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Tariff Headwinds, Tax Tailwinds – India's Textile Industry at a Crossroads

Dear Readers,
Greetings and the best wishes!!!

The Indian textile industry stands at a pivotal juncture, influenced by domestic policy initiatives and evolving global trade dynamics. The industry has entered a period of profound disruption and opportunity as well. The Indian Government's recent roll-out of Goods and Services Tax (GST) 2.0 offers a timely, structural counter-measure against the steep tariffs imposed by the United States of America on India's export-driven textile sector.

In recent months, exports of garments and textiles from India to the USA have felt the impact of an additional 50 % tariff. MSME clusters such as Tirupur have seen order cancellations, sharp wage cuts, and the risk of their existence. While diversification into non-U.S. markets is being explored, the immediate shock cannot be ignored. In this context, the GST 2.0 reforms emerge as a strategic lever for resilience. By rationalizing tax rates across fibres, yarns and fabrics, the government has corrected the long-standing 'inverted duty' structure that hampered cash-flows and increased working-capital burdens for textile manufacturers.

This duality of external challenge and internal reform highlights some major observations for our industry. First, the tariff shock underlines that over-reliance on any one export destination is risky and it is imperative for Indian exporters to diversify and upgrade. Second, GST 2.0 provides a timely structural correction and gives the industry a breathing space: improved input tax credit flows, lower cost burdens, and a more level domestic playing field. Third, for MSMEs and cluster-based units, the reforms give hope of improved viability provided they can adapt operationally and upgrade productivity.

The GST reforms do not immediately offset the full drain of order losses, margin squeezes and factory slow-downs triggered by tariff shocks, especially for MSME units that face resource constraints, skills-gaps and global competition from more favourable tariff regimes countries. The industry must act on multiple fronts: cost efficiency, product-innovation, market-diversification, sustainability credentials and agile supply-chain integration.

While external headwinds from US tariffs challenge our export strengths, the internal tailwinds from GST 2.0 offer a chance to reset and reposition. Our sector sits at a historic inflection point. With the right actions, the disruption can lead to a transformation and India can weave a stronger, more resilient textile industry for the decades ahead.

With best wishes,

Dr. Deepa V. Raisinghani
Chairman
JTA Editorial Board

T. L. PATEL, President

As the President of the Textile Association (India), I'm delighted to share my insights on the current state of the textile industry, particularly in light of recent GST changes and trade agreements. With over 26,000 members, our association is committed to promoting the growth and development of this vital sector.

GST Changes: A Mixed Bag

The Goods and Services Tax (GST) has brought about significant changes in the textile industry. On the one hand, the reduction in tax rates on certain textile products has increased competitiveness and encouraged exports. However, the sector still faces challenges due to the inverted duty structure, which has led to working capital blockages for manufacturers.

Trade Agreements: Opportunities and Challenges

The recent trade agreements, such as the proposed India-USA Free Trade Agreement, are expected to boost textile exports. The Memorandum of Understanding (MOU) signed between The Textile Association (India) and the American Association of Textile Chemists & Colorists (AATCC) is a step in the right direction. This partnership will facilitate knowledge exchange, joint educational programs, and global conferences, ultimately benefiting the Indian textile industry. (https://textileinsights.in/aatcc-and-tai-partner-to-boost-india-usa-textile-ties/)

Territorial Effect: A Boost to Exports

The textile industry is expected to benefit from the territorial effect, which promotes exports and increases competitiveness. With the growing demand for sustainable and technical textiles, India's textile sector is poised to capitalize on these opportunities.

Way Forward

To fully leverage these opportunities, the industry needs to focus on:

Sustainability: Adopting eco-friendly practices and sustainable materials to meet the growing demand for environmentally responsible textiles.

Technical Textiles: Investing in research and development to create innovative products that cater to the needs of various industries, such as healthcare, automotive, and construction.

Skill Development: Providing training and upskilling programs to ensure a skilled workforce that can adapt to the changing demands of the industry. By addressing these challenges and capitalizing on emerging opportunities, the textile sector can continue to grow and contribute significantly to India's economy. As the President of the Textile Association (India), I look forward to working with industry stakeholders to achieve these goals.

The Indian textile industry is concerned about the potential impact of anti-dumping duties (ADD) on essential raw materials. Here are some key points to consider:

Anti-Dumping Duties on Textile Raw Materials

Mono Ethylene Glycol (MEG): The textile industry has urged the government not to impose ADD on MEG, a key raw material for polyester production. The proposed ADD would increase MEG costs by 20%, negatively impacting manmade fibre and textile pricing.

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

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AI-Driven Dyeing: The Next Great Leap Forward in Textile Production

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Abstract:

Background

Now, it is AI and ML which are changing how we dye textiles, introducing greater automation, accuracy, and sustainability to the process. Traditional dyeing processes are frequently embodied by resources consumption, poor quality and test and error based. AI Technologies offer Data driven optimisation, real-time monitoring and compliance to strictening environmental laws.

Methods

This article was written conceptually and analytically, as the authors had conducted a study of the current status of AI application in dyeing. The technologies analysed are computer vision to detect defects, a digital twin to simulate processes, reinforcement learning for control flexibility, and predictive maintenance for machines. Examples of measurable impacts are reviewed from case studies, industry reports and academic literature.

Results

The study demonstrates a considerable advantage of AI-tool integration into dyeing. This leads to FTR-rates of approximately 20% within their color information and a shade accuracy of over 95% at low water and energy consumption of up to 30%. Computer vision allows for defect identification beyond humans' capabilities, while digital twins decrease the risk of repassivation. Adaptability is increased with reinforcement learning, while downtime is reduced by over 60% through predictive maintenance. Nevertheless, certain difficulties remain in terms of data access, the complexity of integration, and the required initial outlay.

Conclusion

AI and ML are revolutionizing the dyeing of textiles, making it an accurate, intelligent and sustainable process. The ability of AI-driven dyeing to overcome adoption barriers and through collaboration between industry, academia and policy makers deliver sustainable and competitive eco-efficient manufacturing. This investigation offers a roadmap for researchers and industrial professionals to enter the next-generation of smart textile fabrication.

Keywords: *AI in Textile Dyeing, Dyeing Process Optimization, Industry 4.0, Smart Textile, Sustainable Dyeing*

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1. Introduction

A technological revolution in the textile coloration sector is on the horizon, in response to the dual demands of sustainability and Industry 4.0 implementation. Traditional dyeing processes, although well-suited to legacy systems, are becoming unsuitable for the agility and responsiveness required in today's high-tech and automated production environment. Artificial Intelligence (AI) and Machine Learning (ML) mixed into dyeing operations to make a high-tech scene, automatized, real-time control and predictive technology [1].

With AI, textile units can save not just energy and water - and taking proactive approach to color formulation, defect detection and predicting equipment failure - it can do so even before the gates are opened. They are also enhanced by integration with IoT sensors, Edge Computing and Digital Twin systems [2].

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Table 1 - Traditional vs AI-Driven Dyeing

Parameter	Traditional Dyeing	AI-Powered Dyeing
Process Control	Manual / supervisory	Real-time automated with sensor feedback
Color Matching	Based on expert judgment	AI-based predictive algorithms + computer vision
Resource Utilization	Fixed values, high wastage	Optimized per batch via ML predictions
Error Detection	Post-process, human inspection	Real-time defect detection via CNNs
Maintenance	Reactive (after failure)	Predictive, based on sensor + ML anomaly analysis
Environmental Compliance	Difficult to monitor	Continuous tracking of emissions and effluents

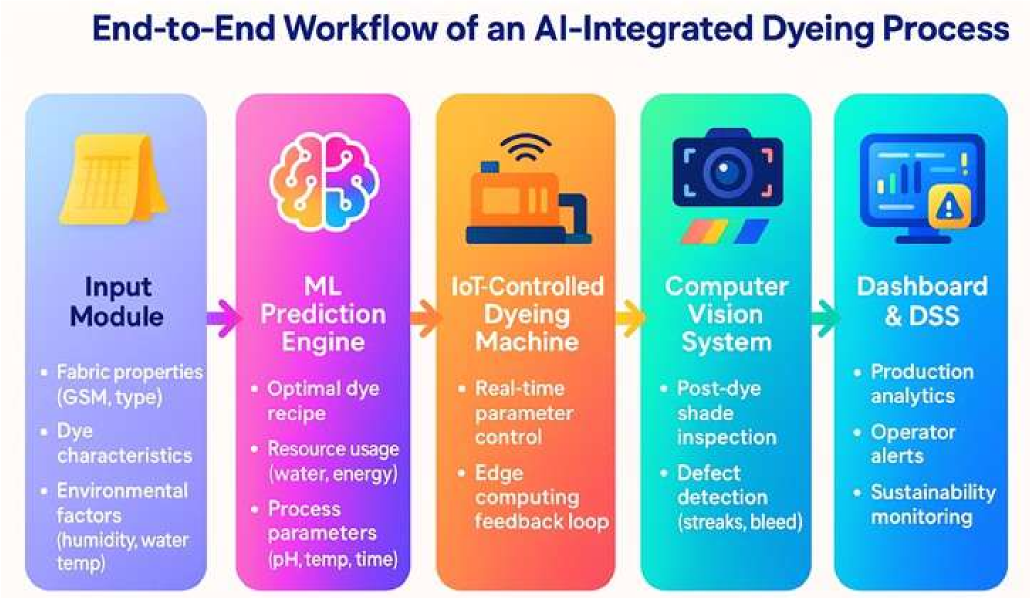

Figure 1 - AI-Driven Dyeing Workflow

2. AI and ML'S Impact on Textile Dyeing

2.1 Enhanced Process Optimization

AI/ML can mean dynamic process optimization, swapping out the static, rule-based models of conventional dyeing for smart systems that learn from the process as it's happening. These algorithms constantly monitor variables such as temperature, pH, pressure, liquor ratio and dye concentration. Models trained with historical data, using supervised learning, provide optimal process parameters for each type of material and batch size [3].

That ability virtually eliminates trial and error, enabling manufacturers to mitigate first-time-right (FTR) failures and dyeing variability [4].

Example: Huntsman Textile Effects implanted an ML control, which was able to cut re-dyeing occurrences by 28% out of 500 polyester batches.

2.2 Matching of Color and Consistency of Shade

Color precision has forever been a fundamental issue in the textile industry owing to substrate diversity and inherent human perception limitations. AI tackles this issue by leveraging computer vision and deep learning models (e.g., convolutional neural networks CNNs) for color data extraction in LAB and RGB spaces and matching it with digital shade libraries [5].

The outcome is finer matching with over 95% shade headroom, even on higher fibre blends.

Key Benefit: AI limits the dependency on manual lab dips and helps support batch-to-batch color consistency a must for retail global compliance.

2.3 Water and Energy Saving

Sustainable targets are focused on resource efficiency [6]. AI calculates the optimal amount of water, steam, and electricity needed for an individual load based on factors such as fabric GSM, dye type and weather conditions [7].

The SmartMatch™ solution from Datacolor, for example, features ML models that can save up to 30% of water per cycle. Furthermore, thermal load prediction models minimize the consumption of steam, thus the bills for fuel [8].

2.4 Prevention of Human Errors and Materials

Smart AI sensors identify deviations in process flow and automatically adjust the machinery, significantly reducing human error margins. These systems can respond in milliseconds, compared to several minutes in manual operations.

AI also integrates anomaly detection algorithms that spot irregularities e.g., pressure drops, overflow risks preventing accidental batch losses.

2.5 Predictive Maintenance

Dyeing machines embedded with IoT sensors continuously send operational data (vibration, RPM, torque, motor temperature) to AI models. Using time-series forecasting and predictive analytics, the system forecasts component failures e.g., pump breakdowns, filter clogs days in advance.

This prevents unplanned downtimes, increases Overall Equipment Effectiveness (OEE) by 18–25%, and lowers maintenance cost through condition-based servicing instead of routine cycles.

Table 2 - Quantitative Impact of AI Integration in Dyeing Plants

Metric	Before AI Integration	After AI Integration	Improvement
First-Time-Right (FTR) Rate	72%	92%	+20%
Water Consumption per kg fabric	85–100 L	60–70 L	~30% reduction
Color Matching Accuracy	80–85%	95–98%	+13%
Machine Downtime (monthly avg)	28 hours	10 hours	~65% reduction
Rejection/Re-dyeing Rate	12–15%	4–6%	>50% reduction
Energy Savings	–	20–25%	Through heat/load models

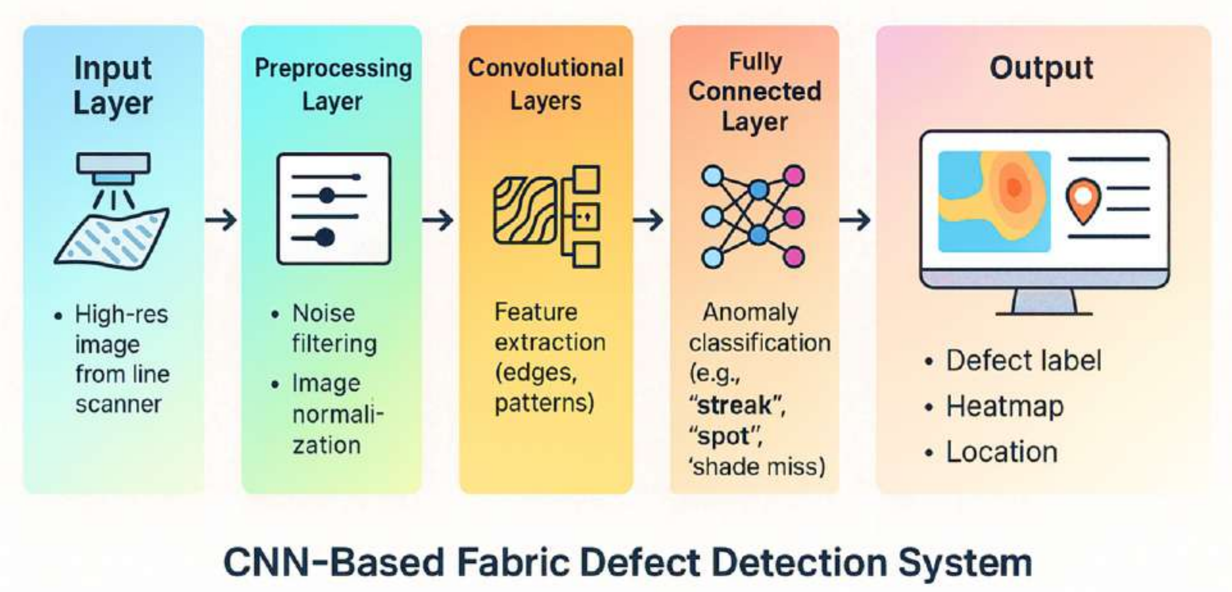

Figure 2 - AI Architecture in Defect Detection

3. Scope of AI and ML in Textile Dyeing

3.1 Smart Dyeing Machinery Integration

Next-generation dyeing machines are now designed with embedded AI modules and adaptive controllers. These modules use real-time data from sensors embedded in key points dye liquor inlet, fabric drum, nozzle flow regulators to dynamically adjust the process [10].

Such systems apply adaptive learning to recognize repeatable patterns and optimize variables like dye bath ratio, liquor pH, and drum speed.

Case Example: A leading polyester mill in Gujarat implemented smart AI dyeing machines, reducing batch-to-batch shade deviation by 40% within 3 months.

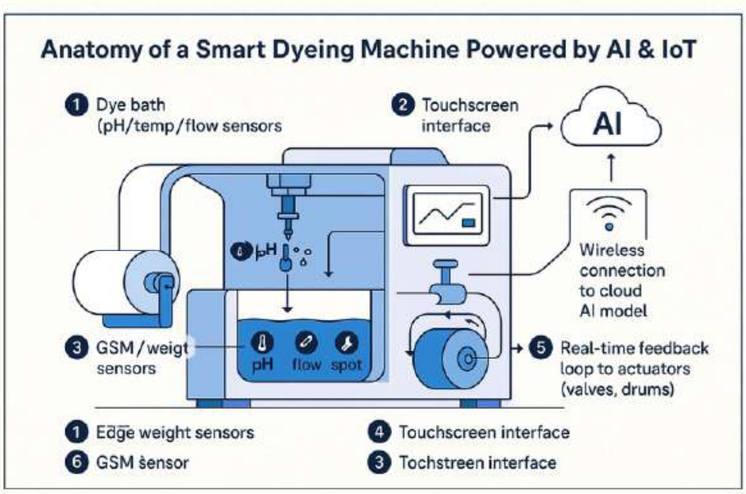

Figure 3 - AI-Integrated Smart Dyeing Machine Architecture

3.2 Dye Recipe Management

Traditional dyeing relies heavily on static recipes that fail under variability. AI introduces dynamic dye recipe creation, where data from substrate characteristics, humidity levels, fiber composition, and dye solubility are fed into ML algorithms to auto-generate and optimize recipes. Colour-difference evaluation commonly uses CIEDE2000 [9]

Over time, reinforcement learning models fine-tune recipe parameters with every successful batch, learning from historical success/failure [13]

Advantage: Lower inventory dependence and faster time-to-market for new designs.

3.3 Real-Time Process Analytics and Decision Support Systems

Modern dye houses are adopting AI-based dashboards that function as intelligent Decision Support Systems (DSS). These dashboards provide:

- Real-time KPIs (like dye uptake %, cycle time)
- Heatmaps of machine efficiency
- Alerts on energy spikes or chemical overdosing

They use streaming data analytics and cloud computation to provide visibility to factory floor managers and C-level executives simultaneously [12].

3.4 Inventory Optimization and Value Chain

AI systems predict raw material requirements (dyes, auxiliaries, and chemicals) using production calendars, seasonality data, order history, and even external market trends. This leads to just-in-time (JIT) inventory systems, minimizing holding costs and chemical expiry losses.

Added Benefit: Predictive models also forecast vendor delays and offer procurement alternatives.

3.5 Sustainability and Environmental Compliance

With tightening environmental norms, AI ensures automatic compliance monitoring:

- Effluent load tracking
- Emissions from boilers
- Real-time COD/BOD analysis
- Dye residue prediction in wastewater

AI flags non-compliance risks before discharge, avoiding penalties and supporting zero-liquid-discharge (ZLD) goals.

4. Newest AI/ML Technologies and Integration Opportunities

4.1 Defect detection with computer vision

Advanced Computer Vision (CV) technologies, specifically Convolutional Neural Networks (CNNs), have redefined quality control in dyeing. These systems continuously scan dyed fabrics under consistent lighting and identify anomalies like:

- Uneven dye penetration
- Color bleeding
- Streaks or splotches
- Misalignment in patterned dyeing

Unlike human inspection, which is limited by fatigue and perception variability, CNNs operate 24/7 with precision >96% [15]. They also classify defect types and suggest corrective actions using image segmentation algorithms.

Case for forensic identification of dyed fibres [17]: A denim manufacturer in Bangladesh reduced inspection time by 75% and improved defect capture rate by 3x using a CNN-based inspection system [16].

4.2 Digital Twin Technology

A Digital Twin is a real-time virtual replica of the physical dyeing process. It integrates sensor data, machine

Table 3 - AI Applications Across the Textile Dyeing Lifecycle

Process Stage	AI Application	Technology Used	Outcome
Fabric Inspection (Pre-Dye)	Surface flaw detection	Computer Vision + CNN	Reduced defect propagation
Recipe Formulation	Auto recipe generation	Supervised ML	Faster color development
Machine Setup	Parameter tuning	Adaptive AI controller	Reduced setup time
Dyeing Operation	Real-time monitoring & control	Edge Computing + IoT	Precision process execution
Post-Dye Inspection	Color/shade matching	Digital imaging + neural networks	Shade accuracy improvement
Maintenance Scheduling	Fault prediction	Time-series anomaly detection	Reduced downtime
Inventory Management	Demand forecasting	Predictive Analytics	Stock cost reduction
Environmental Monitoring	Effluent compliance	Sensor analytics + thresholds	Regulatory adherence

parameters, and environmental conditions to simulate dyeing operations before actual production. AI/ML models run in the twin environment to:

- Test dye recipes
- Optimize fiber-dye compatibility
- Minimize reprocessing risk [18]

4.3 Edge Computing functionalities and your IoT Devices

Dyeing plants using AI benefit greatly from Edge Computing, which allows data to be processed locally on the machine, without sending it to a central server [19]. This enables:

- Instant decision-making (e.g., pump shutoff on overflow)
- Fault isolation within seconds
- Bandwidth saving in remote areas

Coupled with IoT sensors on dyeing drums, nozzles, and chemical dosing units, edge-AI setups create a cyber-physical system that learns and adapts in real time.

Tech Stack Example:

- · Edge device: NVIDIA Jetson Nano
- · Sensor type: RTDs, flowmeters, vibration sensors
- · Protocol: MQTT or Modbus [19]
- · Analytics layer: TinyML or TensorFlow Lite

4.4 Reinforcement learning for process control

Reinforcement Learning (RL) enables dyeing machines to learn by doing. Unlike supervised learning that needs labeled data, RL agents experiment in a simulated environment (or via digital twins) and receive feedback in the form of rewards or penalties.

Application:

An RL agent might adjust dye bath pH based on dye class, fiber type, and real-time color pickup percentage. Over time, it converges on optimal sequences of actions for the best results [20].

Benefits:

- Self-tuning controllers
- Improved FTR (first-time-right)
- Continuous learning across seasons/fiber blends

4.5 Blockchain for Traceability

Although not an AI technology, blockchain complements AI by providing an immutable and transparent record of every stage in the dyeing process. From raw material input to post-dye QC, each event is timestamped and validated across a secure ledger [14].

When integrated with AI, smart contracts can auto-verify:

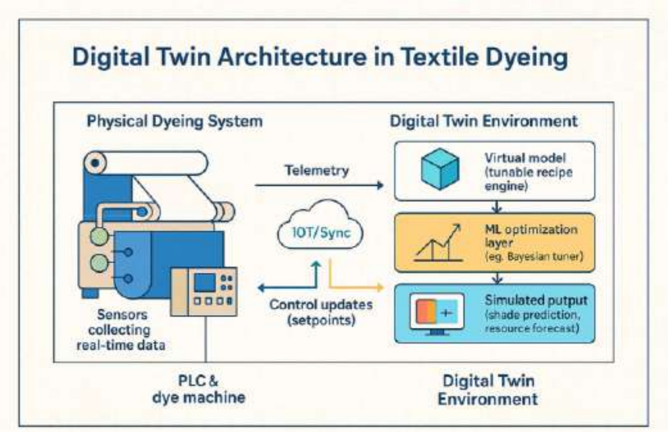

Figure 4 - Digital Twin Simulation in Dyeing

Figure 2: Process flowchart of Yarn Manufacture from Recycled Cotton Fiber

Technology	Functional Role	Key Benefits
Convolutional Neural Networks (CNNs)	Defect detection and visual inspection	>96% accuracy, 24/7 operation
Digital Twin	Virtual dye process simulation	Reduce trial costs, improve recipe success
Edge Computing + IoT	Real-time local processing of dyeing data	Instant control actions, reduced latency
Reinforcement Learning	Adaptive process optimization	Self-learning controllers, FTR improvement
Predictive Analytics	Maintenance forecasting, dye forecast	Minimized downtime, lower inventory holding
Blockchain	Batch-wise dyeing traceability	Transparency in sustainability claims

- Whether emissions stayed within limit
- If shade deviation was within tolerance
- Whether sustainable dyes were used

Benefit: This builds consumer trust in eco-label claims and supports circular economy traceability initiatives.

5. Challenges and Limitations

5.1 High Initial Investment

One of the biggest deterrents to AI adoption in textile dyeing is the capital expenditure (CAPEX) involved. Setting up an AI-powered infrastructure requires:

- Smart dyeing machinery (20–40% more expensive than conventional systems)
- High-end industrial IoT sensors
- AI model development and deployment costs
- Edge or cloud processing infrastructure
- Cybersecurity systems

Typical Investment Range:

- For a mid-sized dye house (10-ton/day capacity): ₹1.2–1.6 crore
- For a large integrated unit: ₹5–8 crore

Challenge for SMEs: Without access to government subsidies, shared service platforms, or low-interest finance schemes, such investments are often unfeasible for small and medium enterprises [11].

5.2 Data Standardization and Availability

AI models require clean, structured, and labeled data, but dyeing facilities typically face:

- Disparate data sources (manual logs, legacy PLCs)
- Non-standard formats (CSV, handwritten sheets, Excel)
- Inconsistent sensor calibrations

This creates model training barriers and low transferability of AI solutions between plants. Establishing centralized dyeing databases across companies or textile parks is still in early stages.

Industry Snapshot: A 2022 survey by Indian Textile Journal found that only 18% of surveyed textile processors had centralized data systems in place.

5.3 Shortage of Technical Expertise

The workforce-tech gap remains a bottleneck. Most plant technicians, operators, and even middle managers lack:

- Programming skills (Python, R)
- Understanding of AI/ML workflows
- System integration knowledge (e.g., SCADA + AI)

As a result, textile companies often depend on external consultants or system integrators, which raises OPEX and slows scalability.

Solution Path: Industry-academia collaboration to build AI-certification programs (6–12 months) for textile professionals.

