structure on dye uptake behavior in reactive dyeing. Thickness and porosity are the most influential parameters, demonstrating strong positive correlations with colour yield. CFF and FFF negatively affect dye penetration, whereas FYF shows a mild positive influence. Interestingly, Weave Factor (P1) alone does not present a decisive effect on dye performance. From a practical perspective, the results underline the necessity of considering structural attributes during dye recipe development, especially when switching fabric constructions. Compact yarn-based fabrics offer better reproducibility and consistency in colour yield, making them preferable for achieving right-first-time dyeing outcomes. The integration of structural knowledge into dyeing practice can significantly improve efficiency and reduce reprocessing costs in textile manufacturing.

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Identifying and Analysing Distribution Problems in the Handloom Textile Sector: A DEMATEL Based Modelling Approach

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Abstract:

Indian handloom textile sector is a living expression of rich cultural tapestry and a key livelihood source for millions residing in rural areas. The sector is the second largest employer in the rural economy after agriculture. Although the handloom sector holds significant social and environmental value, it continues to grapple with fundamental challenges.

With the help of an extensive review of literature, major thematic problems such as infrastructural deficits, technological limitations, policy unawareness and middlemen dependency were identified. A notable gap persists as existing studies provided fragmented descriptive insights and seldom employment of structured analytical frameworks to examine the distributional problems faced by weavers. The study adopted a methodological lens using DEMATEL approach to investigate the nature and visualize the causal interconnections between the variables, distinguishing root causes from superficial symptoms.

Results show that infrastructural inadequacies and policy communication gaps can have a multiplier effect on resolving secondary issues like poor market access and over reliance on intermediaries. The findings offer a strategic insight for policymakers and stakeholders, fostering both academic understanding and practical reforms in India's handloom distribution network.

Keywords: *DEMATEL, Distribution Problems, Handloom Sector, Textile Industry, Weavers*

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1. Introduction

Rooted in centuries of tradition, India's handloom craft reflects a rich cultural heritage and a distinct identity shaped by generations of skilled weavers. It is the second largest employer in the rural non-agricultural sector after agriculture, offering livelihood to over 4.3 million people [1, 2]. With unmatched designs, the knowledge of indigenous weaving is preserved primarily by women specially from marginalized communities. The community practices the skills as a gateway of preserving their culture and support household finances. The unique production skill set is undisputed, while concern arises in the distribution of the goods.

Proper distribution management plays a significant role in smooth flow of goods from the manufactures to the ultimate consumers enhancing the satisfaction and effectiveness of the handloom industry [3]. Distribution channel management is classified as effective and efficient when the right product is delivered at the right time, right quantity and to the right customer [4]. The uniqueness of the sector underscores greater worldwide reach and attention. It has the potential for improving cultural diplomacy and self-reliance but lacks long term sustainability. The gap between production and consumption is eliminated with a systematic distribution channel. An effective distribution channel helps to reduce stagnation among weavers and facilitates regional economic development [5]. Weavers are deprived of access to global market reach due to limited access to adequate information and systemic logistics. The ineffectiveness in management further worsens the sectors growth in domestic and international markets [6, 7]. This paper seeks to diagnose the core distribution problems in the handloom sector through an extensive Review of Literature and DEMATEL model to establish a relationship among the variables and offer a roadmap for prioritizing strategies.

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2. Review of Literature

The Indian handloom sector showcases a unique blend of cultural diversity across regions. The sector is enduring emblem of rich culture, talent and skills passed down through generations. The sector supports rural communities by facilitating jobs and empowering their voices in the society. The sector has also gain global attention for environmentally sustainable production [1]. The sector is highly informal in nature and operates mostly in an unorganised manner. The weaver's functions under a family-based enterprise structure which often lacks exposure to modern technologies and financial limitation. Government schemes such as the "National Handloom Development Programme (NHDP)" and "India Handloom Brand" were launched to support the sector, but inadequate implementation and outreach limit their effectiveness [8]. The handloom products are mostly distributed with the help of local buying agents and middlemen, which lacks transparency and global scalability. The use of modern channel and Omni-channel is limited in the sector which provides greater autonomy due to limited digital literacy and insufficient support system [9]. Price suppression and information asymmetry hinders the growth and continues the reliance on the middlemen dominated networks [10]. The systemic challenges further hinder its integration into formal, scalable and sustainable market channels [3].

The sector provides a life-line to rural livelihoods and preserves the traditional craftsmanship and skills. Being unorganised and fragmented, the resource is often underutilised. Collectively the challenges hold and restrict the growth potential with dynamic consumer preferences. Enabling modern channel with the use of social media can create attention and help the weavers release their true value [1]. Inadequate living standards and insufficient storage facilities constrains broader market accessibility and production capabilities [9]. Disrupted supply chain raises transaction cost and weakens the Indian handloom products competitiveness in the lucrative global market [6]. Weak technological infrastructure and low digital literacy further hinder the inclusive development. Inadequate access to digital tools, stable internet connectivity and secure online payment systems prevents weavers in engaging in the digital marketplaces. This hinders the market reach and reduces the operational distribution efficiency [11]. Weavers struggle to maintain the working capital requirements which holds back their ability and potential in marketing and innovation. Proper access to formal credit and financial services is absent, which pushes weavers to rely on intermediaries and middlemen for capital requirement causing to fall and continue in the loop [12]. Weavers dependability on local fairs and informal networks to sell their products limits the scalability and bargaining power [13]. Regardless of existing various government schemes the low level of policy awareness and procedure to avail among the weavers limits their ability to benefit [14].

Middlemen like buying agent often exposits weavers with gaining greater control over price negotiations. Weavers autonomy is hindered by high intermediary dependence [6]. The market appeal for the handloom products can be increased with innovation in packaging and establishing brand. GI tag helps to safeguard and identify the uniqueness. However, outdated and generic strategy used make it harder to stand out of the competition from other sectors, especially, power loom products where products are often sold by big corporate with hefty expenditure in branding and advertisement [15]. Low levels in products innovation and catering market demand restricts weaver's ability to capture the market [16]. Weavers often follow traditional patterns ignoring the trends and professional design, which limits their chances to capture the market demand [5]. Fluctuation in raw material supply often disrupts the production deadlines and deliveries causing negative customer satisfaction [7]. Transportation and logistics barriers limits weaver's ability to reach urban and global market on time. Inadequate working capital exacerbates the challenges by limiting optimum raw material procurement and production planning efficiently [7]. Collectively the persistent inefficiencies contribute towards the structural constrains and downfall of the age-old handloom sector.

Table 1: Problems in Distribution in Handloom Sector

Sl. No.	Problem
1	Infrastructural Deficit
2	Technological and Digital Divide
3	Financial Exclusion
4	Market Access Barriers
5	Policy Unawareness
6	Unreliable Communication Channels
7	Middlemen Dependency
8	Lack of Institutional Support
9	Lack of Branding and Packaging
10	Low Product Innovation
11	Limited Design Inputs
12	Unstable Raw Material Supply
13	Lack of Working Capital
14	Weak Cooperative Societies Engagement
15	Poor Transport Connectivity

Source: Compiled by Researchers

Despite the sector's critical role in rural employment and cultural preservation, empirical studies have seldom examined the dynamics of distributional problem faced by weavers in a comprehensive manner. The existing literature largely offers fragmented and descriptive accounts without employing a structured analytical framework. To address this gap, the present study seeks to explore key questions, which are outlined below:

a) Which distribution-related problems significantly affect handloom weavers?

b) Is there an underlying structure among these distribution problems?

3. Objectives of the Study

To address the research questions, the study set forth the following objectives:

i. To determine key distribution problems faced by handloom weavers' in the Indian handloom sector;

ii. To examine interconnections among distribution problems faced by weavers in the Indian handloom sector.

4. Research Methodology

The study utilizes "Decision-Making Trial and Evaluation Laboratory" approach to investigate the complex interrelationships among distribution problems in the Indian handloom sector. DEMATEL is employed to dissect complex problem structures and identify cause-and-effect relationships among a network of interrelated factors. DEMATEL enables to convert qualitative expert assessments into a structured model, with clear visualization of interdependencies among variables. The capability to isolate root causes from resultant effects enhances analytical precision and reinforces robustness of the study [17]. The methodological framework followed a multi-stage approach, beginning with the identification of 15 problems based on a comprehensive review of literature.