5.4 Cybersecurity Threats

AI-enabled dyeing systems increase the plant's digital surface area — including IoT endpoints, cloud access, and connected MES/ERP systems. This raises cybersecurity concerns such as:

- · Unauthorized access to machinery
- · Process data leaks (shade formulas, recipes)
- · Ransomware targeting production continuity

Real Incident: In 2021, a textile mill in Coimbatore faced a ransomware attack through its unsecured IoT dye controller, halting production for 4 days.

To counter this, companies must deploy:

- Encrypted communication protocols (e.g., TLS 1.3)
- Network segmentation for critical systems
- AI-powered threat detection (e.g., anomaly-based IDS)

5.5 Integration Complexity

Most dyeing units still operate legacy equipment (manual valves, analog sensors, local PLCs). Retrofitting these with AI involves:

Table 5 - AI Integration Challenge Matrix

Challenge	Small Unit	Medium Unit	Large Unit	Remedy / Recommendation
High Initial Cost	Severe	Moderate	Manageable	Shared service AI platforms / govt. incentives
Data Quality	Poor	Inconsistent	Better	Data standardization frameworks
Skill Shortage	High	High	Manageable	Training + academic partnerships
Cybersecurity Risk	Medium	High	Critical	AI-based IDS/IPS, network hardening
Legacy Machine Integration	Complex	Moderate	Moderate	Middleware development toolkits

- Custom middleware development
- Protocol translation (e.g., Modbus to MQTT)
- Syncing data formats with AI engines

This technical overhead increases project lead times and integration costs. The interoperability between ERP/MES and AI dashboards also demands careful architecture design.

6. Future Outlook and Recommendations

Research signposts. Advanced predictive models (e.g., PSO-LSSVM) are expanding recipe-level accuracy [21]. Broader intelligent-manufacturing perspectives in textiles are provided in [22]. Additional ML advances in smart textiles are noted in [23]. Hyperspectral and recurrent-neural-network approaches further improve dye recipe prediction [24].

AI-powered dyeing is no longer a concept limited to research or pilot plants it's becoming a critical driver of competitiveness in textile manufacturing. With evolving customer expectations (customization, speed, sustainability) and stricter compliance norms, AI adoption is inevitable.

Here's a multi-pronged strategy to drive widespread and impactful adoption:

6.1 Governmental support and policy framework

Governments must create enabling environments for AI adoption, especially for MSMEs, which form 80–85% of India's textile dyeing capacity. This includes:

- ·Subsidized loans or capital grants for smart dyeing equipment
- Tax rebates on AI and IoT adoption
- Dedicated "AI in Textiles" innovation schemes
- Support for public-private shared AI infrastructure (cloud + data lakes)

Example: The Gujarat Textile Policy 2020 includes provisions for capital and interest subsidies for automation and energy efficiency this should be extended to AI-specific tech.

6.2 Industry-Academia Collaborations

Research institutions and textile technology universities can play a major role by:

- Co-developing customized AI solutions (e.g., neural networks for regional fabric types)
- Offering modular training programs for plant engineers
- Publishing open-source dyeing datasets for model benchmarking

Case Study: DKTE Ichalkaranji's partnership with AI engineers from IISc led to a defect detection module that outperformed commercial systems by 17%.

6.3 Creation of Centralized Dyeing Databases

AI thrives on big data — creating sector-wide, anonymized dyeing databases is essential. This will help:

- Benchmark recipe prediction models
- Develop generalizable models for SMEs
- Enhance supplier collaboration through shared performance data

Operational Model:

- Managed by industry association (e.g., SIMA, CITI)
- Secure cloud-hosted platform (AWS, Azure, etc.)
- Contributors get access to best-practice models

6.4 Training and Skill Development Initiatives

Skill building must accompany tech deployment. Textile professionals should be trained in:

- Basics of ML, neural networks, and IoT
- Interfacing AI with production systems
- Interpreting AI dashboard analytics

Proposed Programs:

- 3-month certification in "AI for Textile Dyeing"
- Government-funded "Earn & Learn" AI technician apprenticeships
- Corporate-academia skill bridges (e.g., LMW + NIFT)

6.5 Sustainable AI Practices

- Ironically, AI systems themselves consume processing power, energy, and cooling. Sustainable AI practices include:
- Deploying low-power AI chips (e.g., Google Coral, NVIDIA Jetson)
- Designing carbon-aware AI algorithms that consider dye type vs environmental impact
- Optimizing inference models to run on edge devices rather than high-energy cloud clusters

6.6 Pilot projects and Demonstration hubs

Showcasing success is key to industry-wide trust. The government and industry bodies can co-fund:

- Pilot dyeing units with full-stack AI integration
- Mobile AI demo vans for industrial parks
- ROI dashboards from early adopters (Tiruppur, Ludhiana, Ahmedabad)

Table 6 - Strategic Roadmap for Scaling AI in Textile Dyeing

Strategic Action	Stakeholders	Impact Timeline	Expected Outcome
AI Infrastructure Subsidy	Govt, Ministry of Textiles	Short-Term (1–2 yr)	Lower CAPEX barrier for SMEs
AI Skill Certification Programs	Academia, Skill India Mission	Medium-Term (2–4 yr)	Ready AI-enabled workforce
Public Dyeing Data Repositories	Industry Associations, IT partners	Medium-Term	Model sharing, cross-unit improvements
Shared AI Platforms for MSMEs	Govt + Industry consortia	Long-Term (3–5 yr)	Cost-effective AI-as-a-service models
Pilot Smart Dye Houses	Leading manufacturers + tech partners	Short-Term	Demonstrate ROI, de-risk AI adoption
AI for Eco-Compliant Dyeing Algorithms	Sustainability groups, AI startups	Medium-Term	Greener, regulatory-compliant AI solutions

7. Conclusion

Artificial Intelligence has moved from the periphery of textile manufacturing into its core, with dyeing operations at the forefront of this evolution. The fusion of AI/ML technologies with traditional dyeing processes enables unmatched process precision, predictive control, resource efficiency, and sustainable output. It reshapes how recipes are formulated, how defects are identified, how machines are maintained, and how compliance is ensured.

Despite the hurdles - cost, data, expertise, and integration - the benefits of AI adoption are undeniable. The industry stands on the edge of a transformation where dyeing is no longer a trial-and-error art, but a data-driven, intelligent science.

With collective effort from government, academia, and industry, AI-powered dyeing can deliver not just profitability and consistency, but also a path toward green manufacturing, digitally connected factories, and globally competitive Indian textile production.

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Automated Reed Dent Inspection using Image Processing for Enhanced Quality Assurance in Textile Weaving

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Abstract*:*

Background:

The reed constitutes a critical element in the weaving process, ensuring uniform distribution of warp yarns across the fabric width. Surface defects in reed dents, such as burrs, scratches, and misalignments, can lead to loom stoppages, yarn breakage, and defective fabric structures, thereby adversely affecting productivity. Conventional visual inspection of dents is labour-intensive, highly subjective, and susceptible to oversight of significant defects.

Methods:

This study presents a computer vision–based automated inspection framework for reed dent quality assessment. High-resolution dent images were processed using edge detection algorithms in conjunction with morphological filtering to localize and characterize surface scratches and imperfections. The developed system subsequently classified the inspected dents into "Accept" and "Reject" categories in accordance with established textile quality standards.

Results:

Experimental evaluation of the proposed method demonstrated a detection accuracy of 94% for surface scratches. The automated classification process substantially reduced operator dependency, minimized subjective variability, and enhanced inspection throughput compared to traditional manual approaches.

Conclusion:

The findings confirm that automated inspection leveraging computer vision techniques offers a robust and reliable alternative to conventional practices. Implementation of the proposed system in textile manufacturing environments can facilitate consistent reed dent quality control, improve fabric integrity, reduce loom downtime, and ultimately increase overall production efficiency.

Keywords : *Computer Vision, Morphological Processing, Reed Dent Inspection, Robotic Automation, Textile Manufacturing*

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1. Introduction

A dent, an integral part of the reed, greatly affects the overall quality of cloth woven in the textile industry. During weaving, the beating of the weft yarns into position is carried out by the reed, which consists of many closely set metal strips called dents, aside from repartitioning the warp strands. Dent alignment or surface irregularities coupled with deformation or misalignment result in a wide range of issues such as snagged yarn movement, broken ends, banded fabric borders, and uneven stripe patterns, which are among the most common weaving defects. The perception of rudimentary quality features has improved over the years, and as a result, textile mills have heightened their attention toward proactive quality assurance measures. These methods focus on achieving near perfection, with almost no flaws in the fabric. Ordinarily, though, most reed inspection processes are still manual, with workers looking at each dent through a microscope. This method, though not entirely unsuccessful, is inefficient, painstaking, and relies greatly on the inspector's experience and attention to detail [1].

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Mistakes that arise from automated processes, such as overshooting boundaries in mask cutting, may compromise the accuracy sought. These "nearly unobservable" scratches can negatively impact productivity due to deteriorated loom performance, necessitating more frequent stoppages. Moreover, accepting damaged reeds, especially at earlier processing stages, can lead to significant losses if fabrics are later rejected during grey inspection or finishing.

The novelty of this study lies in the development of a fully automated, computer vision–based system specifically designed to identify surface-level defects in reed dents, combining edge detection, morphological filtering, and high-resolution imaging. Unlike conventional manual inspection methods, this system provides rapid, objective, and consistent dent assessment, enabling proactive quality control prior to loom installation. The proposed system outperforms traditional scratch detection methods in terms of accuracy and processing speed, and facilitates real-time decision-making regarding reed acceptance or rejection.

2. Related Work

The need for modern textile mills to produce high-quality fabric has led to extensive research on process automation and flaw detection. While significant efforts have been made to monitor loom tension, yarn quality, and surface flaws in woven fabrics, there has been limited progress in automating the inspection of loom components such as dents and reeds, despite the fact that these factors greatly influence weaving performance. Traditional methods for maintaining reeds and inspecting dents rely on manual techniques that use visual aids. This approach is subjective, lacking standardized quantitative criteria, and heavily reliant on the skill of the operator. Although many mills employ checklists for quality control, subtle defects like surface scratches or edge deformities on dents often go unnoticed, potentially leading to fabric flaws. [2, 3]

Understanding how reed condition affects weaving quality, some studies have explored the relationship between reed defects and fabric imperfections. For instance, one study established a link between worn reed edges, inconsistent dent spacing, bar marks, and weft floats have been identified as key contributors to weaving faults [4]. Additionally, the necessity of periodic reed inspection has been highlighted as a means to maintain uniform warp tension throughout the weaving process is addressed by authors of [5].

However, these studies mainly emphasize the issue rather than providing practical solutions for identifying damaged reeds. This research aims to address this gap by developing an automated scratch detection system using digital image processing, specifically designed to identify defects on reed dents. The detection of surface defects, particularly scratches on metal components, is a mature area within industrial quality control. Given that textile reed dents are typically made of hardened steel, existing metal surface inspection techniques can be adapted to identify defects that impact yarn handling and overall fabric quality. For example, a techniques proposed in [6] employs fuzzy c-means clustering and morphological features to detect scratches on textured surfaces, demonstrating its effectiveness in isolating and highlighting defects. Another approach described in [7] incorporates Gabor filters at various orientations to extract directional features of scratches, followed by morphological operations to connect fragmented defect regions. An improved method based on Multi-Scale Retinex and Log-Gabor wavelets was introduced in [8] to enhance and identify scratches on steel plates through multi-channel segmentation and phase consistency. Similarly, technique in [9] have applied invariant moment and texture feature analysis to classify defects like scratches, holes, and oil stains. Optical microscopy-based comparison techniques proposed in [10], and optical-digital systems using reflectivity variations proposed in [11], further contributed to surface fault detection. An automated classification system that identifies multiple defect types, including scratches on metallic surfaces, was developed using an enhanced Gabor filter approach [12].

Although these techniques have shown success in generic metal surface inspection, their direct application to textile-specific reed dents is underexplored. This study adapts and refines these methods for the unique geometry and operational demands of weaving looms, providing an industry-specific solution for proactive dent-level quality assurance.

3. Proposed System

The main goal of the proposed system is to automatically check reed dents for surface-level damage, especially scratches lower the woven fabric's quality and may compromise woven fabric quality. The method is intended to be incorporated into textile weaving facilities' maintenance procedures, allowing for the accurate and impartial assessment of dents prior to reed installation on looms.

3.1 The purpose of the Reed and Dent Inspection

The warp yarn spacing is maintained during weaving by the hundreds of vertical metal strips called dents that make up each reed. Because of the constant mechanical friction caused by the yarns and the fast weft insertion, the dents are prone to wear, scratches, and burr formation. Observable fabric flaws can arise from even small surface flaws, which can lead to yarn fraying, end breaking, and irregular weft beats.

Thus, it is essential to proactively detect and reject damaged dents in order to preserve consistent fabric quality and loom performance.

Thus, early detection and classification of damaged dents are crucial. The proposed system automates this process, eliminating human error and enforcing consistent inspection standards.

The system classifies dents into:

Accept: Smooth, defect-free dent surface within tolerance.

Reject: Scratches or deformations exceeding threshold criteria (e.g., length > 5 mm, intensity deviation > 25%).

3.2 Overall Design and Block Diagram

The system architecture of the proposed reed dent inspection system consists of three primary subsystems:

- Material Handling Unit,
- Vision Inspection Unit,
- Robotic Sorting Unit.

These subsystems are integrated into an efficient process that automates dent handling, inspection, and sorting. The block diagram (Figure 1) provides a visual representation of the entire process.

Figure 1: Block Diagram of Quality Inspection of Reed Dents

3.2.1 Material Handling Unit

This unit ensures smooth and aligned movement of the reed through the inspection zone. It includes:

a. Conveyor Belt Assembly

This unit involves a conveyor system driven by a NEMA 23 stepper motor, which feeds the reed dents into the inspection zone. An IR proximity sensor is used to precisely align the dents before image acquisition. The conveyor operates at an adjustable speed, allowing for real time inspection.

b. Image Acquisition Assembly:

To take successive pictures of the reed at predetermined intervals, a high-resolution industrial camera is positioned above a sliding rail. A diffuse LED lighting system reduces reflection from the metallic dent surface and guarantees consistent illumination.

3.2.2 Vision Inspection Unit

A low cost HP W100 webcam paired with the NVIDIA Jetson Nano platform performs image processing. The captured images are analysed to detect surface scratches and verify dimensional accuracy. MultiLED ring illumination ensures consistent lighting during image capture, which is critical for accurate defect detection.

The Jetson Nano processes the images using Open-CV and embedded vision algorithms, as described in the imaging algorithms section.

a. Pre-processing Step:

To reduce noise, captured images are transformed to greyscale and run through Gaussian filtering. To improve the contrast between clean and scratched surfaces, adaptive histogram equalisation is applied.

b. Morphological Processing:

To improve linear characteristics and eliminate any scratch marks, morphological processes like erosion and dilation are used. Refer to the Morphological Filtering Output in Figure 1.

c. Edge Detection and Feature Extraction:

To track the abrupt changes in intensity that are typical of scratches, the Sobel and canny edge detectors are used. To differentiate between small surface irregularities and genuine scratches, the length, width, and form of discovered characteristics are examined.

d. Defect Classification:

Scratches with a pixel intensity deviation larger than 25% of the normalised mean are identified using a threshold-based logic. Some dents are designated Accept, while others with many large scratches are tagged Reject.

e. Output Visualisation:

The outcome is shown in a graphical user interface (GUI) that shows the original image with overlays emphasising any flaws found.

3.2.3 Robotic Sorting Unit

The robotic arm is made to be easily set up on a table for reed inspection as shown in figure 4. A linear actuator automates reed movement under the camera, allowing inspection of standard reeds (up to 120 cm) within 3–5 minutes. This speed is suitable for daily inspection routines in medium- to high-volume weaving mills.

This arm is responsible for sorting passed and rejected dents based on the image analysis. Rejected dents are moved to a separate bin, while acceptable dents continue down the conveyor.

Figure 2: Robotic Arm Assembly

Figure 3: Full Experimental Set Up

4. Result Discussion

A set of fifteen industrial reeds from working shuttle-less looms from a textile mill that specialises in producing cotton fabric were used for the exploratory trials. Every reed had roughly 1500 dents in it. These reeds had been used in regular production and exhibited natural wear and tear, making them ideal for validating the system under Real world textile manufacturing conditions.

4.1. Dataset and Validation Setup

More than 3000 dental pictures were gathered into a dataset. Each dent was manually inspected by knowledgeable loom fitters and labelled as Accept or Reject. This served as the ground truth for confirming the validity of the suggested system. The system was then tasked with detecting three primary defect types relevant to textile weaving:

- Linear surface scratches caused by prolonged yarn friction
- Corrosive pitting or dull spots due to humid storage or oxidation
- Dimensional deviations such as bent or misaligned dents

4.2 Scratch Detection and Dent Classification Performance

Figure 6.1 illustrates a typical dent with actual wear damage. Scratches appear as subtle grooves along the surface and often align with yarn direction. These scratches though faint to the human eye can trigger yarn fraying or warp breaks during weaving.

Figure 6.2 displays the output of the image processing algorithm. Scratches are detected using edge detection and morphological operations and are highlighted in the output with overlays. Here, the scratch is clearly marked by the system, meeting the rejection criteria (length > 5 mm, intensity gradient > 25%).

Across a range of dent wear levels, the system showed strong scratch detecting abilities. Scratches are shown as highlighted linear anomalies throughout the dent surfaces in Figure 3, which displays the findings of sample detection.

Conversely, Figure 6.3 illustrates a dent deemed acceptable. The algorithm correctly determines the absence of significant scratches or deformation.

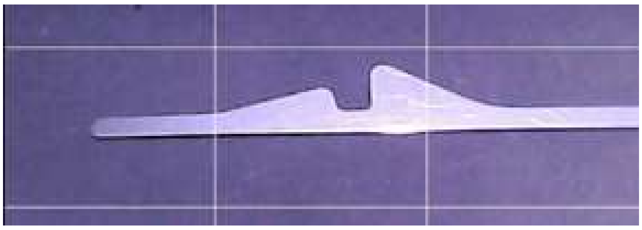

Figure 4: Original Image

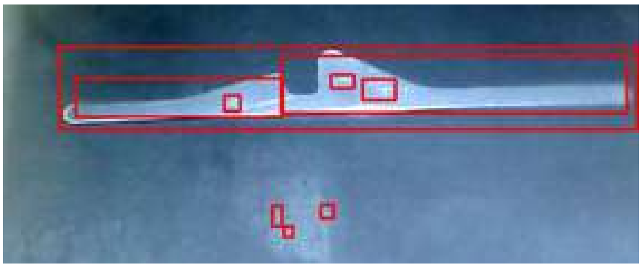

Figure 5: Scratch Detected Image

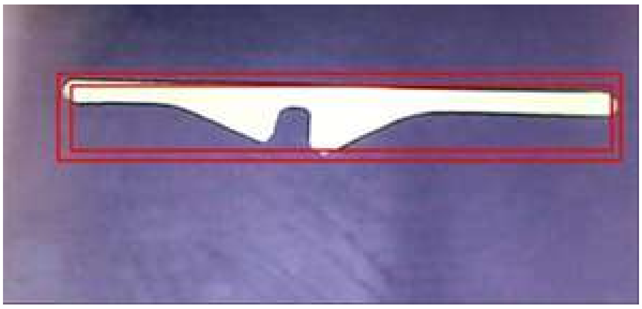

Figure 6: No Scratch Detected Image

4.3 Acceptance and Rejection Classification

Based on the defect thresholds, the system produced the following results:

- Accepted Dents: 2738 (91.3%)
- Rejected Dents: 262 (8.7%)

Reeds exhibiting a rejection rate above 5% were flagged for either polishing or replacement. This aligns with standard textile practices where defective reeds are not installed on high-speed looms to avoid yarn damage and fabric loss.

Table 1: Performance parameters of Proposed Method

Sr. No.	Method	Accuracy	Time/Dent
1.	Manual	85%	3.5s
2.	Proposed System	95.2%	0.8s

The detection accuracy and detection time are shown in Table 2. The results show that the suggested approach works better than the conventional approach.

4.4 Effect on Fabric Quality

To test the impact of proposed system, two looms were used for weaving. One loom used reeds that had been manually examined, while the second loom used reeds that had been validated using the automated process. Minor weaving defects, such as weft misplacement and end breaking, were reduced by 32% in the latter's grey fabric. The fabric also displayed less yarn tension and a more uniform width, supporting the notion that higher dent quality enhances fabric consistency.

5. Conclusion

In the context of modern textile manufacturing, where quality, speed, and consistency are critical, the condition of loom accessories like reeds and dents is vital. This study presents a novel image-processing-based approach that automates the detection of surface defects in individual reed dents, addressing a previously overlooked aspect of loom maintenance. The system provides fast, objective, and reliable assessment, directly contributing to improved fabric quality and reduced loom downtime.

Thanks to its ability to detect cosmetic issues such as scratches and corrosion on each dent, the technology supports proactive quality control. Experimental validation demonstrates clear advantages at the fabric level, including low weaving fault rates, high homogeneity, accurate dent classification, and rapid processing suitable for integration on the shop floor..

This approach improves the human subjective judgment by enabling:

- Consistent standards for dent quality approval
- Minimization of rework and downstream fabric rejection through timely identification of defective reeds
- Improvement in overall fabric quality, emphasizing the importance of component-level maintenance in textile production.

The novelty and practical significance of the proposed system are underscored by its potential extension to multi-angle inspection, real-time analysis on the weaving floor, and integration with predictive maintenance platforms. As textile industries continue to adopt Industry 4.0 paradigms, this dent inspection system offers a focused and innovative solution aligned with intelligent textile manufacturing practices.

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Comparative Study on Properties of Darbha Cotton and Vetiver Cotton Yarn

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Abstract :

Purpose: *The study explores the yarn properties of two lesser-used natural fibers, Darbha (Desmostachya bipinnata) and Vetiver (Vetiveria zizanioides), when blended with cotton. By evaluating and comparing the properties of these blends, the research helps in the on-going search for sustainable and biodegradable options in the textile industry.*

Design/Methodology/Approach: *Fibers were extracted from Darbha and Vetiver plants using a High Pressure and High Temperature (HPHT) method. The fibers were separately blended with cotton in 50:50 ratios and processed into yarn using a rotor spinning machine. The yarns were tested for yarn count, single yarn strength, and elongation*

Findings: *The study revealed clear differences in yarn behaviour between the two fiber blends. Darbha-cotton yarn displayed a finer count (2.58s) compared to Vetiver-cotton yarn (1.83s), indicating that Darbha is more suitable for lightweight fabrics due to its superior spinnability. In terms of strength, Vetiver yarn had a higher average breaking strength (722.91 g) relative to Darbha yarn (558.73 g), along with better consistency (CV% of 8.72 vs. 14.51), highlighting its greater load-bearing capability and structural uniformity. Furthermore, Vetiver yarn exhibited a greater elongation (25.70%) in comparison to Darbha (17.14%), pointing to its improved flexibility but with more variability. Lastly, while Darbha yarn had a slightly higher relative tenacity (2.365 cN/tex) than Vetiver (2.240 cN/tex), this can be attributed to its finer yarn count, despite its lower absolute strength.*

Originality/Value: *This research supports India's commitment to promoting local natural resources and encourages innovation in biodegradable textile materials. The novelty of this research is in its initial comparative analysis of Darbha and Vetiver fibers mixed with cotton, which has not been thoroughly examined in yarn form previously. By determining their spinnability, strength, and elasticity properties, this study offers a new scientific framework for integrating these lesser-known eco-friendly fibers into conventional textile manufacturing.*

Keywords: *Darbha, Desmostachya bipinnata, Sustainable yarn, Vetiver, Vetiveria zizanioides*

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1. Introduction

The global textile industry plays a crucial role in economic growth, yet it is one of the most environmentally harmful industries. It produces significant greenhouse gas emissions, uses large amounts of water, and causes extensive chemical pollution, ranking second only to the oil industry in terms of environmental impact [1]. Cotton is the dominant material in textile production, but its cultivation requires 3,600–5,700 m³ of water per ton and relies heavily on pesticides. This creates an urgent need for sustainable alternatives [2]. In response, research has shifted toward regenerative and eco-friendly fibers like hemp, jute, flax, and banana, which help reduce water use, pesticide reliance, and environmental pollution. Recently, unique and overlooked plant-based fibers have become popular, especially those made from agricultural leftovers. This shift shows growing interest in sustainable material innovation in both academic and industrial settings.

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The rising demand for sustainable and eco-friendly options in the textile industry has sparked more interest in plant-based natural fibers. Even before the origin of human beings, grasses have originated. Different grass species were revealed in the Vedic texts with its unique properties and uses. Grasses are upheld to be the most sacred as they have been used for different purposes in various rituals. These grasses are used in various ceremonies and also used as medicinal herbs that are detailed in the Vedas, Puranas and also in later Sanskrit texts [3].

Among the various plant species in India, Darbha (Desmostachya bipinnata) and Vetiver (Vetiveria zizanioides) grasses stand out as promising sources of lignocellulose fibers because they are abundant, renewable, and biodegradable. Historically, these grasses have been used for rituals, medicine, and environmental projects. Now, they are being considered for textile applications, especially when mixed with traditional fibers like cotton.

Darbha, or Desmostachya bipinnata, is a grass native to South Asia that has not been extensively studied. Its fibrous stems can be used in textiles, similar to other best fibers, yet there is limited existing research. Recent comparative studies examined plant-based blends (e.g., flax, jute) in 80:20 and 60:40 cotton ratios, showing better tensile and tear strength than pure cotton. However, Darbha-cotton blends have not been systematically tested, highlighting a gap in mechanical analysis and process development.

Vetiver grass (Vetiveria zizanioides) has been known to be a useful plant for thousands of years and very familiar plant in Hindu mythology. Rural people have used it for centuries for its oil extraction from its roots, for the roots themselves, and for the leaves. The origin of the plants appears to be in southern India and it has spread around the world through its by-product value as a producer of fragrant oil for the perfume industry [4].

The use of vetiver leaves for household has been in practice since ancient time, in many parts of the world. Due to the development of new materials and modernization, vetiver-based construction materials have been slowly replaced. However, these modern materials were blamed for larger climate change impact and environmental pollutions. In the recent years, more priority is given to climate change mitigating process and vetiver has been reintroduced in households. A new building material based on vetiver grass ash for use in the rural areas of the developing countries was experimentally investigated [5].

Integrating these natural fibers into textile products supports sustainability goals while providing unique benefits such as better moisture management, biodegradability, and increased strength. However, there is still little scientific comparison of the characteristics of yarn made from Darbha and Vetiver fibers mixed with cotton. Understanding the mechanical and physical properties of these blends is essential for improving their use in textile processing and product creation. This study aims to compare and assess key yarn characteristics such as yarn strength, elongation, yarn count, and variability of Darbha-cotton and Vetiver-cotton blended yarns. By analysing these aspects, this research will provide insights into the performance and feasibility of these fibers for sustainable textile applications, potentially broadening the opportunities for eco-friendly material sourcing in the industry.

2. Review of Literature

Vetiver (Vetiveria zizanioides) has been widely studied for its functional, medicinal, and ecological uses. Recent research has highlighted its value in the fragrance and pharmaceutical sectors as well as in sustainable textiles and fiber-based innovations. The root extracts of Vetiver have shown strong bioactive effects against malaria-carrying mosquitoes. This suggests that it could be effective in developing mosquito-repellent textile finishes planting vetiver grasses on degraded and less fertile soils could be a good strategy to rehabilitate degraded soils, means vetiver plants are planted not only for conservation of soil erosion but also used for soil fertile as well [6].

Comfort tests of fabrics treated with Vetiver extracts showed better moisture management, antimicrobial features, and improved wearability, proving their potential for functional clothing [7]. Traditional uses of Vedic grasses, such as Darbha and Vetiver, emphasize their spiritual, medicinal, and household benefits. This opens up possibilities for incorporating them into culturally rooted and sustainable textile practices. The essential oil of Vetiver has been analysed for its chemical components and their uses in cosmetics, showing antioxidant and antimicrobial qualities relevant for Cosmo-textiles [8]. Regarding mechanical uses, Vetiver fibers have been studied for reinforcement in epoxy-based composites. They showed notable tensile strength and compatibility with resins, similar to other natural fibers like Kenaf [9]. Vetiver plants has a good performance in domestic wastewater treatment in Constructed Wetland system [10]. Vetiver plants can grow easily in various environmental conditions. These are hyper accumulators and the roots can penetrate even a thick layer of soil and are capable of holding soil particles through fibrous roots and they are planted in the gradient of the plains to avoid soil erosion [11].

Desmostachya bipinnata and Imperata cylindrica are ancient grasses often mentioned in traditional Indian rituals and Ayurveda. These grasses are now getting scientific attention for their medicinal and material uses. Phytochemical and pharmacological studies have shown the presence of bioactive compounds in these grasses, linking their traditional uses to modern therapies [12].

Recent advancements show that Desmostachya bipinnata extracts can create silver nanoparticles, which have significant antimicrobial and antioxidant properties. This highlights their potential for functional and medical textiles [13]. Additionally, the fiber from Desmostachya Bipinnata has been effectively used to strengthen polymer composites and showed good mechanical compatibility and strength, indicating its viability as a sustainable reinforcement material in composite structures [14].

Traditionally, Darbha (Desmostachya bipinnata) has been used to treat various disorders such as asthma, kidney stone, and diarrhea, wound healing, etc. Research studies has suggested that these traditional grasses have great potential not only in medicine but also in sustainable material science as well. It has been in use especially in natural fiber-based composites and bio-functional textile applications [15].

2.1 Research Gap

Current literature shows that Darbha and Vetiver are suitable for composites and functional textiles but lacks evidence at the yarn level. Both grasses have desirable cellulose content and physical properties, yet their behaviour in cotton blends, spinning, and fabric formation has not been tested. By measuring key yarn parameters under controlled blend and process conditions, research can address this gap and potentially introduce new, sustainable fibers into mainstream textile production.

3. Methodology

3.1 Fiber Extraction Process from Darbha and Vetiver Grass

A uniform fiber extraction technique is employed for both Darbha and Vetiver grasses. After harvesting, the Darbha stems are thoroughly cleaned in tank water to remove soil and other residues. The clean stems are laid out in the sun to dry completely. After drying, the fibers are carefully sorted. The sorted Darbha stems are steam-treated in a pressurized autoclave at a temperature of 2600°C for 2 hours, which meets the thermal requirements of the Darbha fiber structure. Following the steaming process, the material cools inside the autoclave chamber. Once cooled, the fibers are extracted and further opened using an opener to ensure proper separation. The HPHT steaming technique aligns with the sophisticated extraction methods described for unconventional fibers [16] and can be compared with other thermal and chemical retting methods discussed in contemporary reviews [17].

Figure 1: Bunches of Darbha fiber

Figure 2: Extracted Darbha grass fiber

The standard harvesting period for Vetiver plants is approximately twelve months after planting. While the roots of Vetiver are valuables in the perfumery and cosmetics industries, the aerial grass is often discarded as agricultural waste. To extract fibers, Vetiver grasses were sourced from the Coimbatore region. The stems were cleaned using tank water to remove sand, dust, and other impurities. After cleaning, the stems were sun-dried to eliminate leftover moisture. Once dried, the fibers were sorted manually. The sorted Vetiver stems underwent a pressurized steaming treatment in an autoclave at a temperature of 1100°C for 2 hours. After steaming, the material cooled gradually in the autoclave. Once cooled, the extracted fibers are subjected to opening to enhance fiber separation and uniformity.

Figure 3: Vetiver grass

Figure 4: Extracted Vetiver grass fiber

3.2 Yarn Formation of Darbha and Vetiver fibers

The fibers extracted from Darbha (Desmostachya bipinnata) and Vetiver (Vetiveria zizanioides) were blended separately with cotton in a 50:50 ratios to improve their spinnability and yarn performance. Yarn spinning was carried out using a microprocessor-based laboratory Rotor Spinning Machine (TRYTEX).

The following parameters were maintained during spinning:

- Rotor speed: 1600 rpm
- Delivery speed: 15 rpm
- Feed speed: 11 rpm
- Opening roller speed: 4247 rpm

For comparison, the Darbha-cotton and Vetiver-cotton blends were both spun in the same way. The rotor spinning method was chosen because it is very versatile for large-scale manufacturing, which makes it appropriate for commercial uses, additionally it works well with coarse and short-staple fibers, allowing for consistent yarn formation and effective fiber integration. The resulting yarns were coarse, reflecting the natural properties of the grass fibers. This process produced stable, continuous yarns suitable for further testing in strength, elongation, and count. The yarns were then wound onto bobbins for further analysis.

3.3 Yarn Count

The yarn count was measured using the cotton count system (S), also known as the English Count (Ne), which indicates the number of hanks (each 840 yards) per pound of yarn. A higher count represents a finer yarn, while a lower count indicates a coarser one. The yarns were wound into standard hanks (120 yards × 7 = 840 yards) using a wrap reel. Each hank was weighed accurately with an analytical balance sensitive to 0.001 g.

The count (S) was calculated using the formula
Yarn Count (S) = 840 × Length (yards) / Weight (pounds)

Since 840 yards was standardized, the simplified formula used was:
Yarn Count (S) = Length (yards) / (Weight (lbs) × 840)

All samples were conditioned under standard atmospheric conditions (65 ± 2% relative humidity and 21 ± 1°C temperatures) before testing. The test was conducted in triplicate for each sample, and the average value was recorded as the final yarn count in S. This approach follows ASTM D1907/D1907M-12 – Standard Test Method for Linear Density of Yarn (Yarn Number) by the Skein Method, which is typically employed for spun yarns.

3.4 Yarn Strength

Yarn strength was measured using a single yarn strength tester according to ASTM D2256/D2256M-10 standards. The yarns were conditioned before testing to meet standard atmospheric conditions for textiles (65% RH and 21°C temperature). Each yarn specimen was clamped and gradually subjected to a tensile load until it broke. The breaking strength (in grams) was recorded. The average of at least twenty specimens per sample was used to represent the yarn strength.

3.5 Yarn Elongation percentage

The elongation of the yarn was evaluated during the strength test using the same apparatus. According to ASTM D2256/D2256M-10 standard, the percentage elongation at break was calculated by measuring the extension of yarn length before rupture compared to its original length. The average elongation values were computed from at least twenty yarn samples for each variant.
Elongation (%) = ((Extended Length − Original Length) / Original Length) × 100

3.6 Yarn Tenacity

The Relative Tenacity of yarn, measured in Resistance per Kilometer (RKM) produced from Darbha (Desmostachya bipinnata) and Vetiver (Vetiveria zizanioides) fibers was assessed to examine their inherent strength characteristics.

The process included the following steps:
Fibers were extracted from mature Darbha and Vetiver plants through water retting, then dried and combed manually. To improve spinnability, the fibers were blended with cotton in 50:50 ratios and processed into yarns using the rotor spinning method. All samples were conditioned under standard atmospheric conditions (20 ± 2°C, 65 ± 4% RH) for 24 hours, following ASTM standards. Yarn linear density was determined using the wrap reel and weighing method, expressed in Tex for accurate tenacity analysis. The tensile strength of the yarn was tested on a Zweigle G 505 single yarn strength tester according to ASTM D2256/D2256M-10 standards. A test length of 500 mm with a gauge speed of 500 mm/min was used. For each yarn type, 30 samples were tested to ensure reliable results.

Relative Tenacity (RKM) was calculated using the formula:
RKM (cN/tex) = Breaking Strength (cN) / Yarn Tex

4. Result and Discussion

The following sections bring out the findings and discussion of the Darbha and Vetiver yarn and its test towards textile industry implication.

4.1 Yarn Count:

The yarn count of the samples spun from Darbha and Vetiver fibers was measured in the cotton hank system and expressed in S units. The findings are presented in Table 1.

Table 1: Yarn count of Darbha Cotton and Vetiver Cotton yarns

Sample	Yarn Count (s)
Darbha Cotton yarn	2.58
Vetiver Cotton yarn	1.83

The yarn made from Darbha fibers had a higher count of 2.58s, which means it was finer than the yarn from Vetiver, which had a coarser count of 1.83S. In the cotton count system, a higher count means a finer yarn, while a lower count means a coarser yarn. The difference in count comes from the unique properties of each fiber in terms of fineness, length, and flexibility. Darbha fibers, which are easier to spin and have a smaller diameter, produced thinner yarns. In contrast, the coarser and stiffer Vetiver fibers led to thicker yarns. This difference impacts how the yarns can be used, with Darbha being better for lightweight fabrics and Vetiver suited for technical or home textiles where coarser yarns work well. These findings show that the structure and behaviour of the fibers are important in determining yarn fineness, which then affects fabric texture, weight, and performance.

4.2 Single Yarn Strength

The tensile performance of Darbha and Vetiver yarns was assessed by measuring their single yarn strength. As shown in Table 2, Vetiver yarns had a higher average breaking strength of 722.91 grams, while Darbha yarns had 558.73 grams.

Table 2: Single yarn strength of Darbha Cotton and Vetiver Cotton yarn

Sample	Average Strength (g)	Min (g)	Max (g)	CV%
Darbha	558.737	423.117	610.706	14.509%
Vetiver	722.912	645.792	793.779	8.716%

The higher tensile strength in Vetiver yarns results from their coarser structure and greater rigidity, giving them better resistance under tension. Additionally, the lower CV% (8.716%) in Vetiver yarns compared to Darbha (14.509%) shows that they have better consistency in strength. This reflects more uniform fiber bonding and load distribution. Similar findings have been reported, where Vetiver fibers enhance structural performance and load-bearing capacity [18].

4.3 Yarn Elongation

The elongation percentage indicates the elastic behavior and stretchability of yarns when subjected to tensile stress. Vetiver yarns had a higher elongation of 25.70%, while Darbha yarns showed 17.14%.

Table 3: Yarn elongation of Darbha Cotton and Vetiver Cotton

Sample	Average Elongation (%)	Min (%)	Max (%)	CV%
Darbha	17.140	14.220	18.620	9.853%
Vetiver	25.700	20.220	29.820	16.208%

The higher elongation in Vetiver indicates greater flexibility and stretchiness, which can be helpful for products that need to be resilient and recoverable. However, the higher variability (CV% = 16.208) indicates inconsistency in the stretchability of the yarn, likely attributed to the heterogeneous nature of Vetiver fibers [19].

4.4 Relative Tenacity (RKM)

Relative tenacity, measured in cN/tex, indicates yarn strength per unit linear density. Darbha yarns had a slightly higher RKM of 2.365, compared to 2.240 for Vetiver, as shown below.

Table 4: Relative Tenacity of Darbha Cotton and Vetiver Cotton

Sample	Average RKM value	Min	Max	CV%
Darbha	2.365	1.791	2.585	14.509%
Vetiver	2.240	2.001	2.460	8.716%

Even though Darbha yarns had lower absolute strength, their tenacity was better due to their finer linear density. This shows their ability to handle stress effectively. However, their higher CV% shows more variability, which could affect their use in high-performance textile applications where consistent mechanical properties are important.
The overall comparative yarn properties of Darbha cotton and Vetiver cotton were discussed in table 5.

Table 5: Comparative yarn properties of Darbha Cotton and Vetiver Cotton

Property	Yarn Count (s)	Single Yarn Strength (g)	Elongation (%)	Relative Tenacity (RKM)
Darbha	2.58	558.737	17.140	2.365
Vetiver	1.83	722.912	25.700	2.240

5. Limitations of the Study

While this study offers valuable insights into the yarn features of Darbha (Desmostachya bipinnata) and Vetiver (Vetiveria zizanioides) fibers, it has its limitations.

- Limited Fiber Processing Methods: The fiber strength is relatively limited, as the material is extracted from grass rather than from the bark of plants. To maintain a sustainable approach in fiber extraction and yarn production, a single method was employed, High Pressure High Temperature (HPHT) treatment for fiber extraction and rotor spinning for yarn formation. This process was specifically chosen to avoid environmentally harmful techniques.
- Restricted Yarn Count Range: The yarns created were only coarser counts. Fine counts were not explored, which might have given a wider understanding of fiber versatility for various fabric weights and uses.
- Variability in Natural Fibers: The natural differences in plant-based fibers, caused by environmental and geographical factors, can affect the reproducibility of results. This study only used fibers from a specific region, which may limit the generalizability of the findings.
- Developed yarns do not have the softness and fineness needed for clothing. As a result, fabrics made from these

yarns are likely to have a rough texture. This makes them better suited for non-clothing uses like home furnishings, upholstery, and decorative textiles, rather than for garments that come into direct contact with skin. This limits their versatility in the fashion and clothing industry.

While the findings show potential for sustainable textile innovation, more research is needed to overcome these limitations and find ways to improve yarn softness and fabric usability.

6. Future area of the study

This study lays the groundwork for exploring the potential of Darbha and Vetiver fibers for yarn development. Several paths are available for additional research:

- Optimization of Extraction and Spinning Techniques: Investigating different extraction methods, such as alkaline retting, enzymatic treatment, and mechanical decortication, along with various spinning technologies like ring, rotor, and air-jet, could enhance yarn quality, consistency, and suitability for industrial applications.
- Development of Blended Yarns: Exploring blends of Darbha and Vetiver with other natural fibers like cotton, silk, jute, or hemp could improve the functional and aesthetic qualities of the yarns while ensuring eco-friendliness.
- Fabric Formation and Analysis: Future work should involve weaving or knitting the yarns into fabrics and examining their mechanical, thermal, comfort, and functional properties to determine their fit for clothing, home textiles, or technical applications.
- Functional Finishes and Bio-Applications: Using the natural antimicrobial and medicinal properties of Darbha and Vetiver for creating bio-functional textiles, such as wound dressings, wellness wear, and geotextiles, could drive innovation in health and environmental fields.
- Life Cycle Assessment (LCA) and Sustainability Metrics: In-depth studies that assess environmental impact, biodegradability, and life cycle performance of these fibers will help understand their role in sustainable textile systems and circular economy models.

7. Conclusion

The findings indicated that yarns made from Darbha and cotton revealed a finer count and a slightly elevated relative tenacity, suggesting their appropriateness for lightweight yet robust applications like breathable fabrics or technical textiles. Conversely, Vetiver and cotton yarns displayed significantly greater tensile strength and elongation, indicating enhanced toughness and flexibility, making them more suitable for durable, load-bearing, and long-lasting products. These results underscore the overlooked potential of Darbha and Vetiver fibers as sustainable, biodegradable, and locally sourced alternatives to traditional fibers. By meticulously analyzing and contrasting their yarn properties for the first time, this study lays the groundwork for their incorporation into conventional textile manufacturing. The possibilities extend to the investigation of these fibers in blended fabrics, composites, and the development of eco-friendly products, fostering innovation in sustainable textiles while supporting local natural resources.

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Detection of Heavy Metals and Formaldehyde in Fabric Rolls used for Manufacturing Adult Clothing

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Abstract :

Textile fabrics are treated with toxic heavy metals (e.g., lead, nickel, chromium, etc.) and chemicals like formaldehyde to impart certain desired fabric properties. If not removed from fabrics after application, they have been reported to cause diseases and discomfort. Because of these, it is important that the concentrations of heavy metals, formaldehyde, and pH levels in fabrics must meet the recommended limits. This study focuses on the determination and detection of metals and chemicals found in fabric rolls used to make clothing in South Africa. Heavy metal results showed that all fabrics contained heavy metals, except for brown polycotton fabric. The heavy metals concentrations in dark-blue polycotton fabric were higher than prescribed Oeko-Tex limits except for copper metal. White cotton, black polyester, and navy-blue wool fabrics exceeded the recommended limit for nickel. Chromium was found only in dark-blue polycotton and navy-blue wool fabric and its concentration exceeded the recommended limit only in dark-blue polycotton fabric whereas for navy-blue wool fabric it was below the limit. All fabrics contained formaldehyde, and its concentration was below the recommended limit. The pH of white cotton and black polyester fabrics was within the recommended range of 4 - 7.5 while that of dark-blue polycotton, brown polycotton, and dark-blue wool fabrics was above the limit.

Keywords: *detection, Fabrics, formaldehyde, heavy metals, recommended limits*

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1. Introduction

The rapid growth of the textile industry has led to environmental and health concerns due to toxic chemicals being used in the processing and finishing of textile products. In some countries, the textile industry accounts for the largest share of the economy. Health and environmental concerns are being raised as some of the chemicals are toxic and not easily degraded. Some of the toxic chemicals are formaldehyde, pentachlorophenol, halogens like chlorine, and heavy metals such as cadmium (Cd), zinc (Zn), copper (Cu), lead (Pb), mercury (Hg), iron (Fe), argon (Ar), cobalt (Co) and chromium (Cr). In humans, they can accumulate in the body as they are not easily degraded. High levels of chemicals in the body have been associated with lung, liver, brain, and kidney diseases [1, 2]. Accumulation in the environment contaminates the soil and water and as such the health of plants and aquatic animals is negatively affected. Manufacturing processes are the main source of heavy metals. Because of the toxicity of heavy metals, some countries have adopted stringent measures to limit the amounts that can be released into the environment [1].

Heavy metals and chemicals like formaldehyde are used in textile processes for dyeing and printing as well as to impart antimicrobial, water repellences, flame retardancy, and crease-resistant properties. In fibres like cotton, the main source of toxic chemicals is attributed to the chemicals used to treat the fibres. Human beings can acquire these chemicals through direct skin contact, ingestion, and inhalation. Direct skin fabric contact increases the risk of exposure because the body is in constant direct contact with clothes [2, 3]. Sweating also increases the risk of absorbing the chemical residues remaining in finished clothing through direct contact with the skin. The wearer can develop skin infections. Some authors reported that the presence of metals in branded and non-branded clothes for both children and adults was lower, and as such was considered safe [2, 4]. Identifying the source of toxic heavy metals and chemicals in the supply chain is not easy because not all companies involved in the supply chain keep records about the heavy metals or chemicals used in their manufacturing processes. The rapid changes being driven by fashion trends further complicate the identification of sources. Furthermore, materials used in the industry are sourced from or finished in different parts of the world [3].

The main health risk associated with heavy metals and chemicals contained in fabrics is skin irritation due to constant human skin and fabric contact. The amount that can be leached from the fabric due to sweating varies as different individuals have different sweating rates. Lead can cause birth defects, behavioural problems, liver problems, high blood pressure, neurological degeneration, and bone

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deformities. Exposure to high levels of nickel can lead to skin irritation, liver and heart problems. Cadmium can cause respiratory and metabolic problems. Arsenic can accumulate in the liver and is indicated to cause metabolic problems. Chromium has been reported as a carcinogenic, and it is reported to destroy body fat [5, 7]. Cobalt causes skin eczema and lung infection. Formaldehyde is a chemical used to treat textile fabrics is carcinogenic and also causes reproductive, developmental, and skin problems [8, 9]. It also can cause skin irritation. Formaldehyde is used in textile finishing to improve fabric resistance to shrinkage and loss of shape. Not all countries have recommended limits for the presence of metals and chemicals in textile products. In Japan, for formaldehyde, the maximum limits for children under the age of 2 years are 16 µg/g and 75 µg/g depending on the type of textile product. In Finland, it is 30 µg/g and 100 µg/g which are higher than that of Japan [10, 11]. The pH of clothing is another factor that should be taken into consideration when testing the fabrics as it causes skin irritation. The human skin pH is about 5 and the pH of clothing must be closer to a pH of 5 to avoid skin irritation [6].

It is recommended that new clothing should be washed before use because clothing does come with labels indicating the toxic metals or chemicals they contain. Buying from sellers who adhere to the recommended minimum limits of chemicals in clothing is also important to minimise risk [12]. One such method that can be used to determine if clothing is safe for humans about the presence of metals or chemicals in clothing is the Oeko-Tex Standard 100 [13].

Other sources for heavy metal release are laundry and environmental weathering. During laundering dark colour garments, there are bleeding of theses colours resulting in the release of the heavy metal to the wastewater sources. It not only contaminates water sources, also it contaminates soil and subsequently affecting aquatic and soil ecosystems [14]. Due to the environmental weathering effect like ultraviolet rays (UV) rays from sun, temperature, humidity, rain, dew, discarded clothing's are sources of heavy metal release into the environment. The fabric structure breakdown due to the prolonged environmental exposure resulting in the heavy metal release into the environment. This heavy metal may have adsorbed into the fabrics during the usage phase or added to the fabrics as a finishing or coatings during the manufacturing stages. Apart from the water and soil pollutions, heavy metals can change the soil ecosystems affecting microbial growth which are important to maintaining a good soil condition [15]. Furthermore, increase in the toxicity levels of heavy metals due to the environmental exposure can lead to an adverse effect on the environment and ecosystem [16].

Some of the potential solutions to reduce release of formaldehyde from the fabrics is to wash the new garment with detergents before use and then air drying [17, 18]. Using hot water during washing also assisted in removing residual formaldehyde from the garments. Similarly, alternative bio-based phenol-formaldehyde resins with low-emission can be used to reduce the release of formaldehyde from the fabrics [19]. Furthermore, enzyme treatment can break the harmful formaldehyde by converting into water and CO2 [20].

When the concentrations of toxic metals and chemicals are above the recommended limits, clothing is regarded as unsafe [6]. The recommended limits for children are lower than that for adults as children's immune system is not yet as fully developed. Children are at a higher risk because they crawl on the floor and put textile products in their mouths. Human skin and fabric contact is considered the main direct route that humans acquire heavy metals and determining the amount of these metals in clothing is important in reducing the risk of acquiring them. This study focuses on the determination and detection of metals and chemicals found in fabric rolls used to make clothing in South Africa. Pb, Cd, Cr, Ni, and as pose a health risk to humans and the environment due to their toxicity. The aim is to determine the concentration of the contaminants to ensure that they are within Oeko-Tex standard 100 acceptable limits. As a result, the pH levels, formaldehyde levels, and extractable heavy metals were examined.

2. Materials and Methods

2.1 Materials

The fabric rolls, viz. dark-blue polycotton fabric, brown polycotton fabric, navy-blue wool fabric, white cotton fabric, and black polyester fabric were procured from the local fabric suppliers. Furthermore, these suppliers are scouring fabrics from manufacturers/finishers mainly from Asian countries, it is difficult to trace the actual source of materials. Sodium chloride (NaCl), ammonium chloride (NH4Cl), acetic acid (CH3COOH), lactic acid, ammonium acetate, and acetylacetone were purchased from Sigma Aldrich, South Africa.