Expert validation was then conducted with a purposively selected panel of 15 domain experts to ensure representativeness and minimise selection bias. The panel was stratified to include an equal number of experts (n=3) from each key stakeholder being Handloom Textile Officials, Cooperative Society Head Weavers, Self-help group associated weavers, independent weavers and senior academicians ensuring balanced institutional, practitioner and scholarly perspectives. The experts' ages ranged from 48 to 59 years, with professional experience spanning 15 to 29 years, reflecting substantial domain maturity. Prior beginning the collection process, the initial list of 15 distribution-related problems was systematically reviewed and three constructs: Unreliable Communication Channels, Lack of Institutional Support and Weak Cooperative Societies Engagement were excluded based on consensus judgements citing low contemporary relevance. This refinement ensured analytical parsimony and the retention of only substantively meaningful variables. The final validated set comprised 12 problem statements, which the experts subsequently rated on a 5-point scale (0–4), where 0 denoted no influence and 4 represented a high degree of influence.

The responses were collected from the experts in the month of March and April 2025 and were compiled in an Initial Interaction (12 x 12) matrix. The initial Interaction matrix was normalized to form aggregated normalized interaction matrix for ensuring consistency and better interpretability. For each factor, the prominence (summation of the influence exerted by the rows and the total influence received from the columns) and the relation (difference between the influence exerted by the rows and the total influence received from the columns) values were calculated from the aggregated normalized interaction matrix. These values facilitated the classification of variables into causal (driving) and effect (dependent) groups, enabling a structured diagnosis of the problem landscape. Sensitivity testing, widely used in group-based decision and evaluation research involves introducing small perturbations to input data to verify the stability of the casual structure and factor rankings under minor variations [18].

Following the approach, a simple robustness check was conducted by increasing a subset of expert scores by +1 and re-estimating the DEMATEL model. The causal ordering and prominence of the key factors remained unchanged, indicating that the findings are stable and not overly sensitive to minor variation in expert input.

Table 2: Problems in Distribution in Indian Handloom Sector

Code	Problem	Description
S1	Infrastructural Deficits	Inadequate physical facilities hinder production scale and timely market access [6, 9].
S2	Technological & Digital Divide	Limited access to digital tools restricts market reach and operational efficiency [1,11].
S3	Financial Exclusion	Lack of access to formal credit affects broader distribution reach capacity [7, 12].
S4	Market Access Barriers	Difficulty reaching larger markets limits visibility [9, 13].
S5	Policy Unawareness	Lack of awareness about schemes leads to poor scheme utilization & lost benefits [3,14].
S6	Middlemen Dependency	Over reliance on intermediaries reduces earnings and pricing control for weavers [1, 6].
S7	Lack of Branding & Packaging	Weak product identity diminishes consumer appeal and limits premium pricing [14, 15].
S8	Low Product Innovation	Repetition in design limits competitiveness in modern retail environments [5, 16].
S9	Limited Design Inputs	Lack of collaboration with designers results in outdated & low-demand patterns [5, 16].
S10	Unstable Raw Material Supply	Inconsistencies in raw material availability raise costs and disrupt efficiency [3, 7].
S11	Lack of Working Capital	Operational liquidity shortages hinder scalability and timely order fulfilment [7, 12].
S12	Poor Transport Connectivity	Weak logistics infrastructure causes delay and increases distribution costs [3, 7].

Source: Compiled by Researchers

5. Results and Discussion

A group of 15 domain experts rated the association between each dyad of factors using a 0–4 scale which were accumulated using a 12×12 matrix. The rows denote the factors exerting influence, while the columns indicate the factors receiving that influence.

Table 3: Initial Interaction Matrix [A]

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
S1	0	3	2	3	4	3	2	2	2	3	3	4
S2	2	0	2	3	3	2	3	3	2	2	2	3
S3	1	1	0	2	2	2	2	1	1	2	3	2
S4	2	2	2	0	3	3	3	2	1	2	2	3
S5	3	3	3	3	0	2	2	2	2	2	2	3
S6	1	1	2	2	2	0	3	2	2	1	2	2
S7	2	2	2	2	2	3	0	3	2	1	1	2
S8	2	2	2	2	2	2	3	0	3	1	2	2
S9	1	1	1	2	2	2	2	2	0	1	1	1
S10	2	2	2	3	3	2	2	2	2	0	3	3
S11	3	2	3	2	2	2	2	2	2	3	0	3
S12	3	2	2	2	3	2	2	2	2	2	3	0

The Initial Interaction Matrix be denoted as:

$$\mathbf{A} = [a_{ij}]_{n\,x\,n}\,,\; a_{ij} \in \mathbb{R}_{\geq 0}$$

Here aij represents the Direct Influence score of elements i on element j; n being the number of factors under consideration

The matrix reflects the degree of influence (on a scale of 0–4) that each problem exerts on others. It provides the input for progressing the next steps in the DEMATEL analysis: Normalization, aggregate relation matrix and Generation of prominence and relation values.

The Initial Interaction Matrix [A] is normalized to minimize discrepancies using:

$$\mathbf{X} = \frac{A}{\max\limits_{1 \leq j \leq n} \sum_{i=1}^{n} a_{ij}}$$

where: $\sum_{i=1}^{n} a_{ij}$ is the column sums for column j, representing the total direct influence received by factor j from all other factors. $\max\limits_{1 \leq j \leq n} \sum_{i=1}^{n} a_{ij}$ are the maximum column sums across all columns, denoted as.

$$M = \max_{1 \leq j \leq n} S_j, \quad S_j = \sum_{i=1}^{n} a_{ij}$$

where *Sj* is the aggregated influence magnitude of factor j.

M being the scaling constant ensuring the largest column sums becomes coherent after normalization.

The element wise form of the normalization is formed by:

$$x_{ij} = \frac{a_{ij}}{M} = \frac{a_{ij}}{\max\limits_{1 \leq k \leq n} \sum_{i=1}^{n} a_{ik}}$$

Here,

x_{ij} : normalized direct influence of *i*-th factor on *j*-th factor

$$\mathbf{X} = [x_{ij}]_{n\,x\,n} \in [0,1]^{n\,x\,n}$$

The Initial Interaction Matrix is normalized to place all influence values on a common and comparable scale. The column with the highest total influence value was determined and labelled as normalization constant. Each influence score was divided by the constant, which converted all values into a range between 0 and 1. The procedure enables to make the data consistent, easy to interpret and fully reproducible.

In operator notation, the normalization can be expressed as:

$$\mathbf{X} = \frac{A}{||\boldsymbol{A}||_{max-col-\ell_1}}$$

where: $||\boldsymbol{A}||_{max-col-\ell_1}$ defines as the maximum column-wise $||\boldsymbol{A}||_{max-col-\ell_1} = \max\limits_{j} \sum_{i=1}^{n} |a|_{ij}$; ℓ_1 norm being the sum of the absolute values in that column and *max-col* being the

Table 4: Initial Interaction Matrix (Normalized) [X]

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
S1	.000	.097	.065	.097	.129	.097	.065	.065	.065	.097	.097	.129
S2	.065	.000	.065	.097	.097	.065	.097	.097	.065	.065	.065	.097
S3	.032	.032	.000	.065	.065	.065	.065	.032	.032	.065	.097	.065
S4	.065	.065	.065	.000	.097	.097	.097	.065	.032	.065	.065	.097
S5	.097	.097	.097	.097	.000	.065	.065	.065	.065	.065	.065	.097
S6	.032	.032	.065	.065	.065	.000	.097	.065	.065	.032	.065	.065
S7	.065	.065	.065	.065	.065	.097	.000	.097	.065	.032	.032	.065
S8	.065	.065	.065	.065	.065	.065	.097	.000	.097	.032	.065	.065
S9	.032	.032	.032	.065	.065	.065	.065	.065	.000	.032	.032	.032
S10	.065	.065	.065	.097	.097	.065	.065	.065	.065	.000	.097	.097
S11	.097	.065	.097	.065	.065	.065	.065	.065	.065	.097	.000	.097
S12	.097	.065	.065	.065	.097	.065	.065	.065	.065	.065	.097	.000

Source: Compiled by Researchers

selection of the largest sum among all columns. This produces Initial Interaction Matrix (Normalized), standardizing all values within the range of 0 to 1.

The Aggregate Normalized Interaction Matrix **[T]** is calculated to capture both direct and indirect effects among the n factors.
It is defined as:

T= X (I−X)-1

Here,
$\mathbf{T} \in \mathbb{R}^{n \times n}$: aggregate normalized interaction matrix
$\mathbf{I} \in \mathbb{R}^{n \times n}$: identity matrix of order n (n = 12)
$(\mathbf{I-X})^{-1}$: inverse of the matrix $\mathbf{I-X}$.
For each element of t_{ij} of $\mathbf{T}$:

$$t_{ij} = x_{ij} + \sum_{k=1}^{n} x_{ik}x_{kj} + \sum_{k=1}^{n}\sum_{\ell=1}^{n} x_{ik}x_{k\ell}x_{\ell j} + \ \dots$$

Here, tij the total influence with xij the first direct influence term followed by subsequent summation terms.
The operator notation can be expressed as:

$$\mathbf{T} = \mathbf{X}\,(\mathbf{I-X})^{-1} = \mathbf{X}.\ \sum_{m=0}^{\infty} \boldsymbol{X}^{m}$$

Where the summation operator $\sum_{m=0}^{\infty} \boldsymbol{X}^{m}$ generates all higher order indirect influence. Aggregate Normalized Interaction Matrix [T] allows to quantify the changes in one factor indirectly affect others through interconnections in the system.

From the Aggregate Normalized Interaction Matrix [T] key influence metrics were adapted to interpret the systemic dynamics of the distribution challenges in the handloom sector. These include Dispatching Power (D), which indicates the level to influence over other problems (row sum); Receiving Power (R), which captures how much a problem is influenced by others (column sum); prominence, reflecting total significance of the problem and Net Influence, distinguishing the cause factors and effect (negative) factors.

Table 6 represents the deriving results which reveals that Infrastructural Deficits (S1) and Technological and Digital Divide (S2) are the most prominent cause factors with high D−R scores of 1.38 and 1.23 respectively, indicating substantial influence on other challenges while being relatively less influenced in return. The upstream structural problems act as root causes and should be priority intervention areas. Market Access Barriers (S4) and Policy Unawareness (S5) also display positive net influence, suggesting that improving policy communication and removing access bottlenecks can yield systemic improvements. Issues like Middlemen Dependency (S6), Limited Design Inputs (S9) and Lack of Branding and Packaging (S7) have negative D−R values, indicating that they are more often the consequences of other upstream issues. These are effect-type challenges and may resolve automatically once structural causes are addressed.

Table 5: Aggregate Normalized Interaction Matrix [T]

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
S1	.279	.353	.349	.407	.457	.396	.379	.345	.321	.339	.385	.459
S2	.302	.229	.310	.364	.384	.329	.366	.336	.287	.276	.316	.385
S3	.206	.195	.181	.258	.272	.253	.259	.208	.193	.217	.274	.274
S4	.286	.275	.295	.257	.365	.339	.348	.292	.243	.262	.301	.366
S5	.330	.319	.339	.367	.299	.331	.339	.309	.287	.280	.320	.388
S6	.208	.198	.244	.262	.276	.197	.293	.243	.227	.189	.247	.276
S7	.253	.245	.262	.284	.300	.306	.226	.290	.245	.204	.239	.299
S8	.262	.252	.270	.292	.309	.288	.323	.209	.280	.212	.274	.309
S9	.174	.168	.180	.225	.236	.222	.228	.209	.136	.158	.182	.207
S10	.296	.284	.304	.356	.376	.321	.329	.300	.280	.211	.338	.378
S11	.321	.282	.330	.329	.349	.320	.328	.299	.279	.300	.251	.377
S12	.316	.278	.297	.321	.368	.313	.321	.293	.274	.267	.331	.281

Source: Compiled by Researchers

Table 6: Deriving Values

Problem Code	Description	Dispatching Power (row sum)	Receiving Power (column sum)	Prominence	Relation
S1	Infrastructural Deficits	4.61	3.23	7.84	1.38
S2	Technological & Digital Divide	4.31	3.08	7.39	1.23
S3	Financial Exclusion	3.00	3.12	6.12	–0.12
S4	Market Access Barriers	3.91	3.48	7.39	0.43
S5	Policy Unawareness	4.23	4.10	8.33	0.13
S6	Middlemen Dependency	2.85	3.73	6.58	–0.88
S7	Lack of Branding & Packaging	3.22	3.60	6.82	–0.38
S8	Low Product Innovation	3.25	3.33	6.58	–0.08
S9	Limited Design Inputs	2.37	3.07	5.44	–0.70
S10	Unstable Raw Material Supply	3.77	3.17	6.94	0.60
S11	Lack of Working Capital	3.77	3.56	7.33	0.21
S12	Poor Transport Connectivity	3.87	3.55	7.42	0.32

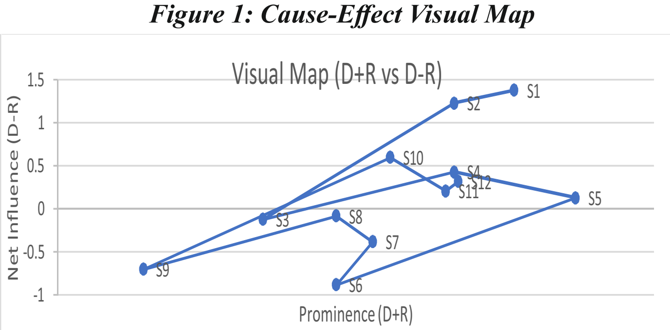
Source: Compiled by Researchers

Problems such as Low Product Innovation (S8) and Financial Exclusion (S3) show near-neutral net influence, suggesting they play intermediate roles in the system both influencing and being influenced by others. Policy Unawareness(S5), Infrastructural Deficits (S1) and Poor Transport Connectivity (S12) were found having the highest scores for the Prominence derived through (D+R). This identifies it as significant and influential factor within the handloom distribution framework. Systemic reforms in this high prominence aspects could improve the existing limitations. DEMATEL analysis helps to determines the dependence and linkage among the distribution problem and highlight the cause-and-effect relationship, facilitating for targeted aspect improvisation.

The Cause effect visual map provides a representation of the relationship among problem factors, if there exists. The map is drawing after extracting data from Aggregate Initial Matrix (Normalized). Prominence is plotted in the x-axis derived by summation of dispatching power and receiving power with ranging from 5.44 to 8.33. Net influence or Relation is plotted in the y axis arrived by subtracting the dispatching and receiving power with the range starting from -0.70 to +1.38. The value arrived from the net influence column distinguishes between cause-and-effect relationship. The positive value highlights the causes whereas negative value represents it as an effect.

Cause–Effect Visual Map reveals that issues such as Policy Unawareness (S5), Infrastructure Deficit (S1) and Transport Constraints (S12) exhibit high positive D − R values, positioning them as primary causal factors. These problems exert significant influence on other challenges within the system, making them critical leverage points for policy intervention.

Figure 1: Cause-Effect Visual Map



Source: Compiled by Researchers

Challenges like Middlemen Dependency (S6), Financial Exclusion (S3) and Design Limitations (S9) are situated in the lower half of the graph, signifying their status as effect variables, representing symptoms resulting from deeper systemic issues. Additionally, problems with high prominence such as Policy Unawareness (S5) and Infrastructure Deficit (S1) not only drive other issues but are also deeply embedded within the network of challenges, reinforcing their importance in strategic planning. The cause–effect differentiation prioritizes root causes over downstream effects in the improvement of handloom distribution systems.