2.2 Determination of heavy metals using artificial sweat solution

The determination of heavy metal method was performed according to ISO 3160/2. Weigh about 20g NaCl, 17g NH4Cl, 5g CH3COOH, and 15g lactic acid and dissolved in 1 litre of distilled water. The pH was adjusted to 4.7 using NaOH solution. Small pieces of dark-blue polycotton fabric (2 cm × 2 cm) were randomly cut. About 2g triplicate of the cut fabric specimens were weighed and each one was mixed with 50 mL of artificial sweat solution. The mixture was mechanically shaken for 24 hours and then filtered. The filtrate was analyzed using the ICP-MS (Inductively coupled plasma mass spectrometry) instrument equipped with a plasma interface. A 10% nitric acid was used for washing samples, before starting next sample analysis. Prior to analysis, the following conditions were used: power of plasma, 1400 W; speed of pump, 30 rpm; coolant flow, 14.00 L/min; auxiliary flow, 2.10 L/min; and nebulizer flow, 0.80 L/min. The same procedure was followed for other types of fabrics.

2.3 Determination of formaldehyde (free and hydrolysed formaldehyde)

Three dark-blue polycotton fabric specimens weighing about 2g were cut. The specimens were cut into smaller pieces with dimensions 0.5cm x 0.5cm and then put into three separate 250 mL volumetric flasks containing 50 mL distilled water. Flasks were shaken and put in an incubator for 24 hours at 49±1°C and after they were allowed to cool to room temperature. Each extract was filtered, and 5 mL of the filtrate was pipetted into a clean test tube followed by adding 5 ml acetylacetone reagent. A blank was prepared by adding 5 ml of acetylacetone reagent into 5 ml of distilled water. Test tubes were placed in water for 24 hours at 40°C and then allowed to cool for further analysis. Formaldehyde measurements were carried out by measuring the absorbance at 412 nm using Optizen Pop UV spectrophotometer. The same procedure was followed for other types of fabrics. The standard solution was prepared by pipetting 0.95 ml of formaldehyde solution (37% m/v) into a 250 mL volumetric flask and filling it to the mark with distilled water. The solution was labelled A. A 2.5 mL solution A was pipetted into a 50 ml volumetric flask and it was filled with distilled water. The obtained solution was labelled B.

2.4 Determination of pH

Three dark-blue polycotton fabric specimens weighing about 2g were cut. The specimens were cut into smaller pieces with dimensions 0.5cm x 0.5cm and then put into three separate 250 mL volumetric flasks, containing 100 mL distilled water and shaken for 2 hours using an orbital shaker. Prior to using the distilled water, the distilled water pH was adjusted to be in the range of 4.7 - 7.5 by boiling and cooling it to room temperature. The extract was filtered and the filtrate pH was measured. The three pH values from the three beakers were used to calculate the average pH. The same procedure was followed for other types of fabrics.

3. Results and Discussion

3.1 Heavy metals

Table 1 shows that the brown polycotton fabric was the only fabric with no heavy metals detected in it, whereas in other fabric types, heavy metals were detected. Dark-blue polycotton fabric contained all metals, with concentrations in the range of 2.263 mg/kg to 4.899 mg/kg. The resultant concentrations were higher than the prescribed Oeko-Tex limits of less than 0.1 and 0.2 mg/kg for the metals except for copper which had a concentration of 3.735 mg/kg which was less than the recommended limit of less than 25 mg/kg. Nickel was detected in all fabrics except in brown polycotton fabric and its concentration exceeded the recommended limit of less than 1.0 mg/kg. Chromium was detected only in dark-blue polycotton and dark-blue wool fabrics and its concentration of 4.899 mg/kg in dark-blue polycotton fabric was higher than the recommended limit of less than 1.0 mg/kg. In contrast, the dark-blue wool fabric concentration of 0.052 mg/kg was less than the limit of 1.0 mg/kg. No lead, copper, arsenic, cobalt, and cadmium were detected in all fabrics. These results show the use of these fabrics poses a risk to humans. Brown polycotton fabric was the only exception with no heavy metal detected in it.

Table 2 - Fabric formaldehyde concentrations and the Oeko-Tex recommended limits

Samples	Formaldehyde concentration (mg/kg)	Recommended concentration (mg/kg)
Dark-blue polycotton	0.242	<16
Brown polycotton	0.199	<16
Dark-blue wool	0.061	<16
White cotton	0.064	<16
Black polyester	0.012	<16

Table 1 - Fabric metal concentrations and the Oeko-Tex recommended limits

Samples	Metal concentrations (mg/kg)								
	Pb 217	Pb220	Cu 213	Cu 327	As 193	Co238	Cr267	Ni221	Cd214
Dark-blue polycotton	2.263	3.464	4.616	2.853	4.593	2.869	3.213	4.899	4.229
Brown polycotton									
Navy-blue wool	-	-	-	-	-	-	0.052	2.464	-
White cotton	-	-	-	-	-	-		2.856	-
Black Polyester	-	-	-	-	-	-	-	2.746	-
Oeko-Tex acceptable limits	<0.2[a] and <1.0[b]	<0.2[a] and <1.0[b]	<25.0[a] and <50.0[b]	<25.0[a] and <50.0[b]	<0.2[a] and <1.0[b]	<1.0[a] and <4.0[b]	<1.0[a] and <1.0[b]	<1.0[a] and <2.0[b]	<0.1

[a] children [b] adults

3.2 pH

Since the skin is in direct contact with the fabric, it is important that the fabric pH must be closer to the skin pH of about 5. Excessive low and high pH is reported to skin irritability and itching. Oeko-Tex recommends the pH to be within the range of 4 - 7.5 as seen in Table 3. The results show that only white cotton and black polyester fabric's pH was within the recommended range of 4 - 7.5, whereas that of dark-blue polycotton, brown polycotton, and dark-blue wool fabrics was above the upper limit of 7.5. These pH results showed that even though the brown polycotton fabric had no toxic heavy metals that were detected in it and met the Oeko-Tex limit concentrations for formaldehyde, however, its pH of 7.96 makes it unsuitable for garment construction.

Table 3 - Fabric pH and the Oeko-Tex recommended limits

Samples	Formaldehyde concentration (mg/kg)	Recommended concentration (mg/kg)
Dark-blue polycotton	0.242	<16
Brown polycotton	0.199	<16
Dark-blue wool	0.061	<16
White cotton	0.064	<16
Black polyester	0.012	<16

Both white cotton and black polyester meet the recommended pH limit as well as for formaldehyde, however, their concentrations for heavy metal limits (see Table 1) were higher than the recommended limits making them not good candidates for fabrics that will be in direct contact with the skin. The pH of dark-blue polycotton, brown polycotton and dark-blue higher than the recommended limit and it will cause skin itching and irritation.

4. Conclusion

Heavy metals were found in all fabrics except in brown polycotton fabric. In dark-blue fabric, the concentrations of all metals were higher except for copper and as such, this fabric poses a significant risk if used as a garment material. The concentrations of formaldehyde in all fabrics were found to be below the recommended Oeko-Tex limits and pose less risk to human beings. The pH had mixed results with some within and outside the recommended range limit. This study showed there is a need to test all fabric rolls for pH, formaldehyde, and heavy metals as there was no fabric that met the recommended limits if the heavy metal formaldehyde and pH tests are to be used to recommend if the fabric is safe to be used to make clothing. The results show the need to test the fabric rolls before use to ensure that the toxic substances are fairly below the recommended limits as the fabric rolls do not come with such information.

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Finishing of Cotton Fabric with Biodegradable NanoComposite using Chitosan and Halloysite

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Abstract:

This study explores the finishing of cotton fabric using a biodegradable nanocomposite composed of chitosan and halloysite nanotubes (HNTs) to enhance its functional and mechanical properties while promoting environmental sustainability. Chitosan, a natural polysaccharide with inherent antimicrobial activity, serves as a film-forming matrix, while halloysite nanotubes, a naturally occurring aluminosilicate clay, act as reinforcing fillers and carriers for controlled release of active agents. The nanocomposite dispersion was prepared by dissolving chitosan in dilute acetic acid, followed by ultrasonication-assisted dispersion of HNTs and crosslinking with citric acid. The finishing was applied to pre-treated cotton fabric via the pad-dry-cure method. Characterization techniques including scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), and mechanical testing confirmed uniform coating, chemical integration, and enhanced tensile and tear strength of the treated fabric. Functional evaluation demonstrated significant antimicrobial efficacy against Escherichia coli and Staphylococcus aureus, along with improved water repellence indicated by an increased contact angle. The finished fabric exhibited increased durability and maintained breathability, highlighting the potential of chitosan-halloysite nanocomposites as eco-friendly finishing agents. This research contributes to the development of sustainable textile finishing technologies that reduce environmental impact while delivering multifunctional performance, positioning biodegradable nanocomposites as promising candidates for next-generation smart and protective cotton textiles.

Keywords: *Antimicrobial, Biodegradable nanocomposite, Chitosan, Cotton fabric, Halloysite nanotubes*

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1. Introduction

Cotton fabric, renowned for its breathability, softness, and absorbency, is inherently versatile but often requires aesthetic finishing to enhance its visual appeal and tactile qualities. Textile finishing enhances cotton fabric's aesthetic and functional properties, making it suitable for diverse applications. This crucial process imparts desired characteristics like wrinkle resistance, water repellency, and antimicrobial activity, moving beyond raw fabric to consumer-ready textiles. The finishing of cotton fabric with biodegradable materials is a rapidly evolving field, driven by the textile industry's shift towards more sustainable and environmentally responsible practices [1]. This approach focuses on imparting desired functionalities to cotton textiles while ensuring that the finishing agents and their byproducts are non-toxic and can naturally decompose after the fabric's useful life [2, 3]. Therefore, the main role of textile-interesting researchers is to explore and develop eco-friendly and safe for human finishing antimicrobials. Recently, nanostructure-based antimicrobials have received considerable attention over traditional antimicrobials in antimicrobial textile finishing due to their amazing characteristics such as low toxicity, tunable morphology, stability, photocatalytic activity, cost- effectiveness, unique chemical, optical, mechanical, physical, and electronic properties [4]. Notably, nanomaterials play an important role in the development of functional smart fabrics with antimicrobial, self-cleaning, insect-repellent, UV-protection, waterproof, flame-resistant, and anti-static qualities [5, 6]. Chitosan, a linear polysaccharide derived from the de-acetylation of chitin found abundantly in crustacean shells and fungal cell walls, plays a pivotal role in biodegradable nanocomposite finishing for cotton fabrics. It functions as an excellent film-former and possesses inherent antimicrobial properties, making it a valuable sustainable finishing agent. Its unique positively charged amine groups facilitate strong adhesion to negatively charged cotton fibers, often serving as the primary binder or matrix for incorporating nanoparticles onto the fabric surface [7]. The efficacy and characteristics of the chitosan finish, including its solubility, viscosity, and film properties, are significantly influenced by its molecular weight and degree of de-acetylation, and it is typically employed in acidic solutions for optimal performance [8]. Halloysite Nanotubes (HNTs), a naturally occurring alumina silicate clay mineral, are increasingly employed in biodegradable nanocomposites for textile finishing due to their unique hollow tubular structure. This morphology enables the encapsulation of various active agents, such as antimicrobials, flame retardants, or fragrances, facilitating their controlled release onto cotton fabrics [9]. Beyond their role as carriers, HNTs also function

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as reinforcing fillers, contributing to improved mechanical properties, offering UV protection, and enhancing barrier functionalities of the textile [10]. A key characteristic influencing their utility is the differential surface charge: the inner lumen is often positively charged, while the outer surface is negatively charged, allowing for selective adsorption. Effective utilization necessitates good dispersion techniques, particularly sonication, to prevent aggregation and ensure uniform distribution within the composite [11].

2. Materials and Methods

This methodology describes the experimental procedures for preparing a chitosan- Halloysite nanocomposite and its application onto cotton fabric to impart desired functionalities.

2.1. Materials

Cloth particulars
Type of fabric = Plain woven cloth
Warp yarn count: - 40`s
Weft yarn count: - 40`s
EPI -130
PPI -110
GSM = 151.2g
Thickness of the fabric = 0.31mm

2.2. Pre-treatment of Cotton Fabric

The fabric sample is washed thoroughly to remove the size paste and foreign matters present in the fabric surface, after washing, the fabric is air-dried, then oven-dried at 60°C for 1 hour to achieve a consistent moisture content. Finally, the fabric is subjected to conditioning in a standard atmospheric condition of 20±2°C and 65±2% relative humidity for 24 hours before further treatment, ensuring its equilibrium with environmental conditions.

2.3. Preparation of Chitosan-Halloysite Nanocomposite Dispersion

The preparation of the chitosan-Halloysite nanocomposite dispersion is a critical step, ensuring uniform dispersion and stability for effective fabric finishing. First, a chitosan stock solution is prepared by slowly dissolving chitosan powder in a dilute acetic acid solution under continuous stirring at room temperature for 12 hours and it becomes clear and viscous [12]. Halloysite nanotubes (HNTs) are dispersed in a small portion of deionized water using mechanical stirring followed by high-power ultra-sonication (400W, 20 kHz) for 30 minutes for create uniform mixtures and suspensions by breaking down large particles and dispersing them evenly and effectively disperse nanoparticles and other fine particles, preventing them from clumping together and an ice bath used is to prevent overheating, ensuring uniform dispersion and exfoliation to minimize aggregation [13]. For nanocomposite blending, the well-dispersed HNT suspension is then slowly added to the chitosan solution with continuous stirring for 2 hours to ensure homogeneous mixing and integrate HNTs into the chitosan matrix [14]. Citric acid is added to the nanocomposite dispersion as a Crosslinking agent along with its catalyst, stirring until completely dissolved [15]. Finally, dilute NaOH is used to pH adjustment to a range of pH 4 using as it can influence the stability and reaction efficiency during the subsequent curing process [16].

2.4. Application of Nanocomposite onto Cotton Fabric (Pad-Dry-Cure Method)

The pad-dry-cure method is the most common technique for laboratory-scale textile finishing. The pre-treated cotton fabric samples (20x30 cm) are immersed in the prepared chitosan-Halloysite nanocomposite dispersion for a dwell time of 5 minutes to ensure complete saturation. The saturated fabric is then passed through a laboratory model two-roll padding machine at a controlled pressure of 0.3 MPa to achieve a desired wet pick-up (WPU), calculated as [(Wet fabric weight - Dry fabric weight) / Dry fabric weight] x 100%. After padding, the fabric undergoes drying into a laboratory oven at a temperature of 80°C for10 minutes to remove water. Subsequently, the dried fabric proceeds to curing in a hot air oven at a temperature of 140°C for 3 minutes; this step promotes crosslinking and permanently fixes the nanocomposite onto the fabric, thereby enhancing its durability and performance. Optimization of both curing temperature and time is paramount. Finally, a post-treatment wash is performed, gently washed the cured fabrics with deionized water at room temperature to remove any unreacted chemicals and loosely adhered particles, followed by thorough rinsing and air drying.

2.5. Evaluation methods

Characterization of Finished Cotton Fabric
Characterization is essential to confirm the successful application of the nanocomposite and evaluate the imparted functionalities.

2.5.1 Morphological Analysis: Scanning Electron Microscope (SEM)

Used to examine the surface morphology and microstructure of nano-coated samples, observing surface textures, particle sizes, microscopic defects, and coating uniformity at high magnifications (100X to 5.5KX).

2.5.2 Functional Properties Evaluation

2.5.2.1 Antibacterial Activity – EN ISO 20645 Test Method

Sterile AATCC bacteria stasis agar plates were inoculated with Escherichia coli and Staphylococcus aureus. 20mm diameter fabric discs were placed on the agar, incubated at 37°C for 24 hours. The antibacterial effectiveness was evaluated by measuring the clear zone of inhibition around the fabric.

2.5.2.2 Contact Angle Test – ASTM D7334 (Water Repellent)

This measures the angle formed between a water droplet and the fabric surface. A contact angle above 90° indicates improved water resistance, with over 120° signifying excellent repellency, crucial for kitchen fabrics.

2.5.3 Chemical Analysis

2.5.3.1 Fourier Transform Infrared Spectroscopy (FTIR)

To confirm the presence of chitosan and HNTs on the fabric by identifying characteristic functional groups (e.g., amide/amine for chitosan, Si-O-Si/Al-O-Si for HNTs) and potential crosslinking reactions.

2.5.4 Mechanical Properties

2.5.4.1 Tensile Strength – ASTM D 5034

Measures the maximum stress a material can withstand before breaking when stretched or pulled. A tensile strength tester clamps a sample and applies force, recording data like maximum force, stretch, and energy absorbed.

2.5.4.2 Thickness – ASTM D1777

Measured using a mechanical gauge with a flat anvil and spring-loaded presser foot, providing accurate readings in millimetres.

2.5.4.3 Tear Strength – ASTM D1424 (Elmendorf Tear)

Evaluates the fabric's resistance to tearing by measuring the force required to propagate a tear in a pre-cut specimen, indicating durability.

2.5.4.4 GSM – ASTM D3776

Determines the mass per unit area (grams per square meter) of fabric samples using a GSM cutter and precision digital balance, indicating fabric quality, weight, and density.

3. Result and discussion

3.1 Morphological Analysis: Scanning Electron Microscope (SEM):

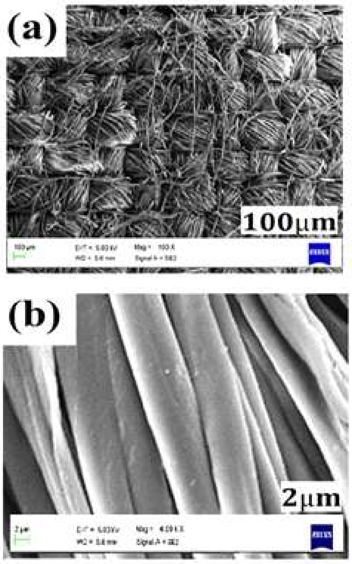

Figure 1: SEM images of untreated (a) and untreated fabric (b)

The SEM images display untreated cotton fabric, with Figure (a) showcasing the macroscopic plain woven structure at 100x magnification, where individual warp and weft yarns are clearly distinguishable. Figure (b) offers a highly magnified view (4000x, 2µm scale bar) of the surface of individual cotton fibers, revealing their characteristic twisted, ribbon-like morphology and inherent smoothness. For the research on finishing cotton fabric with a biodegradable nanocomposite using Chitosan and Halloysite. SEM analysis would directly infer the successful deposition of a uniform nanocomposite coating and the distribution of Halloysite Nanotubes on the fiber surfaces, confirming the physical application of the biodegradable finish.

3.2 Functional Properties Evaluation

3.2.1 Antimicrobial Activity EN ISO 20645 Test Method

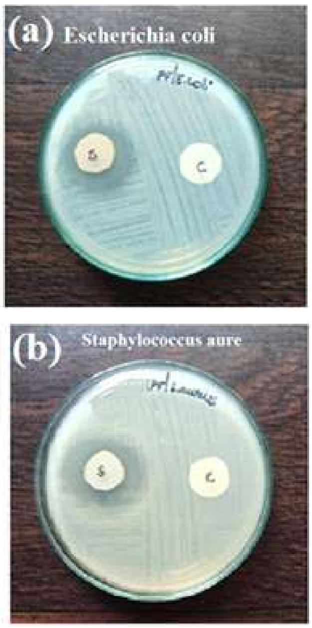

Figure 2: Antimicrobial tests of (a) E. coli untreated (c), treated fabric(s) and (b) S. arus untreated (c), treated fabric(s)

The images display the results of an antimicrobial test using the agar diffusion method against Escherichia coli and Staphylococcus aureus. In both petri dishes, the sample labelled 'S' (presumably the cotton fabric finished with the biodegradable nanocomposite using Chitosan and Halloysite) shows a clear zone of inhibition around it. Conversely, the sample labelled 'C' (likely the control, untreated cotton fabric) exhibits no zone of inhibition, indicating bacterial growth right up to its edge. This distinct difference strongly suggests that the bio-degradable nanocomposite finish successfully imparted significant antimicrobial activity to the cotton fabric, effectively inhibiting the growth of both Gram-negative (Escherichia coli) and Gram-positive (Staphylococcus aureus) bacteria.

3.2.2 Contact angle – ASTM D7334

Figure 3: Contact angle testing

The contact angle measurement was performed using the sessile drop method with a time interval of 1000 milliseconds and a frequency of 21. The contact angle recorded was 89.2°, indicating that the surface exhibits near-neutral wetting behaviour, characteristic of a borderline between hydrophilic and hydrophobic surfaces. This suggests that the bio-degradable nanocomposite finish has successfully imparted hydrophobic characteristics to the inherently hydrophilic cotton fabric. The larger the contact angle (ideally above 90 degrees for hydrophobicity), the more effectively the surface repels water.

3.3 Chemical Analysis

3.3.1 Fourier Transform Infrared Spectroscopy (FTIR)

The FTIR spectrum of the finished cotton fabric with a biodegradable nanocomposite of chitosan and halloysite would provide crucial evidence for the successful application and potential interactions of the components. We would expect to observe characteristic absorption bands from cotton cellulose, including broad O-H stretching around 3300 cm−1 and C-O stretching around 1030 cm−1. Superimposed on these, the presence of chitosan would be indicated by N-H stretching and bending vibrations (around 3300 cm−1 and 1590−1650 cm−1), while halloysite would be confirmed by its distinctive Si-O stretching bands (typically 1000−1100 cm−1) and Al-OH bending vibrations (below 900 cm−1). Any shifts in these characteristic peaks, particularly in the O-H or N-H regions, the appearance of new bands (ester carbonyl as a cross linker), would further infer chemical interactions and crosslinking between the nanocomposite and the cotton fibers, signifying a durable and well-integrated finish.

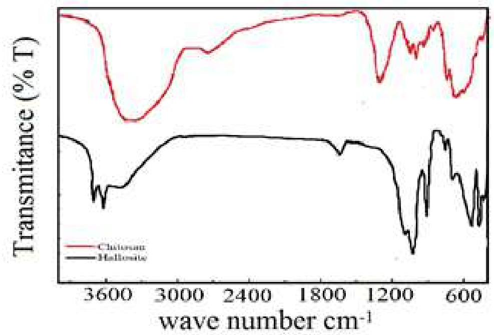

Figure 4: Fourier Transform Infrared Spectroscopy image

4. Conclusion

The use of a biodegradable nanocomposite finish with chitosan and halloysite nanotubes on cotton textile is a major breakthrough in eco-friendly textile processing that successfully couples improved functionality and environmental sustainability. This novel finishing technique provides intense antimicrobial activity, evidenced by distinct zones of inhibition against Escherichia coli and Staphylococcus aureus, rendering the treated fabric extremely well suited for medical and hygienic purposes. Furthermore, the treatment alters the cotton surface to present near-hydrophobicity, as is evident by higher measurements of contact angle, which is beneficial for water-repellent and easy-care fabrics. Chemical analysis through FTIR proved successful incorporation and crosslinking of halloysite and chitosan in the cotton matrix, creating a long-lasting and durable finish. Mechanical testing also showed enhanced tensile and flexibility strength, thickness, and GSM, meaning that not only does the nanocomposite improve performance but also strengthens the structural integrity of the fabric. Both chitosan and halloysite are, however, significant in that they are naturally derived, biodegradable, and non-toxic, fitting in with worldwide trends towards natural, environmental textile solutions. In summary, the research proves that chitosan-halloysite nanocomposite finishing is a viable, eco-friendly method for producing high-quality cotton fabrics with enhanced antimicrobial, mechanical, and barrier properties, opening the way to greener*, high-performance textiles in various applications.*

3.3.2 Mechanical Properties

Table 1: Mechanical Properties of Nano composite using Chitosan and halloysite treated and untreated

Tensile Strength(NF)				Tear Strength(gf)				Thickness		GSM	
Un treated		Treated		Un treated		Treated		Un treated	Treated	Un treated	Treated
Warp	Weft	Warp	Weft	Warp	Weft	Warp	Weft	0.31	0.324	151.2	166.54
241.10	125.90	251.60	132.80	1093.90	635.90	1253.70	698.40				

NF: Tensile strength in N/mm2; Tear strength in gf. The average force in grams per force

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Emerging Adsorption Strategies for Textile Effluents: A Comprehensive Review

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Abstract:

Controlling water contamination has grown increasingly important in recent years. During various stages of textile manufacture and processing, the textile industry produces massive amounts of complex chemical substances in the form of wastewater from underutilized components, including colors. Among the processing sectors, textile dyeing facilities generated considerable amounts of high-strength waste. Textile chemical processing generates significant volumes of wastewater containing a variety of contaminants. In recent years, researchers have placed a greater emphasis on the utilization of low-cost adsorbents for the removal of dyes and other pollutants. Activated carbon derived from natural resources is more effective at treating a wide variety of dyes. This paper examines the literature on a wide spectrum of low-cost adsorbents using contemporary research and literature.

Keywords: *Activated carbon, Dye removal, low-cost adsorbents, pollutants, wastewater*

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1. Introduction

With a vast and unrivaled raw material base and industrial power along the value chain, India has the largest textile industry in the world. After China, the Indian textile sector is the world's second-largest producer and exporter [1]. The Indian economy depends heavily on this industry. To engineer the necessary shape and qualities of the finished product, the textile industry uses a vast range of raw materials, equipment, and procedures. This industry's waste stream is mostly composed of water-based effluent from the several wet textile processing operations. The primary source of this effluent's production is the massive amounts of water used in chemical processing or in subsequent steps like preparation, dyeing, printing, and finishing. However, the wastewater produced by many processes is actually far more contaminated and hazardous than the standard [2]. Pollutants containing compounds that have harmful effects on microbial populations and can be harmful and carcinogenic to animals and mammals are found in dye effluents that are released uncontrolled [3]. Treating this effluent has become crucial due to the stricter regulations on industrial discharge.

2. Overview of Textile Wet Processing

Wet textile manufacturing uses a lot of water and produces a lot of effluent, which is full of all kinds of contaminants. Designing efficient wastewater treatment and pollution control techniques requires an understanding of the contaminants that emerge at each stage of processing.

2.1 Sizing

Objectives: To lessen breakage while weaving, cover warp yarns with a protective layer.

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Pollutants produced include suspended particles, synthetic sizing agents, starch residues, high BOD from biodegradable starches, and perhaps leftover chemicals.

2.2 Desizing

The objective is to eliminate sizing agents so that the cloth is ready for additional treatments.

Pollutants produced include high BOD and COD, oxidizing compounds, soluble starches, enzymes (if enzymatic desizing is employed), and suspended particles.

2.3 Scouring

The objective is to eliminate processing oils and natural contaminants including waxes, lipids, and pectins.

Alkali (caustic soda), saponified fats and waxes, high pH, high BOD/COD, oil and grease, and suspended particles are among the pollutants produced.

2.4 Bleaching

The objective of bleaching is to lighten or remove the fabric's initial hue so that it may be dyed or printed.

The following pollutants were produced: oxidized organic matter, high pH, high COD, chlorinated organic compounds, and residual bleaching agents (hydrogen peroxide, chlorine compounds).

2.5 Mercerization

Enhance cotton and other cellulosic fibers' strength, luster, and dye affinity.

Pollutants produced include dissolved cellulose, sodium hydroxide residues, highly alkaline effluent, and trace amounts of organic matter.

2.6 Dyeing

The objective is to give fibers, yarns, or textiles a consistent color.

Excess dyes, dyeing auxiliaries (salts, dispersion agents, surfactants, and wetting agents), excessive color, heavy metals, high COD/BOD, and high TDS are among the pollutants produced.

2.7 Printing

The objective is to use color in repeating, confined patterns.

Printing pastes (binders, thickeners, and solvents), pigments, unfixed dyes, wash-off chemicals, solvents, high color, and COD are among the pollutants produced.

2.8 Finishing

The objective is to provide ultimate functional or cosmetic qualities (water repellency, wrinkle resistance, and softening).

Pollutants produced include residual formaldehyde, low to moderate BOD/COD, surfactants, finishing chemicals (softeners, flame retardants, resins, fluorocarbons, silicones), and potentially hazardous organics.

2.9 Washing and Drying

The objective of washing is to remove residual chemicals and unfixed dyes or surface localized chemicals and dyes at various stages.

Pollutants generated: Mixture of all above pollutants in diluted form mainly colour, surfactants, salts, low to high COD/BOD, and thermal pollution [4].

3. Dyes in the Textile Industry: Sources, Structure, and Classification

The textile industry has employed dyes as colorants. One of the biggest challenges in wastewater treatment is dye abatement. This is due to the importance of dye treatment; dyes with an azo group are often more stable and more resistant to oxidizing chemicals, heat, and light. Because of this, they are challenging to eliminate using the majority of traditional oxidizing or biodegrading techniques. Other methods include membrane-filtration technologies (Nano-filtration, electro-dialysis, reverse osmosis, etc.), coagulation and flocculation, and photo-degradation. However, because it is expensive and has seldom been used to achieve total color removal, its application is restricted. Usually, Textile dyes are classified according to their application these are:

i. Acid Dyes: The dyes are insoluble in acid the solubility being confirmed by the presence of sulphonic acid group on dyes usually in the form of sodium salt. The acidic conditions are used for dyeing wool and nylon. The three most important classes of acid dyes in basic chemical classes are Azo, Anthraquinoid, and Triphenylmethane.

ii. Azoic Dyes: An azoic colouring matter is a water-insoluble azo compound produced in textile fibres. Azoic dyes are used for dyeing cellulosic fibres.

iii. Basic Dyes: These are amino and substituted amino compounds that are soluble in acid and become insoluble when alkali is added. They are used as dye acrylics or can be used with a mordant dye for dyeing wool and cotton.

iv. Direct Dyes: Direct dyes are inexpensive and have auxiliary chemicals associated with direct dyeing such as sodium salt, fixing agents, and metal salts. Direct dyes belong to several chemical classes like Azo, phthalocyanine, and stilbene.

v. Disperse Dyes: A dispersed dye is defined as a substantially water-insoluble having substantively for one or more hydrophobic fibres. Dyes are used on polyester, polyamide, and acrylic fibres.

vi. Fibre Reactive Dyes: Reactive dyes are coloured components capable of forming a covalent bond between the dye molecule and fibre. Fiber-reactive dyes are mainly used for cotton and cotton blends. 1.9. Mordant Dyes The term mordant dye refers to a dye, which is applied to fibre in conjunction with metallic mordant. Mordant dyes give fast, full but generally dull shades on wool and nylon.

vii. Sulphur Dyes: Sulphur dyes are used for the dyeing of cellulosic fibres in medium to deep shades of generally dull brown, black, olive, blue, green, maroon, and khaki hues.

viii. Vat Dyes: These are water-insoluble dyes, which contain at least two conjugated carbonyl groups that enable the dye to be converted into the corresponding water-soluble ionized compounds.

Several methods are employed for the treatment of textile effluents to achieve decolourization [5].

Pigments and dyes are used by the textile industry to color their goods. Because dyes are hazardous to aquatic life and degrade the aesthetics of the environment, textile businesses' discharge of wastewater containing colors into natural streams and rivers is a serious issue [6].

Table 1: Types of dyes, applications, and chemical classes

Types of dyes	Their application	Properties	Chemical classes
Acid dyes	Nylon, wool, silk, modified acrylics, paper, leather, ink-jet printing, and food	Water-soluble	Azo (including premetallized), anthraquinone, triphenylmethane, azine, xanthene, nitro, and nitroso
Basic dyes	Paper, polyacrylonitrile, modified nylons, modified polyesters, cation dyeable polyethylene terephthalate,and medicine	Water-soluble	Diazahemicyanine, triarylmethane, cyanine, hemicyanine, thiazine,oxazine, and acridine
Disperse dyes	Polyester and some amount of nylon, cellulose, cellulose acetate, and acrylic fibers	Water-insoluble and non-ionicdyes	Azo, anthraquinone, styryl,nitro, and benzo-di-furanone
Direct dyes	Cotton, rayon, paper, leather, and some amount of nylon.	Water-soluble and anionic dyes	Polyazo compounds, alongwith some stilbenes, phthalocyanines, andoxazines
Reactive dyes	Cotton and other cellulosic fibers and some extent wool and nylon fibers	Water-soluble	Chromophoric groups such asazo, anthraquinone,triarylmethane, phthalocyanine, formazan,and oxazine
Solvent dyes	Plastics, gasoline, lubricants, oils, and waxes	Solvent solublewhile water- is insoluble and nonpolar or little polar	Predominantly azo andanthraquinone, but phthalocyanine and triaryl methane are also used
Sulfur dyes	Cotton and rayon	Water-soluble	
Vat dyes	Cotton cellulosic fibres and rayon and wool	Water-insoluble	Anthraquinone (including polycyclic quinones) and indigoids

3.1 Usage of Dyes in Industry

The initial raw material and, consequently, the finished product are colored using textile dyes. Both natural and synthetic dyes are possible. Natural colors are created using materials found in nature, whereas synthetic dyes are created scientifically using chemicals. Textiles are often dyed using a mixture of natural or synthetic colors and water. This method of efficient wet dyeing in textile production uses a significant amount of water. Plants and minerals are used to generate natural dyes, which are then mixed with seaweed and starches to ensure they adhere to the textile. Petroleum and coal tar are typically used to make synthetic colors. Because various materials need different chemicals to make the color adhere, they differ greatly.

The use of dyes results in colored water, which is problematic for the environment. Significant amounts of dyes and other chemicals are lost in the wastewater during the dyeing process. Textiles, rubber, plastics, printing, leather, cosmetics, ink, and other sectors frequently utilize dyes to color their goods. They thus produce an enormous volume of colored wastewater. Over 7 X 105 tons of dye are generated annually, and there are over 10,000 commercially available dyes. An estimated 2% of dyes generated each year are released into related industries' effluents [4].

4. Overview of Wastewater Treatment Techniques

It can be difficult to remove dye compounds; many procedures are needed to bring the dye concentration down to the advised level. Understanding the types of pollutants present in textile industry wastewater, their consequences on the environment, and how to identify the different contaminants is insufficient. In order to safeguard the environment, it is crucial to comprehend and be aware of the many treatments that may be applied to these effluent discharges. This will allow the wastes to be drained into streams in a safe and acceptable manner. It is essential to protect the environment, and in order to achieve this reasonable objective, various treatments are used, and these techniques are often divided into three divisions. There have been reports of physical, chemical, and biological decolorization techniques; nevertheless, the paper and textile industries have not adopted many of these [6].

Along with membrane-filtration techniques (nanofiltration, reverse osmosis, and electrodialysis) and adsorption strategies, several physical approaches are also widely employed. The potential for membrane fouling and the necessity of periodic replacement are the main disadvantages of membrane technology. According to the extensive literature, liquid-section adsorption is one of the best techniques for removing colors from textile wastewater because it produces high-quality treated effluent when the adsorption process is properly designed and the adsorbent is chosen. Chemical strategies include irradiation, electrochemical methods, precipitation-flocculation with $Fe(II)/Ca(OH)_2$, electro flotation, electro kinetic coagulation, coagulation or flocculation combined with flotation and filtration, and conventional oxidation methods using oxidizing sellers (ozone). These chemical techniques are often expensive since concentrated. Sludge accumulates and creates a disposal problem during the removal of dyes.

Since many microorganisms, including bacteria, yeasts, algae, and fungi, can accumulate and degrade specific pollutants, biological treatment methods like biodegradation techniques, which include fungal decolorization, microbial degradation, adsorption via (living or dead) microbial biomass, and bioremediation structures are commonly used in the treatment of industrial effluents. Advanced oxidation techniques, such as photochemical oxidation techniques, are substitutes for traditional techniques. They work by producing hydroxyl radicals and other moderately reactive radicals that can break down the intractable organic materials present in textile effluent. These methods do have some serious drawbacks, though, such hefty startup and operating expenses. Using non-toxic, inexpensive, and easily accessible adsorbents, the adsorption method is a practical and effective wastewater treatment technique [7].

5. Adsorption for Dye Removal Using Low-Cost Adsorbents

A wide range of materials for adsorbent preparations is available. Generally, adsorbent raw materials are classified into three categories (a) Natural material, (b) Agricultural

Table 2: Dye Removal Methods and their Advantages and Disadvantages

Type	Method	Advantages	Disadvantages
Physical	Adsorption	Good removal of a wide variety of dyes	Nonselective to adsorbate
	Membrane filtration	Remove all dye types	Concentrated sludge production
	Ion exchange	Regeneration: no adsorbent loss.	Not effective for all dyes
	Irradiation	Effective oxidation at lab scale.	Requires a lot of dissolved O2
	Electro kinetic coagulation	Economically feasible.	High sludge production
	Coagulation –flocculation	Good elimination of insoluble dyes	Cost of sludge treatment
	Adsorption on active carbon powder coupled with coagulation process	Matter, organic matter, and low influence on colour Fast fouling of suspended matter	Cost of active carbon powder
	RO	Retention of mineral salt and hydrolyzed reactive dyes and auxiliaries	High-pressure process, Fouling with high concentrations
	Nano filtration	Separation of mineral salts hydrolyzed reactive dyes, and auxiliaries	Treatment for the complex solution with a high concentration of pollutant
	Ultrafiltration/microfiltrat ion	Low-pressure process	Inadequate quality for
Chemical	Fenton's reagent	The effective decolourization of both soluble and insoluble dyes	Sludge generation
	Ozonation	Good elimination of colour	No diminution of COD values Extra costs
	Photochemical NaOCl	No sludge production was initiated and accelerates azo-bond cleavage	Formation of by-product release of aromatic amine
	Electrochemical destruction	Breakdown compounds are	High cost of electricity
Biological	Standard Biological degradation	The efficiency of the oxidizable matter is 90%	With low biodegradability of dye, the salt concentration stays constant
Photo catalysis	Post-treatment	Near-complete colour removal	For final polishing only

waste - by-products, and (c) Industrial wastes/by-products [8].

5.1 Various low-cost adsorbents' potential for dye removal: low-cost adsorption

- Natural materials: clay minerals, zeolite
- Bio-adsorbents: Fungal- Bacterial, Algal, Other biomass
- Agricultural and Industrial materials: Leaves, Seeds, Fiber, Bark, Fly ash

Several non-conventional, low-cost adsorbents have been investigated for dye removal. In particular, many adsorbents and activated carbons prepared from various waste materials have been explored for this purpose. Examples include Examples include date stones [9], jackfruit peel [10], banana peels [11], orange peels [12], garlic peel [13], corn cobs [14], rice husk [15], sawdust [16], pomegranate peel [17], bael shell [18], lemongrass leaves [19], bamboo [20], neem leaves [21], coconut shell [22], and papaya seeds [6], among others.

5.2 Reviews on dye removal using agricultural waste

Numerous academics and scientists have worked on dye removal. A synopsis of the various researchers' work is provided. Every researcher's investigation was predicated on physicochemical parameters that were modified to examine the adsorption phenomena, including solution pH, dye concentration, and contact duration.

The potential of garlic peel, an agricultural by-product, as an inexpensive adsorbent for the removal of methylene blue (MB) from aqueous solutions was assessed [13]. Contact time, starting dye concentration (25–200 mg/L), pH (4–12), and temperature (303–323 K) were evaluated in batch studies. With monolayer adsorption capacities of 82.64, 123.45, and 142.86 mg/g at 303, 313, and 323 K, respectively, the adsorption results most closely matched the Freundlich isotherm model, suggesting that the adsorption process was endothermic.

The potential application of bael shell carbon (BSC) as an adsorbent for the elimination of congo red (CR) dye from an aqueous solution was examined [18]. Numerous operational factors, including temperature, pH, contact duration, and dye concentration, were examined for their effects. First-order reversible kinetics, pseudo-first-order kinetics, and pseudo-second-order kinetics were used to represent the adsorption kinetics. At pH 5.7, 7, and 8, the dye absorption process followed the pseudo-second-order kinetic expression, whereas at pH 9, the pseudo-first-order kinetic model suited the data well. Adsorption equilibrium data were fitted using the adsorption models of Langmuir, Freundlich, and Temkin.

There was an investigation on microwave-assisted pyrolysis of corncobs and & it was found to be a very a useful adsorbent for removing methylene blue, a cationic dye, from aqueous solutions [14]. Using scanning electron microscopy (SEM) and Fourier transform infrared spectroscopy (FTIR), the surface properties of microwave-assisted corncobs (MACC) were examined. To forecast the ideal circumstances, the effects of a number of experimental factors were examined, including temperature, adsorbent dosage, solution pH, contact time, and starting MB dye concentration. The various isotherm and kinetic models were used to assess the adsorption equilibrium and adsorption rate data. The isotherm results demonstrated that the Freundlich model yields favorable outcomes for the equilibrium data under study.

A research was conducted to determine how well lemongrass leaf-based activated carbon (LGLAC), which was made utilizing physicochemical techniques, removed Methylene Blue dye from aqueous solutions. pH 12 was found to have the best proportion of methyl red dye eliminated. Thermodynamic parameters were assessed, such as Gibbs free energy change (G0), enthalpy change (H0), and entropy change (S0). The mechanism works on the basis of physisorption, and the adsorption process was endothermic [19].

Orthophosphoric acid was used to turn pomegranate peel into activated carbon. Methylene Blue dye (MB) adsorption from an aqueous solution was done in batch mode. At pH 8, a dosage of 0.25 g/100 mL for 120 minutes of contact time resulted in excellent removal efficiency (above 92%). The Langmuir isotherm is preferred by MB dye molecules at the qmax value of 14.03 mg/g [17].

Table 3: The removal of dyes from aqueous solution using various agricultural low-cost adsorbents

Adsorbents	Adsorbates (Dyes)	Adsorption capacity (mg/g)	Reference
Date stones	cationic and anionic	3.1-7.1 mg.g-1)	[9]
Rice Husk	Methylene blue	476.2	[15]
Bamboo	Methylene blue	67.46	[20]
Lemongrass leaf	Methylene blue	342.9	[19]
Orange peel	Congo Red	11.919	[12]
Neem Leaves	Coomassie violet	39.64	[21]
Jackfruit peel	remazol brilliant blue R	196.05	[10]
Papaya Seeds	Procion Red	73.26	[6]
Banana peel and sugarcane bagasse	Eurozol Navy Blue	32.46, and 27.54	[11]
Garlic peel	Methylene blue	142.86	[13]
Coconut shell	Malachite green)	32.683	[22]

6. Adsorption Principles and Isotherm Models

The material upon whose surface the adsorption takes place is called an adsorbent. Most activated carbon is used as an adsorbent.

Adsorption Principles: The mass transfer and adsorption of a molecule from a liquid or gas onto a solid surface is the fundamental idea behind carbon adsorption. The process used to make activated carbon results in very porous carbon particles with a huge interior surface area. Metals, inorganic molecules, and organic molecules are all drawn to and retained by this porous structure. The following factors contribute to adsorption: i) the contamination is poorly soluble in the waste; ii) the contaminant has a stronger affinity for the carbon than for the trash; and iii) a combination of the two Granular activated carbon (GAC), which is utilized in packed beds, and powdered activated carbon are the two most widely employed carbon adsorption techniques. The activated carbon adsorption process is one of the most applied technologies for the removal of trace organic compounds from an aqueous solution.

Methodology: Batch Flow System: A certain amount of carbon is continually combined with a predetermined volume of wastewater in batch-type contact operation until the pollutant in that solution has been reduced to the required level. After that, the carbon is taken out and either disposed of or recycled for future use. Typically, these procedures are only able to treat a modest amount of wastewater.

Column Flow System: Because adsorption rates are based on the solute concentration in the solution being treated, this method seems to have a number of benefits over batch operation. The carbon is constantly in touch with a new solution in order for the column to function. It is possible to put the solid adsorbent at the top of the column and drain the wasted adsorbent from the bottom.

Adsorption Isotherm: The adsorption process is studied through graphs known as adsorption isotherm.

Freundlich Isotherm: A curve that connects the concentration of a solute on the surface of an adsorbent to the concentration of the solute in the liquid it comes into contact with is known as the Freundlich adsorption isotherm. The isothermal variation of adsorption of a quantity of gas adsorbed by unit mass of solid adsorbent with pressure was empirically stated in this work. The Freundlich Adsorption equation or Freundlich Adsorption Isotherm is the name given for this equation.

The Freundlich Adsorption Isotherm is mathematically expressed as;

$x/m = Kp^{1/n}$ $\log(x/m) = \log K + (1/n) \log p$ or

$x/m = K C^{1/n}$ -----------------(1)

It is also written as $\log(x/m) = \log K + (1/n) \log C$ ----------(2)

Where, x = mass of adsorbate

m = mass of adsorbent

p = Equilibrium pressure of the adsorbate

C = Equilibrium concentration of adsorbate in solution.

K and n are constants for a given adsorbate and adsorbent at a particular temperature.

The amount of adsorption is independent of pressure at high pressure since 1/n = 0, but it becomes dependent on pressure at high pressure. The Freundlich adsorption isotherm has some drawbacks. In an experiment called Langmuir Isotherm, Irving Langmuir released a new model [23]. The Freundlich adsorption isotherm has some drawbacks. He kept the word "isotherm" for gases adsorbed on solids. A suggested kinetic process is the source of this semi-empirical isotherm between the gas phase and the surface, it adsorbs.

The novel model isotherm for gases adsorbed to solids, published by Irving Langmuir was named after him. A suggested kinetic process is the source of this semi-empirical isotherm. It forms a monolayer: adsorbate molecules only deposit on the adsorbent's free surface, not on other adsorbate molecules that have previously been adsorbed. Langmuir developed an equation based on his theory that clarified the connection between pressure and the quantity of active sites on the surface that are undergoing adsorption.

$\theta = KP/1+KP$ --------------(3)

Where,

θ- the number of sites on the surface that are covered with a gaseous molecule,

P - pressure and K - is the equilibrium constant for the distribution of and importance of adsorption and related domains in nature [23, 24].

7. Factors Affecting Adsorption Efficiency

The adsorption of dye can be influenced by variables such as pH, starting dye concentration, contact duration, and adsorbent dose. Here, we address these operational parameter parameters that have an impact on the adsorption process as reported by different studies.

7.1 Effect of pH

Because of the exchange inside the ionization stage and the adsorbents' surface price, a change in pH affects the reaction between dye molecules and adsorbents. The presence of various types of salts (primary and acidic) may also affect the dye effluent's pH.

For instance, how the initial pH affects the MB adsorption equilibrium when employing date stone activated carbon [9]. Variations in pH had an impact on how much dye was removed by activated carbon. Even though the dye removal percentage for ionic dye adsorption increases at low pH, the dye elimination percentage for cationic dye often decreases.

7.2 Effect of adsorbent dose

One of the most important factors in determining the adsorbent's capacity to absorb a specific amount of adsorbate in operational conditions is the adsorbent dosage. An increase in dosage often results in more active sites, which raises the adsorption capacity. A large dosage has an impact on treatment economy and is strongly correlated with the quantity of active sites on the adsorbent's surface. A large dosage, however, congests active areas. For instance, when the amount of the biosorbent was raised from 0.15 to 0.25 g/100 mL, the removal percentage rose from 93.38% to 95.70% utilizing activated carbon from pomegranate peel [17].

7.3 Effect of initial concentration

The initial dye concentration of effluent is one of the crucial criteria to be examined since a certain amount of sorbent material can only adsorb a set quantity of dye. Shaken adsorbent-adsorbate till equilibrium condition may be used to obtain the effect of varying starting dye concentrations over varying time periods utilizing fixed adsorbent dose [19].

7.4 Effect of temperature

The endothermic character of reactions is shown by the adsorption potential increasing with temperature, whereas the exothermic nature of processes is suggested by a reduction in adsorption capacity increasing with temperature. A rise in temperature improves the adsorption capacity in the fashion industry, but a greater temperature is unacceptable. For example. When the solution's temperature was raised from 303 to 323 K, the adsorption capacity rose from 82.64 to 142.86 mg/g, suggesting that the process of batch adsorption of methylene blue from aqueous solution using garlic peel as an adsorbent is endothermic [13].

7.5 Effect of reaction time

It is the amount of time when the adsorbent and adsorbate are in contact. As contact duration increases, adsorbent and dye molecules' active sites are created. The economics of the treatment procedures is impacted by high reaction times since they raise energy needs. with example, the amount of dye (BR29) adsorbed over time at various beginning concentrations using neem leaf activated carbon with an initial dye concentration of 50 mg/L and pH of 8.54 [21].

8. Summary and future scope

In the future, the textile industry's sustainable wastewater management might be completely transformed by including adsorbents made from agro-waste into textile effluent treatment. These inexpensive, renewable resources, which are converted into high-performance activated carbon, show remarkable dye removal effectiveness under a range of operating circumstances, providing a reliable and environmentally responsible substitute for traditional adsorbents.

Valorising agricultural residues for pollutant adsorption is in line with global sustainability goals as sectors transition to circular economy models, reducing waste production while optimizing resource use and cost-effectiveness. It is anticipated that future developments will concentrate on expanding these adsorption systems, refining regeneration methods, and carrying out thorough techno-economic and life cycle analyses to guarantee their feasibility on an industrial scale. Agro-waste-based adsorption technologies have the potential to be a key component in reaching zero liquid discharge targets and promoting cleaner, more environmentally friendly textile production methods globally, provided that they get ongoing innovation and regulatory support. In addition to protecting water supplies, this paradigm change will turn agricultural waste into useful resources for environmental cleanup, propelling industry toward a more resilient and sustainable future.

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Quantitative Evaluation of Smart Textile Adoption in Rural Weaving Communities using Machine Learning

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Abstract:

It is a socio-economic study examining how the inclusion of smart textiles can benefit rural weaving communities in India, and provides an investigation using a machine learning-assisted quantitative method. Based on knowledge in the domain of textile technologies, fiber science, processing, and the inventions of digital fabrics, the study focuses on the outcomes obtained after being exposed to newer tools including the smart fibers, computer-aided design systems and ergonomic working stations, and their impacts on income, productivity, employment structure as well as health. Structured surveys of 200 of the rural weavers in Chanderi, Salem, and Kutch were administered to collect data and were analyzed using descriptive statistics, regression modeling, K-means clustering, and decision tree algorithms. The findings show that there exists a great positive correlation between socio-economic improvement and the adoption of smart textiles. To be more precise, the training on garment technology and exposure to digital tools have proved to be important predictors of increased productivity and earnings. Cluster analysis validated the stratificational socio-economic positioning on the basis of technology access, but the favorable ergonomic differences and fewer sick leaves by smart textiles users were an indication of the health dividend. Moreover, the work changed into formal and more organized jobs representing the improved economic stability. The results highlight how inclusive development in the rural textile industry could be fuelled by such focus to promote investments in smart textile training and infrastructure.