Table 7: DEMATEL Outcomes and Cause–Effect Mapping

Code	Problem Description	D - R (Relation)	Classification
S1	Infrastructural Deficits	+1.38	Cause
S2	Technological & Digital Divide	+1.23	Cause
S3	Financial Exclusion	–0.12	Effect
S4	Market Access Barriers	+0.43	Cause
S5	Policy Unawareness	+0.13	Cause
S6	Middlemen Dependency	–0.88	Effect
/S7	Lack of Branding & Packaging	–0.38	Effect
S8	Low Product Innovation	–0.08	Effect
S9	Limited Design Inputs	–0.70	Effect
S10	Unstable Raw Material Supply	+0.60	Cause
S11	Lack of Working Capital	+0.21	Cause
S12	Poor Transport Connectivity	+0.32	Cause

Source: Compiled by Researchers

The results reveal that Infrastructural Deficits (S1) stand out as the most dominant cause factor, exerting significant influence over other problems in the distribution chain. Other variables such as the Technological and Digital Divide (S2), Policy Unawareness (S5) and Lack of Working Capital (S11) also emerged as high-impact causes. These upstream challenges serve as systemic constraints, shaping the broader performance and efficiency of the handloom distribution network. Unstable Raw Material Supply (S10) and Market Access Barriers (S4) emerged as moderate-impact cause variables. These issues are manifest as operational bottlenecks but are not independent, reflecting a deeper structural vulnerability rooted in infrastructure, capital access and governance.

Key findings:

- Infrastructural deficits, technological divide and lack of policy awareness emerged as foundational issues exerting the strongest causal influence within the distribution system.
- Challenges like middlemen dependency and poor market access were found to be primarily effect-oriented, receiving influence from multiple other factors.
- Financial constraints, including limited working capital and financial exclusion, acted as systemic bottlenecks impacting several downstream operational challenges.
- Improvements in infrastructure and digital connectivity were identified as high-impact leverage points capable of generating ripple effects across the distribution ecosystem.

- Lack of branding, packaging and limited product innovation held a central position in the network, indicating their sustained importance in market penetration and competitiveness.
- Unstable raw material supply and inadequate transport connectivity were not isolated problems but consequences of deeper systemic issues, particularly infrastructure and logistics.
- Limited design inputs and unreliable communication channels were moderate in influence yet acted as key enablers and blockers for smoother market linkage and consumer responsiveness.
- Policy unawareness emerged as a critical causal factor influencing multiple distribution-related problems in the handloom sector. Enhancing weaver's awareness of relevant government schemes, financial services and institutional support systems could serve as a key factor in addressing and broadening the understanding of systemic and interconnected issues
- The DEMATEL model demonstrated that the distribution challenges are highly interlinked, suggesting that isolated interventions may be insufficient without a systemic reform strategy.

6. Policy Implications

The establishment of cluster based "Handloom Infrastructure and Digital Facilitation Zones" is recommended to integrate targeted infrastructure upgrades, digital-capacity enhancement and continuous policy awareness drives within the weaving clusters. Implemented through NGO–enterprise partnerships and formal linkages with private brands, the model directly addresses the dominant causal constraints namely infrastructural deficits, digital divide, policy unawareness and working-capital limitations. A "Raw Material–Market Connectivity Protocol" should also be institutionalised, incorporating a digital raw-material procurement registry, periodic scheme enrolment drives and an automated working-capital credit-trigger system aligned with order cycles. These interventions address the upstream determinants driving systemic inefficiencies and are expected to mitigate downstream issues such as raw-material instability and market-access barriers, thereby strengthening the overall distribution network.

7. Limitations of the Study

Despite the methodological rigor, certain limitations warrant consideration. The DEMATEL approach, while effective in mapping causal relationships, is inherently subjective due to its reliance on expert judgment. Additionally, the findings may not fully reflect the heterogeneity across different regions, as regional variations in distribution challenges were not separately analysed.

8. Conclusion

The study demonstrates the effectiveness of the DEMATEL approach in untangling the interrelated distribution challenges within the handloom sector. The analysis reveals core structural issues as Insufficient framework, restricted technological integration and low levels of program and scheme awareness as the principal causes driving a range of downstream effects. By identifying the root causes with the highest net influence, the study provides a clear direction for targeted interventions. The prioritization enabled by cause-effect classification underscores the need to channel resources toward core issues that have the potential to mitigate multiple dependent problems. The insights reinforce the value of systemic analysis in understanding distributional inefficiencies. Addressing the fundamental barriers can lead to widespread improvements across the distribution system, enhancing efficiency, profitability and autonomy for handloom weavers. Integrating multivariant approaches with evidence-based policy reforms can assist in the sustainable rise in the handloom segment. Finding offer a strategic framework for stakeholders to prioritize actions that resolve systemic inefficiencies and strengthen the sector's resilience.

9. Future Directions

Future studies can enhance the framework by incorporating Fuzzy DEMATEL and Structural Equation Modelling (SEM) to account for uncertainty and latent variables. Agent-based simulations could also be employed to model policy interventions over time. Field-level validation with data collected directly from weavers and region-specific comparative analyses will strengthen the robustness and applicability of the findings.

10. Ethical Consideration

The study adhered to the ethical guidelines. Prior to data collection, the respondent received a detail briefing and key information about the purpose of the research. Through informed consent, the respondent voluntarily participated in the study. The anonymity and confidentiality of the respondent were strictly maintained by avoiding collection of identifiable information and securely storing all responses. The study posed no physical, psychological or social harm to the participants. All data were used exclusively for academic purposes only.

11. Declaration of Conflicting Interests

The authors declare no potential conflicts of interest with respect to the research, authorship and publication of this article.

12. Acknowledgement

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"TEXTILES 2030 - Navigating Geopolitics, Technology Innovations and Global Expectations"

The Textile Association (India), Mumbai Unit organized an International Conference on "TEXTILES 2030 - Navigating Geopolitics, Technology Innovations and Global Expectations" on Friday, 30th January 2026 at Hotel the Lalit, Mumbai. The Conference received overwhelming response with 350 delegates in attendance. The theme of Conference, topics, presentations, and speakers were highly appreciated by one and all. Some of the highlights of the conference are described as under.

Welcome Address by Mr. V. C. Gupte, Conference Convenor & Chairman, TAI, Mumbai Unit

Chief Guest Ms. Roop Rashi, CEO, Khadi and Village Industries Commission, Govt. of India and other dignitaries are lightening the lamp

Mr. V. C. Gupte, Chairman, Textile Association (India), Mumbai Unit and Convener of the Conference, extended a warm welcome to the Chief Guest, Ms. Roop Rashi (IA&AS), Chief Executive Officer, Khadi and Village Industries Commission (KVIC), Government of India; the Guest of Honour; the Keynote Speaker; awardees; speakers; sponsors; members of the press and media; and all delegates. In his address, Mr. Gupte highlighted the efforts of the TAI Mumbai Unit in consistently organizing conferences on future-oriented themes of national and global relevance, culminating in the 2026 international conference themed "TEXTILES 2030 – Navigating Geopolitics, Technology Innovations and Global Expectations." He emphasized that the global textile and apparel industry is at a critical juncture, influenced by geopolitical shifts, rapidly evolving technologies, sustainability imperatives, and changing international trade and regulatory frameworks. He mentioned about the FTAs signed by the Government of India including the most recent FTA signed with European Union which should benefit the T & A exporters and bring back volumes & margins. He suggested to move towards value-added products where competition is less. He stressed on ESG regulations which have become quite stringent, so the awareness should be created amongst the stakeholders. The Conference included a dedicated Panel Discussion by All-Women Panel on the theme of 'Women Leadership driving a Change in T & A Sector' which was unique and for the first time in any Conference.