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

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1. Introduction

The convergence of technology and tradition has opened new avenues in the textile sector, especially through the integration of smart textiles [1]. In recent years, the global textile industry has witnessed a paradigm shift with the advent of smart textiles fabrics embedded with digital components such as sensors, actuators, and conductive threads that provide enhanced functionality beyond conventional materials [2]. While urban markets have adopted these innovations rapidly, rural weaving communities, which form the backbone of many traditional textile economies, are only beginning to experience the socio-economic ripple effects of such advancements [3]. This research investigates how the inclusion of smart textiles into rural handloom practices is transforming the socio-economic landscape of artisan communities and what predictive insights can be drawn using machine learning.

A. Traditional Weaving in Rural Economies: Context and Challenges

Natural communities in such countries as India, Bangladesh, and some of the regions in Southeast Asia have traditionally relied on handlooms and primitive mechanized weaving to earn their income. Such communities are usually described by intergenerational expertise and local arts, which help to uphold heritage and local economy. But the industry has been battling with several obstacles- including no access to the market, poor payment, no intervention of technological tools, and no interest of young generation [4]. As the idea of globalization and mechanization is gaining pace, the economic viability of the rural weavers has been put under pressure. The traditional weaving habits can no longer survive the industrial production concerning productivity, customization, and the innovation based on demand. Therefore, unless they are seriously intervened, these rural economies will be in danger of stagnating or collapsing [5]. Figure 1: This image captures a rural artisan engaged in traditional handloom weaving in Chanderi, Madhya Pradesh.

Figure 1: Traditional handloom weaving in rural India showcasing indigenous textile craftsmanship

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It reflects the cultural legacy and craftsmanship passed down through generations in India's textile villages. The figure represents the baseline weaving environment prior to smart textile integration. It highlights the manual intensity, lack of digital tools, and socio-economic limitations that the study aims to address through technological adoption.

B. Smart Textiles: A Technological Disruption with Socio-Economic Potential

Smart textiles have had the capacity of acting as a disruptive technology that may be used to revive the traditional industries by adding value, range of products, and new markets networks [6]. These smart fabrics have the ability to capture the environmental parameters, detect health conditions as well as the responsiveness of the fabric to stimuli such as pressure, or temperature [7]. These are gaining relevancy in areas of fashion, healthcare, defense and sports. To the rural weavers, more than that of having better products, the absorption of smart textile can mean a possible socio-economic revolution. Introduction of such technologies can result in earning more profits, gaining more skills, having more competitive positions in the market, and social mobility [8]. But it also poses serious concerns in access to knowledge, technological infrastructure, digital literacy and inclusive development. Figure 2, the image showcases a prototype of smart textile clothing embedded with electronic sensors. Such innovations demonstrate the blend of fabric with technology for improved functionality and wearable intelligence. This figure highlights the transformative potential of smart garments in rural weaving communities. By integrating digital components, these textiles enable higher-value products, better ergonomics, and access to new market segments, aligning with the study's emphasis on socio-economic up-liftment through innovation.

Figure 2: Smart Clothing Integration

C. Quantitative Assessment through Machine Learning: A Modern Evaluation Tool

Machine learning will present a sound quantitative platform to measure and forecast the effects of smart textile implements in rural areas [9]. Machine learning models may help to reveal patterns and correlations that may have been overlooked with the help of traditional statistical tools by evaluating extensive data sets that capture economic indicators, production measures, social characteristics, and technology adaptability. Such a measure is expected to enable policymakers and researchers to consider the subtle socio-economic changes, such as distribution of income, labor forms, gender empowerment, and community well-being [10]. The current research will therefore use machine learning to determine in an organized manner the way the smart textile technologies are transforming the rural weaving society with a particular focus on inclusivity of the socio-economic system and data-driven growth.

D. Research Objectives

The Research Objectives of the Study Are as Follows:

- To evaluate how smart textile technologies can help in raising the income and productivity level among the rural weavers.
- To compare the health and ergonomic results with reference to the fact of using digital tools and working stations with textile.
- To divide socio-economically based weavers on the effects of receiving textile innovations in their lives using clustering methods.
- To exam changes in patterns in employment due to integration of technologies in the practices of traditional weaving.

2. Review of Literature

The authors assessed elderly users' intention to adopt telemedicine via IoT-enabled devices in the Chicago Tri-State Region using the UTAUT2 model. Key factors included performance expectancy, effort expectancy, and facilitating conditions [11]. Though centered on healthcare, insights into user perception and contextual factors are also relevant to integrating smart textiles in rural areas. The authors conducted a thorough survey on intelligent systems applied to the COVID-19 prognosis, overseeing the state-of-the-art AI approaches and their suitability concerning addressing the issues related to the pandemic management [12]. Different machine learning and deep learning algorithms have been described in the study and made diagnosis and treatment protocols more accurate and efficient. Their project demonstrated the strength of AI to make real-time information inquiries and judgments, which justified the argument of implementing the same type of intelligent software to evaluate socio-economic effects in the communities that use textile production. The authors performed a systematic review of artificial intelligence and the circular economy applied to sustainability practices within the fashion and textile sectors [13]. Their results indicated how AI can be used to promote sustainable activities, minimize wastes, and streamline resource use throughout the textile supply chain. Not only was the review keen on the positive impact on the environment, but it also casually touched on the socio-economic perks that the stakeholders would accrue in case of a sustainable innovation enabled by smart technologies. The results aligned with the goal of integrating smart textiles into rural communities, highlighting AI's potential in promoting social inclusion and environmental sustainability. The authors explored culturally-adapted no-code machine learning tools for Nigerian high school students, showing improved participation and learning, emphasizing accessibility and customization key for smart textile adoption in rural areas [14]. In a fire risk management system using predictive ML models demonstrated how data-driven solutions can enhance safety, reinforcing ML's value in rural weaving for socio-economic development [15].

The authors compared Industry 4.0 and 5.0, noting that while both leverage AI and IoT, Industry 5.0 emphasizes human-centric, sustainable innovation [16]. Smart textiles exemplify this shift by blending advanced technology with traditional skills like handloom weaving. The lessons learnt in this research were useful in presenting the concept of integration of smart textiles as a futuristic innovation in line with other world trends in industry. The authors focused on application of quantitative methodologies to filter out new technologies in diverse industries and track them [17]. The paper concentrated on the application of bibliometric and patent data on a technological trend and innovation hotspot forecasting. This study was quite relevant in explaining how data-driven framework may be applied to identify emerging technologies at an early stage-which is important methodologically speaking in gauging emergent trends in the rural textile economies specifically with regard to smart textiles. The authors done a case study of the ecological effects of the railway infrastructure development in Belgrade-Novi Sad Corridor [18]. Although the study was more oriented toward environmental sustainability, a socio-economic aspect was used to study the impact that the development projects had on the local communities. Even though not explicitly connected to the textiles, the work of Roy emphasised the necessity of assessment of not only the ecological, but also the social consequences of technological and infrastructural conglomeration, which fit in the general picture of smart textile adoption in rural communities. The authors developed a hybrid ensemble model combining CNN and RNN to detect multimodal cotton plant diseases, effectively merging visual and contextual data [19]. This highlights the potential of intelligent systems in enhancing decision-making in traditional industries, including quality control in textile production. Similarly, presented a detailed survey on machine learning in biomass characterization and sustainable biorefinery processes, emphasizing AI's role in improving efficiency and sustainability—insights that support smart textile integration in rural weaving communities [20].

3. Research Methodology

The methodology used in evaluating the socio-economic implications of smart clothes in weaving communities residing in rural areas, especially the impact on income, productivity, and well-being due to innovations in various areas of textiles that include processing engineering, Textile Technology, fiber science, and digital innovations were documented. Quantitative measure was used and machine learning models were used to give an evaluation using patterns and classification of responses.

a. Research Design

The descriptive-analytical research design has been used, and the research concentrated on cross-sectional data based on structured surveys. The paper focuses on how the development in textile and other sectors like Textile Digitalization, Smart Fiber Materials, and Technical Textile Engineering has changed the weaving system. This involves testing of the available socio-economic change on the adoption of automated looms, smart wires and wearable fabric technologies that are based on Fiber and Material Science.

b. Study Area

The conducted research studied the situation in rural weaving centers where the traditional techniques continuously interjected with the innovation of Textile Manufacturing Engineering and Processing Engineering as follows:

- Chanderi (Madhya Pradesh) - famous in weaving of fabrics with recent training through smart fibers.
- Salem (Tamil Nadu) a semi-automated processing and digital textile printing centre.
- Kutch (Gujarat) combines invention in technical textile design with fiber-blend using local cooperative weavers.

c. Population and Sample

Rural weavers on the continuum of traditional to digitally-neighborhood-based weaving technologies design have been added to the target population. A stratified random sample of 200 respondents were picked to facilitate diversity of demographic characteristics and levels of skills. The sample is of the participants who have received some training in such aspects as:

- Smart Garment Technology in terms of, e.g., e-fabrics with sensors
- Mature Dyeing and Fiber Commencing
- Textile Designing with the use of CAD
- Processing Engineering of wrinkle free/ fire-retardant fabric

d. Data Collection Tools and Techniques

Primary and secondary data were used [21]. The key pieces of data were the structured questionnaire that was provided both in the local languages and covered such areas as:

- · Textile Digitalization & Smart Fabric Technologies exposure
- · The altered income/productivity with automated weaving tools

- Training in Clothing & Garment Technology modules
- Among secondary sources there were:
- Cooperative society of report on improvement in fiber processing
- Technical textile training data of NGOs

Population data points on governmental subsidies of smart weaving and adoption of engineering

This study's dataset comes from 200 people who filled out a standardised questionnaire including both Likert scale and categorical variables. Demographic information including age, gender, area, education level, and years of weaving experience are some of the main data categories [22]. Economic statistics collected include monthly revenue (recorded both before and after the implementation of smart textile technology), current job status, and average daily productivity assessed in units produced per day. The collection includes information about the use of smart fibres, the quantity and type of training modules completed [23], and the tools or machines used in weaving when it comes to technology exposure. We also obtained health-related statistics, focussing on how comfortable the machines were to use and how long people used them each day on average. Table 1 is a depiction of the relationship between textile innovations and demographic factors in each socio-economic indicator (income, productivity, health and employment). As an example, the monthly income is explored as related with the level of smart textile use and exposure to contemporary processing methods, whereas the ergonomic well-being is correlated with the innovations in the technology of clothes and the use of equipment. Targeted analysis and evidence based textile policy recommendations are supported through this mapping [24].

e. Research Variables

This table 1 shows the correspondence between dependent socio-economic outcomes and independent variables that are based on the field of textile technology and engineering.

Table 1: Mapping of Research Variables with Textile Domain Concepts

Dependent Variables	Independent Variables
Monthly Income	Smart Textile Adoption, Processing Engineering exposure
Daily Productivity	Fiber Type Used, Training in Digital Textile Manufacturing
Health & Ergonomic Wellbeing	Machine Use Time, Ergonomic Smart Workstations (Clothing Technology)
Employment Status	Level of Technical Textile Integration, Region, Age, Gender

f. Statistical and Machine Learning Techniques

ANOVA Paired t- Tests and Descriptive Statistics were used in assessing differences in means of productivity and income [25]. To capture textile engineering:

Linear regression forecasted the changes on the basis of:

- Improved exposure to Fiber Science-based training
- Digital weaving novelty

The K-means clustering assisted in grouping of weavers by:

- Right to Textile Manufacturing Engineering
- Smart yarns and wearable tech productivity of Smart yarns and wearable tech productivity

Determinants measured using Decision Trees were:

- Garment Technology training
- the use of ergonomic workstations

Formulae Applied

Percentage Change in Income

$$\boldsymbol{Income\ Change}\ (\%) = \left(\frac{\boldsymbol{Post - Income - pre - Income}}{\boldsymbol{pre - Income}}\right) \text{x}\ \mathbf{100}$$

Productivity Index (PI)

$$\boldsymbol{PI} = \frac{\boldsymbol{Units\ Produced}}{\boldsymbol{Working\ Hours}}$$

Linear Regression Model

$$\boldsymbol{Y = \beta_0 + \beta_1 X_1 + \beta_2\, \text{X}\, 2 + \beta_3 X_3 + \in}$$

Where:

Y: Predicted income

X_1: Training Level

X_2: Productivity

X_3: Smart Textile Exposure

$\in$: Error Term

The table 2 below presents the machine learning models used in this research, their respective purpose, some of the input characteristics of the problem based on the textile industries, and the anticipated output of the models based on socio-economic outcomes [26].

As indicated in table 2, linear regression, clustering, and decision tree models are being used in analyzing and predicting principal socio-economic parameters affected by textile innovations. The findings are expressed in terms of linear regression of income being estimated with respect to smart textile-related aspects and segmenting the respondents in terms of socio-economic cadres through K-means clustering and current aspects of productivity (such as ergonomic conditions and knowledge of processing) as the primary determinants identified through decision trees in data-driven importance of textile domain variables in the contexts of productive insights.

Table 2: Machine Learning Models and Purpose (Expanded for textile relevance)

Model	Purpose	Input Features	Output
Linear Regression	Predict income from textile innovations	Smart Textile Training, Fiber Type, Machinery Use	Monthly Income
K-Means Clustering	Segment socio-economic impact groups	Ergonomics, Tech Exposure, Fiber Material Used, Weaving Hours	Cluster Group (Low/Med/High)
Decision Tree	Identify productivity determinants	Age, Gender, Smart Fiber Use, Ergonomic Setups, Processing Knowledge	Productivity Category

g. Integration of Key Textile Concepts

This analysis combines various aspects of textile and allied fields very well. Textile Technology is reflected as the use of weaving aids, as well as, CAD be based design systems by weavers. The Dye, finishing and post- weaving treatment practices portray Processing Engineering. Fiber and Material Science are explored, which involves smart fibers, blending of yarns and use of nanocoating materials. Technical Textile Technology The need to take care of specialized applications like health, defense among others is taken care of by the creation of fabrics used to cater to these applications. Clothing and Garment Technology is also considered as carrying out ergonomic testing with regard to tailoring and assembly procedures. Textile Digitalization and Innovation is experienced during the exposure of digital looms, sensor thread, and computer aided pattern making. Finally, the Textile Manufacturing Engineering is measured in terms of switching to automated looms, accuracy cutting systems, and smart packaging solutions.

h. Validity and Reliability

To achieve rigor of the method, pilot testing was done among 20 representatives of the other regions resulting in refining the questionnaire with such domain vocabulary as digital yarn systems. The instrument also showed good internal consistency because there was a Cronbach Alpha of 0.81. Interquartile range (IQR) technique was used to clean the data to accommodate outliers especially in the data of income and productivity of respondents working in the advanced processing engineering.

4. Result and Discussion

The analytical results of 200 rural weavers are given based on special statistical and machine learning methods that can comprehend the socio- economic effects of smart textile adoption.

i. Descriptive Statistics of Socio-Economic Variables

This table 3 shows the summary statistics of the key socio-economic variables such as income, productivity, use of machines, ergonomic conditions of rural weavers engaged in the practises of smart textile.

Table 3: Descriptive Statistics of Key Socio-Economic Variables

Variable	Mean	SD	Min	Max
Monthly Income (Rs.)	11,400	3,250	4,500	21,000
Daily Productivity (units)	38.2	11.1	12	72
Machine Use Time (hrs)	5.4	1.6	1.5	8.0
Ergonomic Work Rating (1–5)	3.9	0.8	2.0	5.0

The high variation of 4,500 to 21,000 per month with a mean 11.400 implies that the income depends highly on technical ability and applications. The overall rate of productivity is good (38.2 units / day) and the amount of time using the machines is moderate (5.4 hrs), which can be deemed as an efficient working routine of the majority of the respondents. The 3.9 ergonomics work rating suggests that there are favorable working environments, generally speaking, that could be enhanced with the help of smart clothing technologies and ergonomic solutions.

j. Regression Analysis: Predicting Income Through Textile Exposure

The given table 4 presents the outcomes of a multiple linear regression model predicting monthly income with regard to the factors of the exposure to smart textiles and productivity, as well as training level, among rural weavers.

Table 4: Regression Coefficients for Income Prediction

Predictor	Unstandard-ized B	Std. Error	t-value	p-value
Constant	4,700	550	8.55	0.000 ***
Smart Textile Exposure	1,820	300	6.07	0.000 ***
Productivity	75	20	3.75	0.002 **
Training Level	980	230	4.26	0.001 **

$R^2 = 0.62$, $F(3,196) = 31.45$, $p < 0.001$

Regarding the regression analysis, it appears that the strongest predictor of monthly income is smart textile exposure (B = 1,820, $p < 0.001$), followed by the level of training and productivity. The model also has a significant predictive value since it accounts 62 percent of the variance in income. All predictors are statistically significant and this confirms that introduction of smart textile innovations and skills development is an essential contribution to the improvement of economic performances of rural artisans.

k. Cluster Analysis: Socio-Economic Segmentation by Technological Integration

This table 5, they exhibit the socio-economic division of rural weavers into three groups based on the integrative stage of the textile activities practiced in those stages.

Cluster	Description	Avg. Income (?)	Product-ivity	Tech Exposure
C1	Low-tech Traditional Weavers	6,200	21 units	Minimal
C2	Mid-tech Semi-digital Practitioners	10,500	34 units	Moderate
C3	High-tech Smart Textile Adopters	16,800	51 units	High

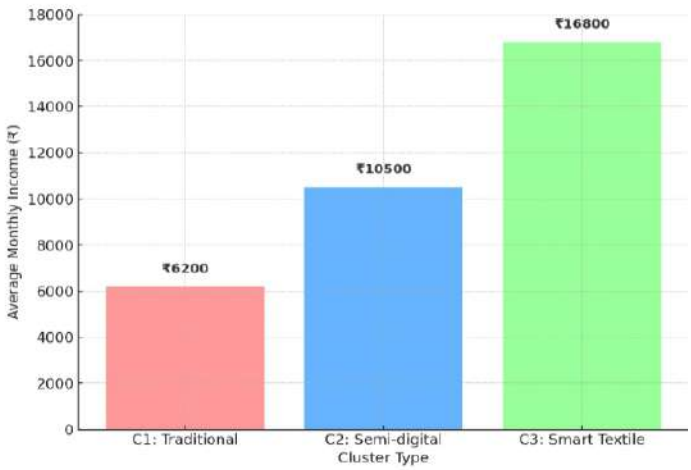

Figure 3: Average Monthly Income by Cluster

Economic inequality is very much on the same line with access to innovation where Cluster 3 (smart adopters) does better than the rest. Cluster analysis indicates the existence of a sharp gradient between economic and productivity outcomes compiled on technology accessibility. The income and output are the least among the traditional weavers (C1) but those who are adopting smart textile (C3) are far ahead of others with an average income of 16, 800 and 51 units of daily productivity. The findings put into outlook the life-changing power of digital textile inventions and intelligent machinery in rural lifestyles that call upon specific technology adoption schemes.

l. Ergonomic and Health Outcomes by Technological Usage

This table 6 compares ergonomic comfort, health ratings, and sick leave frequency among weavers using varying levels of textile technology.

Table 6: Comparative Health and Ergonomic Index by Technology Exposure

Group	Avg. Ergonomic Score (1–5)	Self-Reported Health (1–10)	Avg. Sick Days/Month
Traditional Weavers (Manual)	2.9	5.2	4.3
Semi-Digital (Processing Tools)	3.7	6.9	2.6
Smart Textile Users (CAD, e-Fibers)	4.5	8.3	1.2

With the rampant use of technology, there was a lot of improvement in the ergonomic satisfaction and health outcomes. The smart textile users had the best ergonomic rating (4.5), health rating (8.3), and the least number of sick days (1.2 days a month) on average. This shows how the measurement of physical well-being in any given weaving community has improved as a result of embracing CAD systems, wearable-technologies, and ergonomic workstations.

m. Decision Tree Analysis: Predicting Productivity Levels

To find the most influential factors determining the productivity of rural weavers on a daily basis, a Classification and Regression Tree (CART) model was drawn. The dependent variable, productivity, was divided into three categories, namely low, medium, and high; this was determined by the number of units that a company produces in a day. These independent variables were:

- Garment technology training,
- Smart or blended fibers usage

Availability of ergonomic working arrangements, Age, and Ensuring understanding of processing engineering methods. An analysis under the decision tree displayed that formal training on garment technology was the most vital predictor of productivity. The participants who were those ones who had received organized trainings on garment assembly, handling of textiles or even learning automated tailoring methods had significantly higher chances of falling in the high-productivity bracket. It was particularly so in case when this training was combined with the smart textile materials as mixed yarns or sensor embedded fibers. The second fork revealed that fiber type and availability of ergonomic workstations were important in the model. Skilled weavers who could make use of newer fiber materials and work in ergonomically adjusted workplace (with upgrades such as adjustable loom, good light, and rests to support the feet) could easily exceed a production output of 50 units of fiber per day. On the contrary, the ones without such advantages were likely to be at the low to medium range of productivity. Interestingly, although demographic variables (such as age and gender) were milled into the model, their variance contributions in terms of productivity were insignificant. This implies that technical exposure and the design of work environment is much more determinant than the traditional demographic factors that predict weaving output.

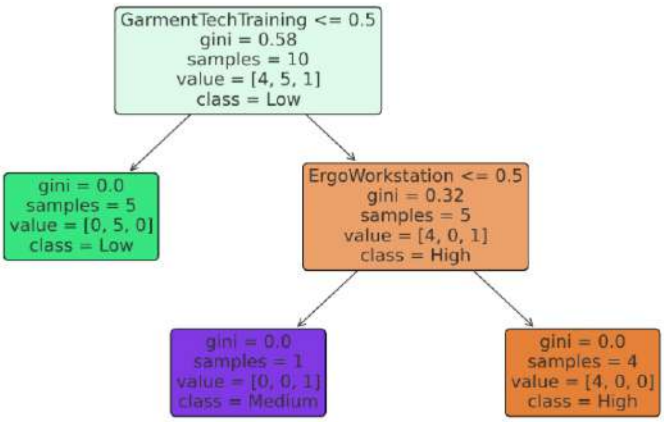

Figure 4: Decision Tree Model for Productivity Classification

The decision tree model shows the technology training related to garment as the most critical influence to the productivity of weavers in the rural areas, while the use of smart fiber and the availability of the workstations that have ergonomics come as the next in rank among the factors. The implications of these findings reiterate focus skills development and innovation in the workplace as strategic measures in improving performance in the rural textile communities.

n. Employment Pattern Shift

The comparison of the pre-and post-exposure to the smart textile technologies provides an analysis of a different form of employment towards somewhat more stable and cooperative-linked ones.

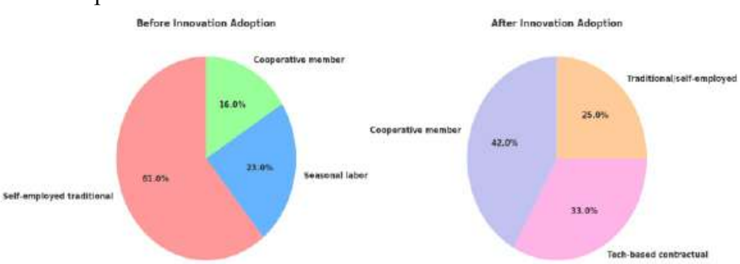

Figure 5: Employment Type Distribution Before and After Innovation Adoption

The shift from informal to structured/cooperative roles highlights the economic stabilization offered by technical textile engagement.

o. Discussion

The analyses are unanimous and demonstrate that the exposure to the modern textile engineering, the smart fibers and CAD tools is associated with:

- Increased income and increased productivity (verified through regression)
- Enhanced health and ergonomics (T6 supported)
- Upward employment mobility (as it is observed in the pie chart)
- Technological differentiation of socio-economic classes (through clustering)

Policy Implication: Weaving sector can be lifted substantially with investment in training infrastructure in textiles, ergonomic work stations and subsidized smart tools. The economic and health enhancements will be guaranteed because of strategic upskilling in garment processing and fiber science.

5. Conclusion

The research draws a conclusion that enforcement of smart textile technology, namely the digital garment tools, advanced fibre materials and the ergonomically designed home workstations, have a strong positive effect on the socio-economic position of the rural weavers. Regression, clustering and decision tree modelling results indicate a significant increase of income, productivity, physical health and employment security in weavers who have a training opportunity in understanding garment technology and exposure to knowledge of smart materials. Adoption of self-employed positions to non-employed (cooperative and contractors) is also an indication of structural advantage in technological adaptation. Higher ergonomic standards and less sick time among users of smart textiles are evidence of its health benefit of the modernized weaving rooms. In general, the evidence can prove that strategic investments in the textile training infrastructure, innovations in processing, and digital tools have the capacity to bring significant economic and professional changes to rural weaving communities.

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Digital Skilling of Textile Artisans: Designing Smartphone Interfaces for Low-Literate Users

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Abstract:

Textile artisans with limited literacy often face barriers in adopting digital skilling tools, restricting their participation in the evolving technological landscape of textile production. This study explores how smartphone interface design can be optimized through visual affordances to support low-literate users. Using a human-cantered design approach, the research involved ethnographic interviews, observational walkthroughs, and participatory co-design sessions with a Madhubani artisan from Maharashtra. Visual cues categorized as Discover, Look, and Go were analyzed and mapped within existing mobile interfaces to support task recognition, flow, and feedback. Key interface adaptations included the use of domain-specific iconography, minimal textual dependency, and consistent visual markers to enhance usability. These adaptations improved comprehension, engagement, and learning outcomes within digital skilling environments. The paper proposes a replicable design framework tailored for low-literate user groups in the textile sector, contributing to inclusive technology integration and skill-based economic resilience. Digital skilling empowers textile artisans by enhancing their access to markets, improving production efficiency, and fostering economic resilience in a rapidly digitizing industry.

Keywords: *artisan empowerment, digital skilling, inclusive interface, low-literate users, participatory design, visual affordance*

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1. Introduction

India's informal textile sector comprises over 7 million artisans, many of whom specialize in region-specific crafts such as Madhubani art and handloom weaving. Despite the rapid growth of mobile phone usage with rural mobile internet penetration crossing 37% in 2022, a significant portion of this population remains digitally excluded due to literacy-related barriers [1]. Government initiatives like Skill India, GeM, and ODOP aim to integrate artisans into mainstream markets and upskill them through mobile-first platforms. These platforms typically include mobile applications and web portals that offer access to training modules, product listing services, buyer-seller interactions, and digital payment systems. These schemes, while well-intentioned, often rely on text-heavy interfaces or English/Hindi-centric designs that are misaligned with the cognitive and linguistic realities of many rural users [2, 3 & 4].

While previous studies have explored digital access among rural populations, few have examined interface-level interactions from the standpoint of low-literate users especially within the fashion and textile artisan domain [5, 6]. This gap persists despite clear policy focus on digital inclusion and women-led entrepreneurship [6, 7 & 8]. Artisans increasingly rely on smartphones to source raw materials, follow craft tutorials, and connect with buyers. As a result, mobile interfaces have become a critical gateway to digital skilling and market participation. When artisans are unable to navigate digital tools independently, it leads to low adoption rates, poor learning retention, and missed opportunities for growth. The digital divide becomes a design divide, particularly for women artisans who may already face social mobility constraints [7, 9].

This study addresses a critical usability barrier in the design of mobile interfaces for low-literate artisans. This study draws on the Visual Interaction Cues Framework, originally developed to guide users through complex digital environments. It adapts the framework's core concepts to smartphone interface design [4]. The framework outlines how visual cues such as layout emphasis, directional markers, and attention anchors can guide navigation, focus, and task initiation. These visual strategies are integrated within a human-centered design approach. This alignment connects interface logic with real-world artisan workflows and proposes practical alternatives for textile-focused digital ecosystems [3, 4]. The resulting visual framework-based interface model is intended for integration into skilling platforms that serve craft-based clusters. Additionally, the paper provides field-validated behavioral insights to support more inclusive UI/UX practices within textile technology applications [1, 9]. This paper bridges that gap and offer a tool for improving digital confidence, scalable interface strategy grounded in both visual affordance theory and artisan behaviour [1, 4].

2. Literature Review

The use of smartphones to support craft-based livelihoods has gained momentum in recent years, particularly within informal sectors such as textile production [5]. Mobile-based skilling platforms, digital marketplaces, and training applications have opened new avenues for artisans to learn, promote, and commercialize their work. However, many

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low-literate artisans particularly women in rural settings these opportunities are constrained by persistent usability challenges.

2.1 Smartphone Usage among Low-literate Artisans

Low-literate individuals, in the context of this study, are those whose formal education levels range between Standard Four and Standard Eight in the Indian State education system [6]. This group often includes skilled informal laborers and craft workers who, while lacking formal education, display strong manual and visual expertise [7]. Within the textile sector, artisans increasingly depend on smartphones to source materials, follow tutorials, and engage with buyers. However, their mental models based on tactile learning, analog workflows, and visual pattern recognition are often misaligned with abstract, text-heavy interface designs [2, 3]. This mismatch leads to low technology adoption, frequent task abandonment, and a lack of confidence in digital environments. Thus, the core challenge shifts from access to usability requiring visually intuitive, domain-specific, and cognitively lightweight design.

For the purpose of this study, the term low-literate users encompass two distinct groups:

- Low-literate individuals : Users who face difficulty reading, writing, and understanding short digital messages or instructions.
- Artisans : Skilled craftspeople engaged in traditional trades, often producing handcrafted goods using heritage techniques. Despite their expertise, many artisans struggle with digital literacy, particularly in interpreting abstract icons, navigating app hierarchies, and completing multi-step tasks.

In India, the Digital Empowerment Foundation [8] highlights how platforms like Skill India and GeM assume proficiency in Hindi or English, however users face challenges in changing language to their local language. Visual Cues are colour cues, shape cues and spatial cues, help in deeper understanding of how users learn and encode them. This includes ensuring the visibility of affordances, providing clear conceptual models, establishing natural mappings, and offering feedback for actions involving these elements. Visual cues help people understand and navigate technology in their everyday lives [9].

2.2 Visual Interaction Cues Framework (Adapted from Dillman's Framework [10]

This framework was originally proposed by as proposed by Dillman, Mok, Tang, Oehlberg, and Mitchell [10] in the context of video game environments and augmented reality. It systematically categorizes visual cues to support new users in navigating complex digital interfaces. Although designed for gaming, its emphasis on visual affordance and cue-based guidance makes it highly relevant for low-literate users in mobile-based skilling platforms. To analyze and structure visual interface design for low-literate users, this study applies a visual interaction framework that categorizes cues across three dimensions: Task / Purpose, Markedness(Visual Affordance), and Trigger. This structured approach enables a deeper understanding of how interface elements influence user behavior and comprehension, particularly in low-literacy contexts. The current study adapts this framework to the context of textile artisans based on a literature review and field observations. Prior research has emphasized that low-literate users prefer visual interfaces over text-heavy designs, and that visual affordances such as color, size, and alignment significantly improve usability and task performance [11, 6 & 12].

2.2.1 Dimension 1: Task / Purpose

This dimension relates visual cues to user intent.

- Discover cues enable users to identify interactive elements, such as pulsating buttons or highlighted sections.
- Look cues draw sustained attention to critical areas through color contrast, animation, or motion.
- Go cues support task execution and flow, including directional arrows, breadcrumb trails, or progress indicators.

2.2.2 Dimension 2: Markedness

Markedness refers to the visual salience or prominence of interface cues.

- Subtle cues are softly integrated (e.g., notification dots) without breaking interface harmony.
- Emphasized cues use shadows, outlines, or color intensity to stand out.
- Integrated cues are embedded within existing elements (e.g., profile pictures in chat bubbles).
- Overlaid cues are layered above the interface (e.g., popups, tooltips, or banners).

2.2.3 Dimension 3: Trigger

This dimension classifies how cues are activated or surfaced.

- User-Triggered cues appear upon user interaction (e.g., tapping a thumbnail).
- Context-Triggered cues emerge based on environmental or behavioural context (e.g., location-based alerts).
- Agent-Triggered cues are system-driven responses, such as status messages or error prompts.
- Persistent cues are always visible to ensure ongoing guidance (e.g., sticky icons or top-bar menus).

This framework is particularly useful for evaluating mobile UI experiences for low-literate users, as it emphasizes visual comprehension over textual literacy and aligns closely with the workflows of non-traditional digital users such as rural artisans. The framework's three dimensions Task/Purpose, Markedness, and Trigger were refined through field engagement and expert feedback, and their application is elaborated in the Methodology section.

3. Methodology

This study employed a human-centered design methodology using a qualitative case study approach. The research focused on a single artisan participant, Ranjana Chaudhary a Madhubani artist and community art trainer based in Palghar district, Maharashtra. Fieldwork was conducted between January and March 2024 in her semi-urban artisan cluster. While the study centered on Ranjana and her learners, this choice was intentional to allow for deep contextual immersion and iterative design feedback. Ranjana was selected through purposive sampling due to her active engagement in traditional textile arts and her representative digital experience. A supplementary group of ten artisan learners attending her community-based training sessions provided comparative insights across experience levels. The findings are not intended to be generalized across all Indian textile arts but rather to inform design principles for similar low-literacy artisan contexts.

A three-phase iterative design process was adopted.

- Phase 1 – Contextual Inquiry: Ethnographic interviews and observational studies were conducted to understand Ranjana's digital behavior, mental models, and interface challenges.
- Phase 2 – Co-Design Exploration: Participatory workshops were organized to explore visual cue preferences using card sorting and prototype walkthroughs with 10 artisans.

The study focused on how visual affordances icons, layout, color, and image metaphors can support task navigation for users with limited literacy. Ranjana, who occasionally receives orders via WhatsApp but has minimal exposure to structured digital skilling platforms, was selected through purposive sampling for her active involvement in traditional textile arts and her representative digital experience.

In addition to the core case study, the research included a supplementary session with ten artisan learners (Fig. 1, center), who attend Ranjana's community-based training classes. This extended participant group provided comparative insights on interface predictability and cue interpretation across experience levels

The integration of field-based observations, visual feedback, and cue testing provided rich qualitative data for analyzing how low-literate artisans interact with mobile interfaces in the context of textile training and production.

3.1 Data Collection Methods

Three qualitative methods were used to gather insights from the participants:

- Ethnographic Interviews: Conducted in Hindi and Marathi over five sessions, these interviews explored Ranjana Chaudhary's daily routines, her perceptions of smartphone-based platforms, and past experiences with digital self-skilling attempts.
- Participatory Design Exercises: Structured design workshops with 10 artisans including Ranjana Chaudhary were held in two iterative loops, including:
- Visual Cue Reviews: Stimuli boards were prepared using a mix of realistic images, hand-drawn illustrations, and clipart styles. These were printed and laminated for tactile interaction during workshops
- WhatsApp-Based Interface Analysis: Sample conversations involving order placement, image sharing, and payment queries were used to observe icon recognition and action predictability.
- YouTube Tutorials: Commonly accessed videos such as “Madhubani Art for Beginners” and “Handmade Textile Techniques” were used to study navigation behavior and cue interpretation. These were selected based on participant recall and viewing history.

Each activity was repeated with feedback validation to finalize the participant's preferences on navigation flow, visual structure, and interface clarity. All activities were documented through field notes, audio recordings, and photo captures. Observations were systematically categorized using the Visual Interaction Cues Framework by Dillman, Mok, Tang, Oehlberg, and Mitchell [10] and validated through participant feedback loops.

Figure 1: Left: Ranjana Chaudhary, Madhubani artist and art trainer. Centre: Artisan student showcasing artwork.

3.2 Ethical Considerations

Informed verbal consent was obtained prior to all field sessions. The participant was briefed on the research purpose and data usage. All recordings and photographs were made with explicit permission. Participation was scheduled around her professional hours, and all data were anonymized for publication. Identity disclosure, where applicable, was included only with written consent.

4. Results

The findings from this case study are organized into three thematic clusters derived from the Visual Interaction Cues Framework: Discover, Look, and Go. These themes capture how the participant, Ranjana Chaudhary a Madhubani artisan engaged with mobile-based applications, particularly WhatsApp and YouTube, in the context of skilling, content access, and task navigation. The analysis is based on observational sessions, co-design exercises, and post-task interviews.

4.1 Visual Cue Reviews: Style and Predictability

To evaluate how different graphic styles influence visual recognition and navigational accuracy, a card-sorting activity was conducted with 10 artisans, including Ranjana Chaudhary. Visual elements were grouped into three categories real-life photographs (Figure 1), clipart illustrations (Figure 2), and black-and-white abstract icons (Figure 3) each depicting textile-related tasks such as stocking, sourcing, and selling.

The purpose of this comparison was to assess which style of visual representation was most effective and accurate for low-literate artisan users, rather than to compare identical content. While the visual styles were standardized to represent similar tasks, some inconsistencies in contextual relevance were noted. For example, the photograph depicted a saree store, the clipart showed a modern apparel outlet, and the icon resembled a fruit shop. These mismatches were acknowledged during participant feedback and are considered a limitation in stimuli design. However, the comparative exercise successfully revealed that real-life photographs consistently enabled clearer recognition, emotional relevance, and task confidence, validating their superiority for UI design in artisan contexts.

Across participants, real-life photographs emerged as the most recognizable and confidently interpreted. Images showing fabric stacks, stitched materials, or close-up work (e.g., hands embroidering) were quickly associated with known tasks from their daily practice. One artisan remarked that "pictures with people doing the work help me understand what to press." Clipart illustrations, while visually distinct, often led to partial or incorrect interpretations. Retail storefronts were sometimes understood, but abstract characters or generic scenes such as a suited figure holding papers were misinterpreted as unrelated actions like "school admissions" or "bank work." Black-and-white abstract icons were consistently the least effective. Icons representing stalls, warehouses, or interactions lacked emotional

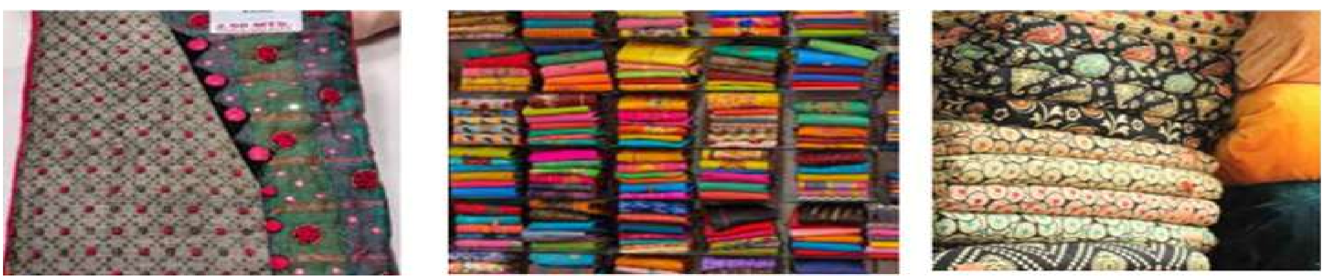

Figure 1: Real-life

Figure 2: Clipart illustrations

Figure 3: Black-and-white abstract icons

relevance and were frequently ignored or misunderstood. As one participant noted, "flat pictures don't tell me what is happening."

Quantitative Support: Among the 10 artisan participants:

- · 9 preferred real-life photographs
- · 6 partially understood clipart illustrations
- · All 10 misinterpreted or ignored abstract icons

These findings confirmed that predictability and interpretability in UI visuals increase significantly when images are grounded in real-world, domain-specific context. To ensure contextual validity, all tested elements drew from familiar textile metaphors tailoring tools, artisan workflows, and WhatsApp interactions previously identified as highly intuitive by the artisan participants. For users operating in hands-on, visually grounded environments like textile craft, realism not abstraction is critical for clarity, confidence, and task completion.

4.2 WhatsApp-Mapped Visual Affordance Framework

Following the card-sorting activity, participants engaged in an interface walkthrough using WhatsApp, identified as the most familiar and frequently used application among all 10 artisan participants. This exercise involved mapping interface elements such as icons, screen layouts, and interaction flows, against a structured visual interaction framework. The goal was to assess how users respond to real-world mobile navigation, focusing on how visual cues support comprehension and task execution in low-literacy contexts.

Task-Purpose Dimension

Visual cues were observed in relation to three dominant user purposes:

- Discover Cues: Participants relied more on color, shape, and spatial position than textual labels to identify clickable elements. Familiar indicators, like the double tick mark for message delivery, were consistently recognized across all users. Highlighted sections within the interface played a key role in helping participants distinguish categories and understand functionality, especially in visually complex layouts [13].

- Look Cues: Real-time animations (e.g., "typing…" indicators) and high-contrast visuals maintained user attention and signalled interaction continuity. These cues were most effective when supported by consistent visual patterns and emotional relevance. These mirrored real-time feedback such as changing red prompts, and animated overlays were used to warn users of high-risk events [14].

- Go Cues: Directional symbols like green call buttons or paper plane icons enabled task execution due to their metaphorical familiarity. However, unfamiliar or ambiguous icons introduced hesitation. Prior studies support this by advocating breadcrumb trails, tick marks, and visual confirmations to boost confidence during action-taking.

- These observed patterns reinforce the idea that purpose-driven visual cues play a critical role in enhancing navigation clarity and supporting user decision-making. By aligning interface elements with user intent, designers can create more intuitive and accessible digital experiences, particularly for audiences with limited literacy.

Markedness Dimension

Visual cues were further categorized by their importance:

- Subtle Cues: WhatsApp's small notification dots served as gentle indicators of unread messages, similar to softly glowing markers in language-learning apps. For instance, a soft-glow icon next to new vocabulary words to signal review actions without disrupting interface consistency [15].

- Emphasized Cues: Red alert badges for missed calls or messages were highly effective in capturing user attention. Similarly, the use of bold outlines around active icons within task sequences helped guide focus and support decision-making, demonstrating how visual emphasis can enhance interface usability [16].

- Integrated Cues: Embedded elements, such as profile images within chat threads, supported user recognition.

- Overlaid Cues: Features like call banners or popups prompted time-sensitive responses. These layered visuals proved successful in enhancing task urgency and preventing missed actions.

Among these, integrated and Overlaid cues not explored while designing UI for low-literate users.

Trigger/Action Dimension

Cues were examined for how they were activated:

- User-Triggered: Actions like tapping on WhatsApp statuses or YouTube thumbnails showed that participants were most comfortable with direct, touch-based interaction. These cues reinforced user confidence and task independence.

- Context-Triggered, Agent-Triggered, and Persistent Cues: These were either minimally used or rarely noticed by participants. System-generated prompts, time-based triggers, or static icons did not significantly influence user behavior indicating limited engagement with non-direct cues in current usage patterns.

User-triggered cues such as tapping on WhatsApp statuses or YouTube thumbnails emerged as the most effective interaction pattern. Research confirms that tap-based interactions, especially when coupled with simplified screens and familiar icons, enhance accessibility for low-literate users [2]. In contrast, context-triggered, agent-triggered, and persistent cues were relatively underutilized in mainstream applications, despite their potential to provide timely guidance and reduce user errors. Broader integration of these cues could substantially support digital independence among low-literate populations.

These findings align with existing insights in human-computer interaction, highlighting the importance of inclusive design cues in guiding user attention within complex interfaces [17]. Emphasizing visual elements during the discovery phase, such as breadcrumb trails, culturally familiar icons, and responsive feedback has been shown to significantly improve navigation for non-literate users [3, 13]. Additionally, visual indicators like color-coded arrows in mobile financial tools can effectively replace textual instructions for semi-literate audiences [13]. Cues such as "Look" and "Go" have also been found to encourage independent action among low-literate users in digital advisory platforms [18].

Unlike previous work that isolates visual interventions to specific screens or functions, this study integrates cue-based design across the complete task flow. It demonstrates that domain-relevant and context-specific visuals especially photographs and tactile metaphors are not only more intuitive but also essential for task execution and trust-building among low-literate textile artisans.

5. Discussion

Field-Validating Visual Affordances in Textile Technology
This study applies a visual interaction framework within a real-world textile skilling context, moving beyond theoretical exploration through direct field validation. The use of domain-relevant visuals such as tailoring tools, process-based photographs, and WhatsApp interface elements grounds the interface design in practical, artisan-centered use cases. The integration of domain-relevant visuals such as textile tools, craft photographs, and WhatsApp-based interaction mapping anchors the interface model in real-world use cases. Furthermore, the combined ethnography and co-design methodology enhances both contextual relevance and transferability. By aligning findings with visual affordance theory, the study contributes replicable design insights for inclusive textile skilling platforms. The combination of ethnographic fieldwork and co-design workshops provided deep contextual insights while allowing for iterative testing. These findings not only reinforce visual affordance theory but also demonstrate replicability for interface design in other textile skilling contexts. While the findings reinforce visual affordance theory, the practical application and replication of these insights require clearer task-level recommendations. To address this, future work will detail specific UI actions such as image forwarding, group management, and location sharing that artisans perform on smartphones, along with corresponding visual design strategies.

6. Conclusion

This study investigated how low-literate textile artisans interact with smartphone interfaces, specifically WhatsApp, to evaluate the role of visual affordances in digital navigation. By applying a structured visual interaction framework, the research examined how the function, prominence, and activation of visual cues influence user engagement and comprehension. Field-based participatory co-design revealed that domain-specific visuals such as realistic photographs and metaphor-driven icons significantly enhance task orientation and user confidence. Emphasized and spatially consistent cues were found to support intuitive navigation, while persistent and context-sensitive triggers improved usability and learning in mobile skilling environments.

By grounding interface design in the behaviors and cognitive patterns of artisans, the study presents a replicable and technically sound framework for inclusive UI development in the textile sector. These findings contribute to more effective digital onboarding, self-skilling, and commercial participation among low-literate artisan communities, supporting broader goals of inclusive growth within the Indian textile economy. Although this study focused on visual elements, it acknowledges that text and language options remain critical. Future iterations will explore the balance between visual and textual content, especially in multilingual contexts where English/Hindi-centric designs may not align with user realities.

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Woven Heritage: A Comparative Study of Design, Aesthetic, and Symbolism in Mughal and Persian Carpets

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Abstract:

Carpet weaving, an intricate and exquisite art form, has flourished over centuries, functioning as both a practical craft and a significant medium of cultural expression. The Persian and Mughal carpet-making traditions are among the most influential in textile design, each distinguished by artistic depth, technical mastery, and symbolic richness. This study examines how the Mughal Empire reinterpreted Persian carpet aesthetics, blending geometric precision with botanical realism to establish a distinct visual identity. The research explores motifs, color palettes, weaving techniques, and compositions through an analytical comparison of Persian and Mughal carpet designs. The research utilizes historical texts, archival records, and visual analysis. A comparative qualitative methodology is employed to assess design adaptations. Mughal carpets retained Persian symmetry while incorporating local elements, vibrant hues, and realism. Trade and diplomacy fostered cross-cultural exchanges, shaping their evolution and reinforcing both traditions' lasting impact on global textile heritage through adaptation and innovation

Keywords: Carpets, Design, Heritage, Motifs, Mughal, Persia

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1. Introduction

Carpet weaving, an intricate and sophisticated art form, has a rich and complex history that spans centuries and regions. It serves not only as a functional commodity but also as a fundamental medium of cultural expression. Two of the most esteemed carpet-making traditions that have significantly influenced this field of textile design originated from Persia and the Mughal Empire. Due to their distinct cultural and creative backgrounds, both civilizations are renowned for their mastery of design, techniques, and symbolism [1].

The roots of Persian carpets may be traced back to ancient civilizations. These carpets are known for their intricate geometric patterns, symmetrical designs, and brilliant color schemes, all containing profound symbolic meanings. It was during the Safavid era that the art of carpet weaving developed, and it was at this time, these carpets reached their maximum artistic potential [2]. Arabesques, floral medallions, and garden-inspired themes were some of the most common designs found on Persian carpets.

The Mughal Empire, on the other hand, which rose to prominence in India in the 16th century, was highly affected by Persian artistry, notably in the early phases of carpet manufacture. This was especially true in the early stages of carpet production. However, Mughal artists quickly established their distinctive style by combining Persian methods with local Indian aesthetics. This allowed them to create unique works of art. These carpets have intricate depictions of local flora and wildlife, such as blossoming plants, birds, animals, and geometric patterns inspired by Persian art [3].

These rulers deeply appreciated the arts and encouraged a vibrant cultural interchange between India and Persia. While scholars have extensively studied Persian carpets, the transformation of Mughal carpet design from its Persian origins remains an underexplored area of research. Understanding this evolution is significant for several reasons. First, it provides insights into the artistic adaptation and innovation that occurred within the Mughal Empire, demonstrating how Persian influences were absorbed, modified, and reinterpreted to suit local tastes. The fusion of Persian symmetry with Mughal realism and botanical naturalism represents a unique cultural synthesis that speaks to the empire's broader artistic and architectural achievements. Second, the study highlights the role of trade, diplomacy, and royal patronage in facilitating cross-cultural exchanges between Persia and the Indian subcontinent. The Mughal emperors, particularly Akbar, Jahangir, and Shah Jahan, played a crucial role in fostering this artistic exchange, commissioning carpets that blended Persian techniques with distinct Mughal aesthetics.

Furthermore, analyzing the evolution of Mughal carpets in comparison to Persian carpets contributes to a broader understanding of how textiles functioned as cultural artifacts. Carpets were not only luxury commodities but also symbols of power, status, and artistic excellence. Their designs reflected the social, religious, and aesthetic values of their respective cultures, making them valuable historical documents. By examining motifs, color schemes, weaving methods, materials, and pattern compositions, this research aims to uncover the nuanced transformations that occurred as Mughal artisans adapted Persian influences to develop a unique visual language.

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This study is particularly relevant in the context of global textile heritage. Persian and Mughal carpets continue to inspire contemporary textile design, and understanding their evolution offers valuable lessons in cross-cultural artistic exchange. By addressing this gap in research, this study seeks to contribute to the appreciation of carpet weaving as an evolving art form that transcends geographical and temporal boundaries, shaping both historical and modern design sensibilities.

1.1 Research Questions

Building on the existing literature, this study formulates the following key research questions:

i. What were the key similarities and differences between Persian and Mughal carpet designs in terms of motifs, color palettes, weaving techniques, and compositions?

ii. How did trade, diplomacy, and cultural exchanges between Persia and the Mughal Empire influence carpet weaving traditions?

iii. What is the lasting impact of Persian and Mughal carpets on global textile heritage and contemporary design sensibilities?

2. Review of Literature

The study of Persian and Mughal carpet aesthetics is fundamentally based on the broader theoretical constructs of creative adaptation, cultural hybridity, and textile historiography. Historically, textiles have functioned as essential cultural artifacts that mirror the social, political, and economic exchanges among civilizations [4]. Carpet weaving is acknowledged as both an artistic tradition and a dynamic craft influenced by regional factors and external interactions [5].