Mr. Rajiv Ranjan, President, Textile Association (India), Mumbai Unit, in his Presidential Address, highlighted the rapidly changing global landscape facing the textile and apparel industry. He noted that geopolitics, trade realignments, sustainability expectations, and technological disruption are now as influential as cost and quality in global trade. Referring to recent U.S. tariff actions, he emphasized that trade today is increasingly shaped by alignment and perception. He welcomed the signing of the India–EU Free Trade Agreement as a significant opportunity to improve market access, reduce duty disadvantages, and strengthen India's position as a reliable sourcing partner for Europe, while stressing that preparedness will be key to benefiting from it. The address underlined that while domestic demand remains strong, exports face pressures from global slowdown, intense competition, and rising compliance requirements. To remain competitive, Indian textiles must combine cost efficiency with sustainability, digital enablement, and innovation. Calling Textiles 2030 a mindset rather than a milestone, he urged the industry to embrace automation, AI, ESG, circularity, design, and branding, and stressed the need for closer collaboration between industry, academia, and government. He concluded by reaffirming India's resilience and commitment not just to adapt to the future, but to design it.

Mr. R. K. Vij, President, Textile Association (India), in his address, emphasized the importance of a forward-looking and globally aligned approach as the textile and apparel industry moves towards the TEXTILES 2030 vision. He highlighted the need for the industry to remain resilient and responsive to changing geopolitical dynamics, evolving global trade environments,

Presidential Address by Mr. Rajiv Ranjan, President, TAI, Mumbai Unit

Address by Mr. R. K. Vij, President, TAI

and rising international expectations. Mr. Vij underlined the role of strategic planning, policy alignment, and collective industry efforts in strengthening India's position in the global textile value chain. He appreciated the initiative of the TAI Mumbai Unit in organizing the international conference and stated that such platforms play a vital role in fostering dialogue, knowledge exchange, and long-term vision for the sustainable growth of the industry.

Mr. G. V. Aras, Conference Chairman and Trustee, Textile Association (India), Mumbai Unit, briefed the delegates on the structure of the conference, including the selected topics and distinguished speakers. He stated that the program was carefully curated to address the conference theme “TEXTILES 2030 – Navigating Geopolitics, Technology Innovations and Global Expectations” from the perspectives of the organized industry, MSMEs, and international stakeholders. He emphasized that the conference aimed to provide a comprehensive outlook on the future direction of the textile and apparel sector, keeping in view evolving global market dynamics, policy environments, and industry expectations. He further informed that the conference would feature knowledgeable and expert speakers. He informed that there would be a 'All-Women panel discussion speaking on the Women Leadership driving a change in the T&A Sector.

Address by Conference Chairman, Dr. G. V. Aras

Key Note Speaker Mr. Prashant Agarwal, Co. Founder & Jt. Managing Director, Wazir Advisors Pvt. Ltd. addressing the gathering

Mr. Prashant Agarwal, Co-Founder and Joint Managing Director, Wazir Advisors Pvt. Ltd., in his Keynote Address, provided a comprehensive overview of the TEXTILES 2030 landscape, highlighting how geopolitical shifts, evolving global trade dynamics, regulatory frameworks, and changing consumer and market expectations are shaping the future of the textile and apparel industry. He emphasized the need for Indian textile enterprises to align their long-term strategies with global developments, emerging market opportunities, and sustainability-driven expectations to remain competitive in the decade ahead. He noted that with its strong manufacturing base and growing global relevance, the Indian textile and apparel industry is well positioned to play a pivotal role in the international value chain leading up to 2030.

Guest of Honour, Mr. Murugan Thenkondar, President & Head - Marketing and Business, Development (Fibre Marketing), Cellulosic Business, Grasim Industries Ltd. addressing the gathering

Mr. Murugan Thenkondar, President and Global Head – Marketing and Business Development, Birla Cellulose, Grasim Industries Ltd., the Guest of Honour, addressed the gathering and appreciated the relevance and timeliness of the conference theme "TEXTILES 2030 – Navigating Geopolitics, Technology Innovations and Global Expectations."

He commended the TAI Mumbai Unit for organizing a forward-looking international conference that brought together diverse perspectives from across the textile value chain to deliberate on the future direction of the industry.

The Textile Association (India), Mumbai Unit continued its long-standing tradition of recognizing distinguished personalities for their outstanding contribution to the Indian textile industry.

At the present International Conference, the Lifetime Achievement Award was conferred upon Mr. Amrishbhai Patel, Chairman, Deesan Group of Companies; President, SVKM; and Chancellor, NMIMS, in recognition of his exemplary leadership and enduring contribution to industry, education, and society. In his remarks, Mr. Patel expressed his gratitude to the TAI Mumbai Unit for the honour and acknowledged the role of the textile sector in nation-building and long-term socio-economic development.

Mr. Chintanbhai Patel receiving The Lifetime Achievement Award on behalf of his father Mr. Amrishbhai Patel, Chairman, Deesan Group of Companies by the hands of Chief Guest Ms. Roop Rashi

Mr. Mikhail Menezes receiving The Industrial Excellence Award on behalf of his father Mr. Edward Menezes, Executive Chairman, Rossari Biotech Ltd. by the hands of Chief Guest Ms. Roop Rashi

Mr. Sunil Chari, Managing Director, Rossari Biotech Ltd. receiving The Industrial Excellence Award

Release of Book of Papers

The Industrial Excellence Award was jointly presented to Mr. Edward Menezes, Executive Chairman, and Mr. Sunil Chari, Managing Director, Rossari Biotech Ltd., in recognition of their significant contribution to innovation, growth, and leadership in the textile chemicals sector. The awardees thanked the TAI Mumbai Unit for the recognition and reaffirmed their commitment to contributing to the future growth of the Indian textile industry in a globally evolving environment.

Chief Guest Ms. Roop Rashi, CEO, Khadi and Village Industries Commission, Govt. of India addressing the gathering

Ms. Roop Rashi (IA&AS), Chief Executive Officer, Khadi and Village Industries Commission (KVIC), Government of India, and Chief Guest of the event, addressed the delegates and highlighted the significance of the conference theme TEXTILES 2030 in providing a holistic and forward-looking perspective for the development of the textile and apparel sector.

She emphasized the need for the industry to align with evolving global expectations, policy frameworks, and market dynamics while strengthening India's position in the international textile value chain.

Ms. Roop Rashi appreciated The Textile Association (India), Mumbai Unit for selecting a timely and globally relevant theme and for organizing the international conference as a meaningful platform for dialogue, knowledge sharing, and strategic thinking for the future of the textile industry.

Informative technical sessions

There were three Technical Sessions – each Session had 3 papers and a Industry First All Women's Panel Discussion.

Technical Session I

Ms. Vaishali Kamble, Assistant General Manager -Future Fibre, Birla Cellulose, Grasim Industries Ltd., delivered the opening technical presentation of the conference on behalf of Mr. Shaymlal Patnaik, Jt. President, Head – Specialty Products. In her presentation, she spoke on the innovation in the cellulose fibres which would provide advantage over present fibre, but also meet the ever changing regulations and compliances. The presentation provided valuable insights into how the industry can align with global requirements leading up to 2030.

L to R: Mr. Mikhail Menezes, Director – Technical, Rossari Biotech Limited, Ms. Vaishali Kamble, Assistant General Manager -Future Fibre, Birla Cellulose, Grasim Industries Ltd., Ms. Nidhi Kaushik, Sr. Vice President (Treasury), Kotak Mahindra Bank

Mr. Mikhail Menezes, Director – Technical, Rossari Biotech Ltd., delivered the second technical presentation of the conference. In his address, he dwelled on innovation in Surfactants which are treated as work horse of the chemical industry.

He introduced 'Green Surfactant' which would meet sustainability and regulations. He talked on biosurfactants which are derived from vegetable oils like palm oil, coconuts etc. These are highly biodegradable with lower toxicity and there is increasing consumer demand for green lables and stricter environmental regulations. He also laid stress on their functional advantage in textile processing. The presentation offered practical insights into aligning chemical solutions with future-ready textile manufacturing practices and was well appreciated by the delegates.

Ms. Nidhi Kaushik, Senior Vice President (Treasury), Kotak Mahindra Bank, delivered the third technical presentation of the conference. She provided an overview of the global financial and trade environment in the context of the TEXTILES 2030 vision, highlighting the impact of international market movements, currency trends, and trade dynamics on the textile and apparel sector. Her presentation offered valuable perspectives on financial planning, risk awareness, and preparedness for textile enterprises operating in an increasingly interconnected global marketplace. The session generated keen interest among the delegates and concluded with an interactive question-and-answer segment.

Technical Session II

Mr. Rahul Bhajekar, Managing Director, Global Standards GmbH, delivered a technical presentation addressing the evolving regulatory and compliance landscape of the textile and apparel industry. He introduced ESG Regulations to the audience. He highlighted 5 regularity pillars impacting textiles and apparel industry. He talked about the regulation more specific to the European Union. He specified Europe's headline regulations for textiles and apparel, like ESPR, Waste/Circularity, CSRD, CSDDO and Anti-greenwashing. He explained all these regulations.

He also briefed on very recent new levy on fast fashion by Germany. He presented on Eco-modulation specific about France, Spain and Italy.
He also talked about regulations in US and Asia-Pacific. At the end, he also what Indian Textile and Apparel need to follow minimum viable compliance stack. His presentation provided clarity on ESG regulations and It was very highly appreciated by the delegates.

L to R: Mr. Rahul Bhajekar, Managing Director, Global Standard GmbH, Germany, Dr. Leonie Vaas, General Manager – Sustainability, Hirdaramani Apparel, Sri Lanka, Mr. Navodit Babel, Co-Founder and CTO, Green Story Europe B.V., Netherlands

Mr. Navodit Babel, Co-Founder and Chief Technology Officer, Green Story Europe B.V., Netherlands, delivered a technical presentation focusing on the transition of the textile and apparel industry towards greater transparency and accountability. He showed three main points for regulatory timelines, for example Green Claims Directive by 2023, ESPR adoption by 2024 and Digital Product Passport by 2027. He explained the three regulations in detail. He also presented the consequences of non-compliance in terms of Heavy Penalty, Market Access and Brand Trust. He presented strategic roadmap for brands. The presentation highlighted the importance of credible data, traceability, and clear communication of sustainability efforts to international stakeholders. The presentation was very well appreciated.

Dr. Leonie Vaas, General Manager – Sustainability, Hirdaramani Apparel, Sri Lanka, delivered a technical presentation highlighting how her organization has implemented ESG goals across its manufacturing campuses in six countries as part of its long-term vision. She shared practical insights into the company's approach towards embedding environmental, social, and governance principles across operations, supply chains, and workplace practices. Drawing from real-world implementation experiences, her presentation illustrated how structured ESG strategies can drive responsible growth and resilience across geographically diverse operations. She presented at the end of the presentation highlighting that ESG Readiness is Not A Cost, but it is Strategic Investment.

The theme of the Panel Discussion was "Women Leadership Driving a Change in the Textile & Apparel Sector", bringing together a distinguished group of women leaders from industry, technology, sustainability, heritage, and global business. The session drew an enthusiastic response from delegates and underscored the growing role of women leadership in shaping the future of the textile and apparel industry.

The Panel Discussion was moderated by Ms. Neha Gupta, Founder, International Fashion Business Exchange Council.

The panel discussion served as an insightful platform for industry stakeholders to understand the perspectives, experiences, and leadership journeys of women professionals who are actively driving transformation across the textile and apparel value chain. The session highlighted the increasing influence of women in decision-making roles and their contribution to innovation, sustainability, and inclusive growth in the sector.

The panel included eminent women leaders from diverse segments of the industry:

Ms. Seema Srivastava, Executive Director, India ITME Society

Ms. Smita Yeole, Managing Director, Oriental Weaving & Processing Mills Pvt. Ltd.

Ms. Shefali Gopalka, Partner, National Dyechem Industries

Ms. Katyayani Agarwal, Freelance Consultant, Museum Curator, Cultural Heritage Specialist

Ms. Anoushka Veljee, Chief Revenue Officer, Frontier.Cool Inc., California, USA

Mrs. Smita Joshi, Vice President – Home Textiles and Exports, Sutlej Textiles & Industries Ltd.

Ms. Neha Gupta skilfully moderated the discussion, guiding the panel through a wide range of topics covering leadership journeys, challenges faced by women in the textile and apparel industry, opportunities for growth, and the evolving role of women in shaping global business practices.

The panel discussion covered several key areas, offering valuable insights to the delegates, including:

L to R: Ms. Anoushka Veljee, Ms. Shefali Gopalka, Ms. Smita Yeole, Ms. Katyayani Agarwal, Ms. Neha Gupta, Dr. Seema Srivastava, Mrs. Smita Joshi

1. Women Leadership and Industry Transformation

The panelists shared how women leaders are contributing to the transformation of the textile and apparel sector through:

- Strategic leadership and decision-making
- Driving innovation and operational excellence
- Strengthening sustainability and ethical business practices

2. Challenges and Opportunities

The discussion addressed challenges faced by women professionals, including:

- Navigating leadership roles in traditionally male-dominated segments
- Balancing professional growth with organizational and social expectations
- Creating inclusive workplaces that support talent development

At the same time, panelists highlighted emerging opportunities for women leaders as the industry becomes more global, diverse, and innovation-driven.

3. Building Inclusive and Future-Ready Organizations

The panel emphasized the importance of:

- Encouraging diversity and inclusion at leadership levels
- Mentorship and capacity-building for young professionals
- Creating organizational cultures that support collaboration and long-term growth

4. The Way Forward

A recurring theme of the discussion was the need for collective efforts by industry bodies, organizations, and leadership teams to:

- Enable greater participation of women in leadership roles
- Foster inclusive growth across the textile and apparel value chain
- Prepare the industry for future global expectations under the TEXTILES 2030 vision

The session concluded with an interactive question-and-answer segment, where delegates actively engaged with the panellists on leadership development, career pathways, and the evolving role of women in the textile and apparel industry. The panellists provided thoughtful and inspiring responses, further enriching the discussion.

The event was widely appreciated by the delegates, who represented a broad cross-section of the textile and apparel ecosystem, including manufacturers, exporters, designers, technology providers, academicians, and policy stakeholders. Participants commended the conference and panel discussion for offering thoughtful, balanced, and forward-looking perspectives on the challenges and opportunities shaping the textile and apparel industry.

In concluding the session, the moderator summarized the key takeaways, emphasizing the importance of:

- Adopting a strategic and globally aligned outlook to remain competitive in international markets
- Encouraging innovation and adaptability to address evolving industry and market requirements
- Integrating sustainability and responsible practices into long-term business strategies
- Preparing organizations and professionals for changing global expectations and future industry dynamics

The conference concluded with a strong collective message that while the textile and apparel industry faces significant global challenges in the coming decade, it also holds substantial opportunities for growth, resilience, and leadership on the world stage. Delegates highlighted the need for collaborative efforts, informed decision-making, and long-term vision to successfully navigate the road to TEXTILES 2030.

The Distinguished Audience

Vote of Thanks by Mr. Haresh B. Parekh, Hon. Secretary, TAI, Mumbai Unit

There was active interaction between speakers and delegates during the question-and-answer sessions as well as informal discussions during tea and lunch breaks, enabling meaningful exchange of ideas and effective dissemination of insights aligned with the conference theme.

Mr. Haresh B. Parekh, Hon. Secretary, Textile Association (India), Mumbai Unit, proposed the Vote of Thanks, expressing gratitude to the speakers, panelists, sponsors, delegates, and organizing committee members for contributing to the success of the International Conference, which was attended by around 300 participants.

COLORANT

Quality is Colorant

COLORANT signed MoU for Colorant - Centre of Excellence with TIT&S

MoU for "Colorant - Centre of Excellence" Signed in the Esteemed Presence of Shri Giriraj Singh Ji, Hon'ble Union Minister of Textiles, Government of India

In a noteworthy advancement towards strengthening industry–academia collaboration in India's textile sector, Colorant Limited, Ahmedabad, led by its Founder & Managing Director Mr. Subhash Bhargava, entered into a strategic partnership with The Technological Institute of Textile & Sciences (TIT&S), Bhiwani, through the signing of a Memorandum of Understanding (MoU) for the establishment of the Colorant Centre of Excellence (CoE) – Dyes Synthesis and Application.

The MoU was formally signed on 28th February 2026 during the International Conference on Advanced Textile Structural Composites and Geosynthetics (ATSCG-2026) held at the Central Auditorium of TIT&S, in the august presence of Shri Giriraj Singh Ji, Hon'ble Union Minister of Textiles, Government of India. The agreement was signed by Mr. Subhash Bhargava, Founder & Managing Director, Colorant Limited, and Prof. Dr. B. K. Behera, on behalf of TIT&S, Bhiwani, who also contributed to the conference through technical deliberations on advanced textile structural composites.

The conference witnessed the participation of eminent academicians and global researchers including Prof. Savvas Vassiliadis (University of West Attica, Greece), Dr. Michal Petru (Technical University of Liberec, Czech Republic), Prof. Frantisek Novy (University of Žilina, Slovak Republic), Prof. Robert Böhm (HTWK Leipzig, Germany), and Dr. Rajesh Kumar Mishra (Czech University of Life Sciences, Prague), reflecting the international significance of the platform.

Further adding to the collaborative spirit of the event, doc. Ing. Aleš Kocourek, Rector, Technical University of Liberec (Czech Republic) addressed the gathering on future academic–industrial partnerships and presided over the signing of MoUs with participating industries.

Amidst this global academic congregation, the establishment of the Colorant Centre of Excellence emerged as a pivotal initiative aimed at integrating real-time industrial practices within academic learning environments. With its operational expertise based in Vatva, Ahmedabad, Colorant Limited will supply, install, and commission the necessary dye synthesis testing and application equipments, while TIT&S will provide laboratory infrastructure and oversee operational maintenance, as outlined in the MoU framework.

Talking about the occasion, Mr. Subhash Bhargava emphasized the importance of creating practical learning ecosystems for future textile technologists. He noted that the Centre would enable students and researchers to gain hands-on experience in dye chemistry, process optimization, and industrial-scale application methodologies aligned with evolving global textile demands.

The initiative stands as a testament to Colorant's commitment to transforming academic insight into industrial innovation, thereby contributing meaningfully to India's growth story. The Colorant Centre of Excellence is envisioned to evolve into a dynamic hub where research meets application, fostering innovation-driven growth across the textile value chain.

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USTER® The game-changer in fabric quality assurance

Uster Fabriq Vision 2 was developed to help fabric producers' transition from manual to automated inspection – with the same staff.

Why do many fabric producers still feel the need to rely on manual inspection? It's understandable that they are nervous about safeguarding their fabric quality, given that it is the basis for customer satisfaction. Yet the skilled personnel they rely on to secure that quality can now be the success factor in a massive leap of progress – to automated inspection with the new Uster Fabriq Vision 2. Smarter, more reliable inspection, creating bigger yields and avoiding the dreaded quality claims.

Fabriq Vision 2 was developed to enable the smooth and simple transition from manual to automated inspection, with the confidence of knowing that the same knowledgeable staff are still a vital part of the process, the safe hands that make the upgrade worry-free for producers.

It's true that fabric inspection solutions still occupy something of a niche position, despite years of development. Even with the extra possibilities from AI integration, manual inspection is still preferred by many companies. The required investment in time and expertise for set-up and adapting to different fabrics has likely been a barrier. What's needed is a game-changer – a system that is the perfect fit with existing staff skills to protect quality standards, reputation and profitability.

Smarter, simpler, more reliable

Uster developers are always innovating with latest technology, but they realized that progress in fabric inspection automation would need to focus on reducing the complexity for style configuration and setups, so the skills of current staffs could readily be applied. They also prioritized user-centric workflows, to avoid overly sensitive settings that might result in over-detections and time-consuming album reviews.

With these smart concepts, Uster Fabriq Vision 2 becomes the game-changer the industry needs. Proven defect detection reliability is enhanced with cutting-edge AI technologies. But importantly it follows the unique approach of using human intelligence where needed – and automating the rest.

This new fabric inspection system doesn't need an Uster expert or a specially-trained technician to operate it. Simplicity is the key, so existing staff have required skills. They can already define what a fabric defect is, with the ability perfected over years working on manual fabric inspection. Uster Fabriq Vision 2 is based on a user-friendly workflow, simplifying complex tasks, so the system is transparent, intuitive, and quickly up and running.

Style tuning in 10 minutes

Uster's latest-generation fabric inspection system benefits customers through AI-supported style tuning, based on textile parameters, enabling startup of new articles in less than 10 minutes.

Users with a basic understanding of the appearance of common defects can quickly create new detection settings for a specific fabric, guided step-by-step by a wizard which uses known textile parameters along with live images from the system cameras.

The integrated intelligence then applies this information to preset and adjust the necessary detection parameters to create an initial article setting. Inspection parameters can be visually fine-tuned, based on true color images, allowing quick and confident decision-making while setting adjustments, as well as creating classification rules.

Uster Fabriq Vision 2 - The simplicity of fabric quality assurance

Camera of Uster Fabriq Vision 2 – and reddot award winner 2025 for innovative and industrial design

Uster's machine learning classification reduces over-detection, using transparent rule-based methods, alongside real-time defect classification with individually customizable defect codes. Furthermore, the Super Inspection feature enhances process and quality assurance by allowing higher sensitivity background detection, making detailed information available whenever needed.

These simple and smart workflows are the key to improving both inspection reliability and operational efficiency.

Fast, intuitive… and already a hit

The fully integrated platform of Uster Fabriq Vision 2 brings together an advanced inspection system, AI-supported workflows, and powerful analysis and reporting tools in one seamless solution. This holistic approach enables fabric producers to achieve consistent quality, increase yield, and make informed, data-driven decisions with greater ease and confidence. Uster Fabriq Vision 2 achieves all this with reduced cost of ownership, thanks to lower user skill requirements, faster adoption times and self-maintenance possibilities.

First introduced at ITMA Asia + CITME in Singapore in 2025, Uster Fabriq Vision 2 was a hit with visitors to the show. Its improved user-centric workflows and usability, enabling customers to rely on their own quality inspection staff as operators, proved its value in meeting modern demands for automated fabric inspection. First-hand information will again be available at the upcoming Techtextil 2026 in Frankfurt, Germany. Meet the Uster fabric inspection experts with Uster agent Elmatex, at its booth D05 in Hall 12.0 from April 21 to 24. Curious fabric producers are warmly welcome!

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KARL MAYER (China) celebrates its 30th anniversary

On February 6, KARL MAYER (China) celebrated the new year and its 30th anniversary. Employees and the management team at the Changzhou location, as well as representatives from management in Germany, Italy, and Hong Kong, were invited to the festivities. A special highlight was the visit by Lutz Wolf, CEO of KARL MAYER.

"Our subsidiary in China holds immense importance to our group. We are proud to operate in this key market with such a strong and dynamic location serving our customers. I am very impressed by the extraordinary drive, flexibility, and deep understanding of customer requirements shown by our employees," said Lutz Wolf, commenting on the importance of KARL MAYER (China).

The establishment of a separate company in China in the mid-1990s was a bold and strategically consistent step. KARL MAYER focused on globalization early on and established production sites in its key markets in order to operate close to its customers. At that time, however, the idea that China would become the world's most important market one day was still a vision of the future.

From belief in China as a location to fully localized series production

In the early 1980s, KARL MAYER collaborated with the Wujin Textile Machinery Factory in Changzhou for joint production and to promote knitting technology in China.

In 1995, the two partners joined forces with NIPPON MAYER to found KARL MAYER WUJIN Textile Machinery Co., Ltd. The joint venture was the first company with foreign roots in the Changzhou Wujin High-tech Zone. It started with 400 employees on a 70,000 m² plot of land and was completely taken over by KARL MAYER just four years later.

Building on its own Chinese organization named KARL MAYER Textile Machinery Co., Ltd., KARL MAYER (China) Ltd. was founded in 2005 and has been continuously expanded ever since. In 2008, the company moved into a new factory with an area of 175,000 m². In 2011, the production portfolio was expanded to include the manufacture of warp preparation equipment, and a further expansion of capacity took place the following year to increase the production of high-end models. The latest milestone in the success story of KARL MAYER's Chinese location was the opening of a new showroom in October 2024, featuring an exclusive selection of textile highlights, trend themes, and innovative solutions from all business units. By 2025, KARL MAYER had invested over 150 million yuan in technological upgrades, including the introduction of fishbone production and SAP-networked intelligent logistics.

KARL MAYER (China) currently employs around 750 people in Changzhou. In February, they all celebrated 30 years of successful development together.

Press Release
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BENNINGER

Leading technologies in continuous wet processing and jet dyeing

Benninger's must-see dyeing and finishing solution at Knit-Tech 2026

Benninger, a complete system supplier with leading technologies for continuous wet processing and discontinuous dyeing, as well as technical textiles, reinforces its commitment to sustainable textile production with resource-efficient machinery that increases both top and bottom line performance. At Knit-Tech 2026, scheduled from 6 – 9 March 2026 in Tirupur, Tamil Nadu, India, Benninger will showcase SynthMaster. Its innovative horizontal jet dyeing machine combines unmatched fabric quality, low resource consumption, and compact, versatile design.

The gentle treatment for sensitive fabrics. Now launching in India

SynthMaster – 160+ years of wet processing mastery

Benninger places sustainability and responsibility at the heart of SynthMaster's operations. Benninger's solutions can process today's and tomorrow's fibers and blends with the highest first-time-right rates. Visitors to the upcoming Knit-Tech are invited to engage with experts on sustainable dyeing and finishing. Visit Benninger at booth A22!

The versatile solution for compression-free precision dyeing

The SynthMaster sets a new benchmark in horizontal jet dyeing, combining harmonic, unique, and Swiss-made design with unparalleled fabric care. Its smooth, tension-free fabric transport guarantees no compression creases, ensuring perfect quality every time. Built on the same innovative principles as Benninger's well-known FabricMaster, it features a smart nozzle, lowest lift, and an elbow plaiter running the full length of the machine. The SynthMaster delivers consistent performance and fabric integrity.

Thanks to its advanced dewatering and chamber design, the SynthMaster operates at lower liquor ratios, optimizing resource efficiency. At approximately 4.5 meters in length, it is the only machine that can be seamlessly combined with dyers' round machines, drastically saving valuable factory space. The SynthMaster is the ideal complement to the FabricMaster, sharing key components and offering unmatched compatibility.

Swiss precision, global standards

Benninger aims – always did and always will to set new standards for efficiency, quality and precision in textile dyeing processes. The FabricMaster, the dyeing machine for discontinuous dyeing and the SingeRay flame singeing machine are other good examples, defining new benchmarks for efficiency, sustainability, and process reliability thanks to cutting-edge technology. These innovations often become references for best practices worldwide.

By integrating energy-saving designs, water and chemical reduction technologies, and waste heat recovery (e.g., through the BEN-Eco systems), Benninger advances global environmental standards. Their machines help customers meet or exceed international sustainability targets. The long history of Benninger, including the long list of achievements as well as the number of years of experience and the flexibility makes the company one of the most reliable providers for high-performance solutions in the textile industry. In a nutshell: You can feel it's Benninger!

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Kala Ghoda Arts Festival 2026

From Waste to Worth: Women-Led Craft and Innovation Model Showcased at Kala Ghoda Arts Festival 2026

Mumbai - February 2026

At the vibrant Kala Ghoda Arts Festival 2026, amidst art installations, performances, literature discussions, and creative showcases, a modest yet meaningful stall quietly narrated a powerful story of dignity, sustainability, craft, and grassroots innovation.

Presented by Anveshanam Foundation, the stall featured thoughtfully handcrafted bags, jewellery, hair accessories, and utility products created by women from Mumbai's urban slums. Designed using pre-consumer textile waste, these products demonstrated how traditional craft skills combined with simple innovation can transform discarded materials into aesthetic, functional, and market-ready creations.

Participation at Kala Ghoda Arts Festival 2026

The Foundation's participation was guided by a clear objective: to provide women organized under Self Help Groups (SHGs) a dignified public platform to showcase their craft, creativity, and entrepreneurial potential.

Kala Ghoda, one of Mumbai's most respected cultural festivals, offered an ideal bridge between grassroots artisans and an aware urban audience that values design, sustainability, and authentic craftsmanship.

Stitching Hope Through Craft and Innovation

Working in small community spaces, women apply quilting techniques, fabric layering, and thoughtful design adaptation to transform textile waste into aesthetically appealing and innovative products.

Each piece reflects:

- Craftsmanship
- Creativity
- Resilience
- Pride

What began as survival-driven work is steadily evolving into structured micro-enterprise rooted in skill refinement and design innovation.

A defining feature of this initiative is its transparent and empowerment-driven model:

100% of the profits earned at the stall were transferred directly to the women artisans.

Anveshanam Foundation does not retain any commission. Its role is to strengthen capacity through:

- Skill enhancement and craft training
- Design inputs and product innovation guidance
- Marketing and branding support
- Financial literacy orientation
- Value-based education

This ensures ownership, dignity, and sustainable growth.

Festival Experience and Public Response

Over four days, the stall received an encouraging response with steady sales throughout the event. Handmade hairbands crafted from repurposed textile waste emerged as a crowd favorite appreciated for their design sensibility and sustainable innovation.

More significantly, the experience marked important milestones for many artisans:

- First direct interaction with customers
- First opportunity to present their craft publicly
- First exposure to structured market appreciation
- First earnings in a formal cultural setting

The transformation was visible - hesitation gradually gave way to confidence, and craft was expressed with pride.

Visitors appreciated:

- The fusion of sustainability and design
- The ethical and transparent business model
- The environmental responsibility
- The authenticity of handmade craft
- The social innovation dimension

Several expressed interest in continued engagement beyond the festival.

Circular Economy in Action

The initiative demonstrated a practical model of circular economy in action converting textile waste into thoughtfully designed accessories while generating income at the grassroots level.

By integrating craft with simple innovation, the model reduces environmental burden and promotes conscious consumption, aligning with global Sustainable Development Goals.

About Anveshanam Foundation

Anveshanam Foundation was incorporated on 21st March 2023 as a Section 8 non-profit organization and is registered under 12A and 80G, reflecting its commitment to transparency, accountability, and ethical governance.

The word "Anveshanam" means exploration symbolizing the discovery of human potential. The Foundation was established with the belief that meaningful development must integrate education, livelihood, values, environmental responsibility, and innovation rather than addressing them in isolation.

It works inclusively across communities irrespective of caste, creed, gender, financial status, or background. Since its inception, the Foundation has directly and indirectly impacted over 2,000 beneficiaries, focusing on structured, sustainable, and innovation-driven impact.

Vision

"Harmony and Happiness at All Levels."
This reflects harmony within the individual, family, society, and nature emphasizing ethical, inclusive, value-based, and sustainable development.

Key Areas of Work

Education & Literacy
- Support to schools and higher education institutions
- Scholarships and interest-free educational loans
- Career guidance and Universal Human Values education

Skill Development, Craft & Women Empowerment
- Strengthening Self Help Groups
- Vocational training and craft refinement
- Design development and product innovation
- Entrepreneurship and market linkage support
- Financial literacy programs
- 100% profit transfer model ensuring artisan ownership

Environmental Sustainability
- Promotion of Refuse, Reduce, Reuse, Repurpose, Recycle principles
- Encouraging responsible material use and eco-conscious design

Healthcare & Community Wellbeing
- Preventive healthcare awareness initiatives

Digital Literacy & Innovation
- Digital empowerment programs
- Research and innovation aligned with Sustainable Development Goals

Leadership Perspective

Dr. Ela Manoj Dedhia, Founder Director of Anveshanam Foundation, states:

"Transformation through Universal Human Value Education for a Peaceful Society and Harmony in Nature."
She

"True empowerment lies in nurturing skill, craft, and innovation so that individuals earn with dignity and confidence. When a woman's creativity is recognized and valued, families and communities move towards harmony."

Looking Ahead

Following the encouraging response at Kala Ghoda 2026, the Foundation aims to deepen product innovation, expand market linkages for women-led craft enterprises, and scale sustainable livelihood models rooted in skill, creativity, and environmental responsibility.

Media Contact
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Founder Director
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Mumbai, India

We deliver high standards so that you too can deliver the same to global brands.

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