Prior studies on Persian carpets have predominantly concentrated on their symbolism, artistry, and significance within Safavid court culture [6, 7]. Researchers have emphasized the importance of geometric symmetry, arabesques, and floral patterns in Persian carpets, frequently linked to notions of divine perfection, paradise, and cosmic order [8]. These carpets had intricate designs that conformed to rigorous mathematical perfection, embodying the philosophical and aesthetic tenets of Persian creativity.

On the contrary, the Mughal Empire, which arose in India during the 16th century, was significantly shaped by Persian creative traditions, especially in the initial stages of its carpet manufacture [9]. Over time, Mughal artists integrated Persian techniques with native Indian aesthetics, resulting in a unique visual identity. This shift can be examined via the lens of cross-cultural artistic exchange [10], which investigates the absorption, modification, and reinterpretation of artistic traditions across many cultural contexts.

The Mughal methodology in carpet design was shaped by their admiration for naturalism, botanical accuracy, and vivid colour schemes, deriving inspiration from India's abundant flora and animals [11]. In contrast to Persian carpets, which prioritized structured geometric designs, Mughal carpets frequently illustrated verdant gardens, flowering plants, avian species, and fauna, yielding a more organic and dynamic aesthetic. This transition exemplified a wider tendency in Mughal art and architecture, illustrated by miniature paintings and garden designs commissioned by emperors like Akbar, Jahangir, and Shah Jahan [12].

The historical development of Persian carpets has been thoroughly documented, with researchers analyzing their materials, techniques, trade networks, and symbolic significance [13]. The evolution of Mughal carpet design as a unique creative development separate from Persian traditions has been insufficiently investigated. Historians recognize that Mughal carpets were influenced by Persian designs, although the precise methods by which they deviated and evolved their distinctive stylistic features remain inadequately examined. Nonetheless, there has been no scholarly attention on how these contacts directly impacted the development of Mughal carpet weaving skills and artistic sensibilities. This study seeks to address this disparity through a comparative visual and textual examination of Persian and Mughal carpets, investigating the subtle shifts in design motifs, colour palettes, weaving techniques, and overall composition.

2.1 Evolution of Persian carpet weaving and its influence on the Mughal Empire

The history of Persian carpet weaving extends across centuries, characterized by developments in methods, themes, and cultural symbolism. Persian carpets, which originated over 2,500 years ago, attained prominence during the Safavid era, especially under Shah Abbas I, the emperor who founded royal workshops in Isfahan, Kashan, and Tabriz [14]. These workshops enhanced complex knotting techniques, vivid colours, and motifs, including medallions, arabesques, and garden themes representing paradise. Persian carpets gained significant demand throughout trade routes, impacting worldwide creative traditions, notably those of the Mughal Empire [15]. Akbar, the Emperor Mughals amalgamated Persian weaving techniques with Indian themes, allowing Persian weavers to set up workshops in Agra and Lahore. His successors, Jahangir and Shah Jahan, enhanced Mughal carpet-making by integrating Persian sophistication with indigenous artistic sensitivities [16]. This artistic amalgamation produced a unique Mughal style, embodying both Persian expertise and Indian cultural elements, thereby reinforcing the global legacy of Persian-influenced carpet making.

2.2 Influence of Trade Routes: Mughal Emperors' Adaptation of Persian Aesthetics

The exchange of culture through trade routes was essential in the Mughal Empire, enabling Mughal monarchs to include and modify Persian motifs in various creative forms, particularly carpets. The Mughal rulers, Akbar and his successors, embraced Persian aesthetics, viewing them as emblems of luxury and sophistication [17]. Persian artisans and their exquisite works, including medallions, floral motifs, and opulent landscape designs, became esteemed in the Mughal court due to trade. Indian artisans created and adapted these designs, including native materials, motifs, and symbols, culminating in a unique style that reflected the cultural fusion of Persian sophistication and Indian artistic identity [18]. The incorporation of Persian artistry significantly impacted the local economy, leading to the establishment of vibrant workshops in cities like Agra and Lahore, where Persian artisans collaborated with Indian weavers. This relationship created jobs for local artisans and revitalized the textile industry, promoting economic growth through the production of exquisite carpets for both domestic and international markets. Mughal carpets, embedded with Persian motifs, became emblems of imperial grandeur, reflecting the emperors' authority and cultural significance while illustrating the dynamic interactions between Persian and Indian cultures, thereby creating a legacy of artistic synergy that enriched both traditions.

3. Methodology

This research employs a qualitative, comparative methodology to examine how the Mughal Empire reinterpreted Persian carpet aesthetics. The study examines the development of themes, colour schemes, weaving methods, and design compositions using historical writings, archival documents, and visual data. Selected Persian and Mughal carpets are subjected to a thorough visual examination to spot advances and stylistic parallels. Both primary and secondary sources were used to get the data for this study. Historical manuscripts are examples of primary sources. Scholarly texts, art historical journals, and historical trade records are examples of secondary sources. Through the use of an integrative methodology, it is possible to gain a deeper knowledge of how Mughal carpets incorporated Persian aesthetics, demonstrating both artistic innovation and cross-cultural discourse within the region's textile traditions.

4. Results and Discussion

4.1 Craftsmanship and Techniques

4.1.1 Persian weaving techniques and knot styles

Persian carpet weaving is intricately rooted in Iranian culture and heritage, with each region nurturing its weaving techniques, knotting patterns, motifs, and colour schemes. Persian carpets are distinguished by their superior craftsmanship, intricate designs, and the use of premium natural materials such as wool, silk, and cotton.

Persian carpets are known for two main types of knots:

4.1.1.1 Persian (Senneh) Knot – Asymmetrical Knot

This knot (Figure 1A) includes a single warp and crosses behind another warp before being pulled through. This asymmetry enhances design precision and fine details, making it the optimal technique for producing high-quality carpets with rich floral and curvilinear themes. Carpets from Isfahan, Nain, Qom, and Kashan are often noted for their elaborate designs and luxurious silk or wool textures.

4.1.1.2 Turkish (Ghiordes) Knot – Symmetrical Knot

This technique entails (Figure1B) encircling the yarn around two adjacent warp threads and drawing it through the Centre of the loop. This results in a denser and more durable weave, improving the carpet's density and strength [19]. It is employed in Tabriz and tribal carpets, especially those made by Bakhtiari and Kurdish craftsmen.

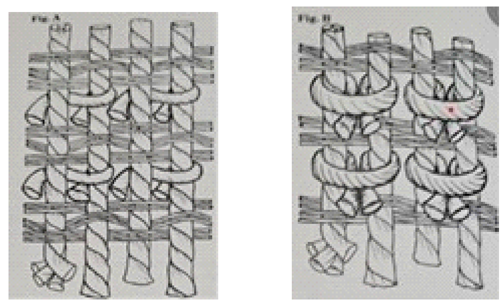
(A)  (B)

Figure 1: (A) Asymmetrical Knot, (B) Symmetrical Knot

4.2 Mughal adaptations: blending Persian techniques with Indian motifs and materials

The Mughal Empire symbolized a period of artistic synthesis marked by the harmonious amalgamation of Persian influences and Indian cultural aspects, particularly in carpet making. The weaving techniques of Mughal carpets were profoundly influenced by Persian artistry, while also incorporating Indian adaptations, culminating in a unique Indo-Persian textile legacy. Mughal carpets were founded on the asymmetrical Persian (Senneh) knot, enabling exquisite elaboration and sophisticated curvilinear patterns. This method, brought to India by Persian craftsmen, enabled the creation of exquisitely detailed floral, medallion, and arabesque patterns. The warp and weft structures were initially influenced by Persian designs; however, Indian weavers integrated cotton warps for increased durability with silk or pashmina wool for a more refined texture. The knot density in Mughal carpets was exceptionally high, often exceeding 1,000 knots per square inch, making them some of the finest carpets for their time.

Persian carpets notably follow highly structured designs, often with a central medallion, symmetrical borders, and repetitive floral motifs. Under Mughal influence, these patterns evolved to embrace a more organic and dynamic look. Mughal carpets displayed spontaneous, fluid floral designs that more accurately reflected nature, rather than succumbing to rigid repetition [20]. The Mughals used narrative and figurative elements, such as hunting scenes, depictions of animals, and courtly figures motifs, rare in Persian carpets yet characteristic of Mughal craftsmanship [21].

4.2.1 Expanding the Persian Color Palette with Indian Innovations in the Mughal Period

The colour innovations in Mughal carpets were significantly influenced by Persian dyeing traditions, though they were greatly enhanced by the incorporation of Indian natural dyes. Persian carpets traditionally exhibited a rich but limited colour palette, primarily consisting of deep reds, blues, and ivory hues, sourced from natural materials such as cochineal, madder root, indigo, and pomegranate rinds. The colours were carefully layered to establish contrast and depth, with Persian weavers typically preferring evident symmetrical designs that accentuated elaborate floral and geometric patterns. The introduction of Persian weaving techniques to India under Mughal patronage resulted in a transformation of the colour palette, incorporating a wide range of Indian botanical and mineral dyes. The Mughals added more vivid and varied hues to their carpets while retaining the Persian skill at creating durable, fade-resistant colours [22]. The introduction of indigo from Rajasthan intensified the blues, while lac and madder root from Gujarat enhanced the reds with a more nuanced spectrum, spanning from crimson to burgundy. Turmeric from Bengal provided vibrant golden yellows, enhancing floral and architectural designs, while pomegranate rinds and saffron from Kashmir offered deep brown and golden tones, facilitating detailed shading and depth. The advancement in dyeing techniques not only improved the aesthetic allure of Mughal carpets but also positioned them as some of the most opulent and coveted textiles in both Indian and global markets.

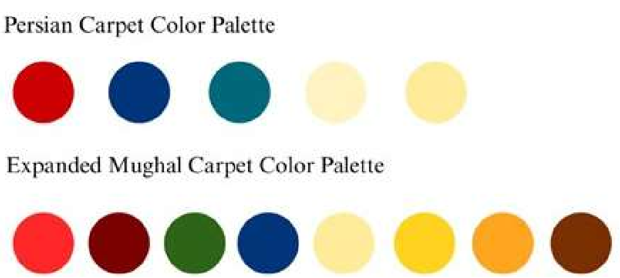


Figure 2: Persian and Expended Mughal Carpet Color Palette

4.3 Design and Motif Analysis

4.3.1 Common Themes and Symbolism

Persian and Mughal carpets are renowned for their intricate designs and deep symbolism, reflecting the cultural, religious, and philosophical ideals of their respective periods. Both traditions often highlight themes like nature, spirituality, and the depiction of ideal gardens, incorporating elements such as flowers, vines, trees, and animals. These elements symbolize life, eternity, and divine beauty, influenced by Islamic and regional motifs [23]. Geometric patterns, arabesques, and medallions are prevalent in both genres, symbolizing oneness, harmony, and the limitless nature of the world. Mythological and spiritual symbols, such as the Tree of Life, frequently represent the connection between the terrestrial and the celestial. Persian carpets exemplify elegance and precision with symmetrical designs, while Mughal carpets integrate Indo-Persian aesthetics with a more naturalistic depiction of flora and wildlife. These carpets collectively reflect the shared legacy and intercultural connections between the Persian and Mughal empires, creating a tale of beauty and symbolism that transcends historical bounds.

Figure 3: Tree of Life Designs according to different cultures

All religions that believe in one God share the tree as a common theme. Cypress, date palm, pomegranate, fig, olive, wine, beech, and oak are just a few of the plants that have been used as symbols of the tree of life by different cultures. The Tree of Life (Figure 3) is both a symbol of death and a link between the three realms (this world, the next, and the afterlife) in Turkish mythology, where it is believed to have originated. Even though the boy's body will eventually die, his soul will remain eternally, and the tree of life will reveal its future path. Mughal carpets featuring the Tree of Life represented paradise (Jannat), prosperity, and eternity. Its beautiful woven designs, which blended Persian and Indian influences, reflected imperial grandeur and spiritual symbolism; they featured floral patterns, birds, and vines [24].

4.3.2 The distinct iconography of motifs in Persian and Mughal carpets

The iconography of Persian and Mughal carpet motifs reflects their rich artistic traditions and cultural heritage, combining aesthetic beauty with symbolic depth. Carpets served both practical and symbolic functions, representing a magical space where the border signified the terrestrial realm and the field symbolized the divine. Persian and Mughal carpets feature three primary ornamental groups. The first includes geometric motifs like eight-pointed stars (Figure 4), swastikas, and hooked diamonds, filling open spaces. The second consists of floral and leaf patterns, notably the rosette and palmette, the latter being especially prominent in Persian design since the 16th century.

The third group comprises distinctive motifs unique to specific regions, appearing in both field and border designs. This iconographic richness showcases artisans' skill while preserving cultural narratives, beliefs, and values through intricate patterns, making carpets enduring artistic and historical records.

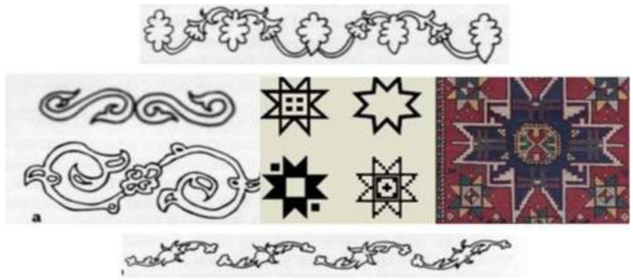


Figure 4: "s" shaped Designs and eight-pointed star Patterns

4.3.2.1 Floral Motifs

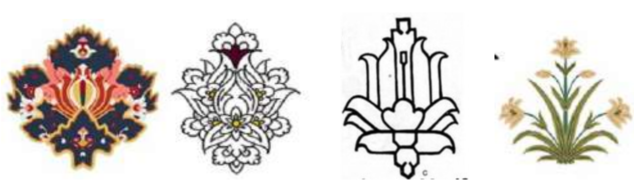
Floral motifs are integral to both Persian and Mughal carpets, symbolizing paradise, beauty, and the harmony of the natural world. Persian carpets frequently feature floral motifs, including stylized depictions of the lotus, lilies, roses, and the cypress tree, which represent eternity and resolve. Typically arranged in the chahar bagh (four-garden) layout, these designs embody the Persian ideal of paradise as a lush, orderly garden, symbolizing beauty, abundance, and a harmonious connection with nature.

The lotus, a repeating motif, symbolizes purity and spiritual enlightenment, illustrating its profound association with Persian intellectual and mystical traditions.

i) Rose: Frequently illustrated in stylized clusters, the rose represents divine love and the ephemeral essence of worldly beauty.

ii) Cypress Tree: A towering, evergreen tree frequently depicted in Persian art, the cypress represents longevity and resilience, serving as a metaphor for strength in the face of hardship.

iii) Shah Abbasi Design: This design (Figure 5A) is characterized by symmetrical arrays of stylized floral patterns, predominantly lotus and palmettes, emanating from a central medallion. It represents unity, order, and the prominence of the divine presence.



5A 5B 5C

Figure 5: A) Shah Abbasi Motif, B) Lotus Flower, and C) Tulips

Mughal carpets exhibit considerable Persian influence while using native Indian flora, including the lotus, Champa, and marigold, thus enhancing the designs with local symbolism and aesthetic appeal. Mughal artists favoured realistic depictions, illustrating flowers with meticulous botanical precision that reflected the emperors' fascination with the natural world. These carpets also exhibit floral arrangements, like flowering plants in vases or blossoming trees, mirroring the Mughal kings' affinity for gardens and their idealized representation of paradise [25]. Under Akbar's reign, the garden symbolized paradise, and flower motifs on Mughal carpets often encapsulated this idea, blending Persian stylization with Indian authenticity.

i) Lotus: It (Figure 5B) maintains its symbolic connection to purity and enlightenment, although it is depicted in gentler, more naturalistic forms. This reflects its hallowed importance in Indian culture and its Islamic implications.
ii) Chrysanthemum, Iris, and Tulip: These flowers (Figure 5C), frequently illustrated in full bloom, exemplify Mughal artistic sophistication and their admiration for natural beauty.
iii) Charbagh Layouts: In contrast to Persian carpets that utilize stylized garden motifs (Figure 6), Mughal carpets sometimes integrate garden layouts directly into their designs. Separated by paths or flowing water channels, these carpets reflect the architectural elegance of Mughal gardens such as Shalimar Bagh.

Figure 6: The Chahar Bagh Rug at The Albert Hall Museum In Jaipur (Image Source: https://nazmiyalantiquerugs.com/blog/indo-persian-chahar-bagh-gardens-and-rugs)

4.3.2.2 Arabesque Patterns

Arabesque patterns (Figure 7A), consisting of flowing, symmetrical curves and interlacing lines, are essential to Persian and Mughal designs, representing infinity and divine harmony. In Persian carpets, arabesques are exceptionally comprehensive, with rhythmic details that symbolize the timeless essence of the world and divine creation. Persian arabesques, which are frequently paired with floral patterns and center medallions, represent a mystical perspective that echoes Sufi ideas of interconnectivity. These patterns integrate effortlessly with other design aspects, establishing an overall flow that encapsulates both intricacy and spiritual balance [26].

Arabesques have a softer approach in Mughal carpets (Figure 7B), merging well with vegetal and floral patterns to create a more natural and realistic look. Mughal artists preferred scrolling vines and intertwined floral motifs, imparting a feeling of development, connectedness, and equilibrium that embodies Indian aesthetic concepts [27]. Therefore, although influenced by Persian designs, Mughal arabesques offer a more fluid and organic rendition, reflecting the empire's admiration for creative amalgamation and the elegance of nature.

7A 7B

Figure 7: (A) Safavid Arabesque carpet fragment, 16th century, Iran. Austrian Museum of Art, (B) Indo-Persian carpet with floral carpet with palmettes, Herati and arabesque pattern

4.3.2.3 Animal Patterns

Animal motifs in Persian and Mughal carpets reveal distinct approaches, though both traditions use animals to convey power, grace, and divine symbolism. Animal images on Persian carpets (Figure 8A) are frequently stylized and tastefully incorporated into garden or hunting motifs. Mythological animals with strong symbolic significance, such as dragons, griffins, and Simurghs (Persian phoenix), represent cosmic order, knowledge, and protection. The Simurgh represents knowledge and longevity, whilst dragons signify guardianship and might. Animal themes in Persian artwork are frequently abstracted to emphasize symbolic rather than literal depiction because it is strictly prohibited by Islam to show live things [28].

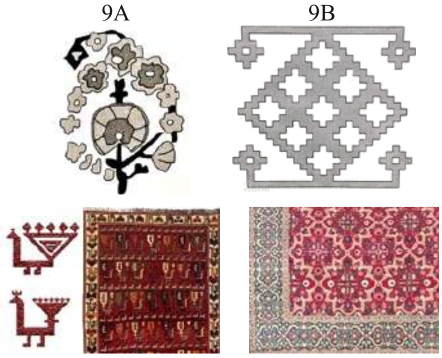
Mughal carpets (Figure 8B), however, portray animals more boldly and with naturalistic detail, reflecting the Mughal fascination with the natural world and hunting culture. Indigenous fauna such as elephants, peacocks, tigers, and deer are shown with meticulous accuracy, reflecting the Mughals' admiration for realism and their affinity for the Indian ecosystem. Peacocks signify beauty and immortality, and elephants denote strength and regal majesty, enhancing the carpets' symbolism of royal power. Animal themes in Mughal carpets often depict hunting or garden settings, blending Persian-inspired designs with uniquely Indian portrayals of nature and elegant existence [29].

4.3.2.4 Geometric Patterns

Geometric patterns (Figure 9A, 9B, 9C) play a vital role in both Persian and Mughal carpet traditions, representing cosmic order, unity, and harmony. Persian carpets typically exhibit intricate geometric grids, star motifs, and medallions, symbolizing balance and spiritual unity. Persian artists used geometry to develop a systematic arrangement that reflected the belief in the harmony of the world [30]. These designs represent a belief in a divine, harmonious universe, where intricately structured patterns signify an appreciation for balance and spiritual values. Medallions, frequently employed as focal points, represent oneness with geometric shapes that extend outward in complex, mathematically exact patterns reflecting Persian religion and mythology.

In Mughal carpets, geometric designs retain significant value, however, they are softened by the use of floral and naturalistic elements. Mughal artists preserved the symmetry of geometric shapes while integrating floral motifs, vines, and arabesque designs (Figure 9D), achieving a harmonious balance between fixed order and natural beauty [31]. Mughal carpets frequently have medallion-centered designs encircled by flowing floral motifs, blending geometric accuracy with a natural harmony that reflects Indian creative values. The outcome is a unique Mughal interpretation of geometry that respects the structured, spiritual importance of the Persian style while embracing the softer, naturalistic beauty of Indian art [32].

9A 9B



9C 9D

Figure 9: (A) geometric botah, (B) Star Medallion, (C) Peacock motif on the Persian Carpet, (D) 17th Century Mughal Carpet

(Image source: A, B & C https://letsgopersian.com/blog/decoding-traditional-motifs-and-designs-in-persian-carpets/, D https://www.theculturegully.in/post/the-mughal-legacy-in-india-s-carpet-industry-from-agra-to-the-world)

8A 8B

Figure 8: (A) Safavid carpet, Herat, mid-16th–early 17th century, Shah Tahmasb I or Muhammed Khudabanda Period, (B) The Thyssen Mughal Hunting Carpet at Sotheby's – HALI

4.4 Differences in the Iconography of Persian and Mughal Carpet

Persian carpets are renowned for their stylized floral, arabesque, and geometric motifs, often featuring medallion designs that incorporate symbolic representations of paradise and divine order. In contrast, Mughal carpets, though inspired by Persian tradition, display naturalistic flowers, birds, and animals with a strong sense of realism influenced by miniature paintings. Thus, while Persian iconography emphasizes abstraction and symbolism, Mughal carpets highlight naturalism and a fusion of Persian and Indian artistic elements. Here is the iconography of Persian and Mughal carpets

Table 1: Iconography of Persian and Mughal Carpet

Aspects	Persian Carpet	Mughal Carpet
Historical Context	Developed over thousands of years, with significant advancements during the Safavid Dynasty(1501-1736). Persian carpets were highly prized both domestically and internationally, and often used as diplomatic gifts. The art form reflects the socio-political context of Persia, showcasing the empire's wealth and craftsmanship.	Flourished during the Mughal Empire from 1526 to 1858. Significant patronage from emperors like Akbar, Jahangir, and Shah Jahan, who established royal workshops. The period is marked by a blending of Persian art with Indian influences due to extensiv e cultural exchange.
Influences	Influenced by various cultures including Mongol, Tatar, and Islamic artistic traditions. Persian carpets often served as models for other Islamic carpet-making traditions across the region. The Safavid period saw an influx of artistic ideas from China and Europe, further enriching Persian designs.	Heavily influenced by Persian designs, Mughal artisans adapted these styles to incorporate local themes and motifs. The interaction with European art through trade introduced new elements to Mughal designs. Indian flora and fauna were integrated into traditional Persian patterns, creating a unique hybrid style.
Common Motifs	Rich floral motifs, including palmettes, arabesques, and stylized flowers, dominate the designs. Geometric patterns are highly developed, often forming complex repeat designs that convey symmetry and harmony. Calligraphy may be incorporated into borders or central medallions as a reflection of Islamic art.	Predominantly floral patterns featuring roses, lotuses, and intricate vine scrolls. Geometric shapes are used but often blended with organic forms; motifs like medallions are common. Scenic landscapes often depict gardens or nature scenes, symbolizing paradise.
Notable Techniques	Notable for the 'Vas e Technique' where vases filled with flowers are depicted prominently; intricate knotting methods allow for detailed imagery that is both delicate and durable. - Use of rich colors achieved through natural dyes like indigo and cochineal creates striking vi sual contrasts within patterns.	- High knot density (up to 500 knots per square inch) allows for detailed imagery; complex weaving techniques recorded in Ta'lim(manuals). - Use of vibrant dyes derived from natural sources enhances color richness; techniques like abrash (color variations) add depth to designs.
Color Symbolism	Symbolic and Traditional: Red (power and passion), blue (spirituality), green (paradise, used minimally due to religious context), black (mystery). Deep, vibrant hues dominate.	Rich, Luxurious, and Natural Tones: Red, green, gold, blue, and yellow, reflecting royalty and wealth. Green symbolizes paradise, while gold represents luxury and divine grace. Colors tend to be softer and more naturalistic than Persian carpets.
Floral Motifs	Stylized and Geometric: Common flowers include lotus, cypress, and palmette, arranged symmetrically. Symbolize purity and eternity.	Naturalistic and Detailed: Flowers like lotus, tulip, iris, and poppy, are depicted with lifelike detail. Reflect the lush I ndian flora. Represent paradise on earth.
Botanical Layouts	Symmetrical, Structured Gardens: Designs often follow a structured layout with repeating floral patterns, aiming to represent cosmic order and harmony.	Garden-inspired with Quadrants (Chahar Bagh): Inspired by Mughal gardens, motifs are often placed in garden - like layouts, representing paradise gardens with detailed flower beds.

Aspects	Persian Carpet	Mughal Carpet
Animal Symbols	Mythical and Symbolic Animals: Lions, gazelles, and mythical creatures like dragons and phoenixes symbolize strength, spirituality, and protection. **Deer and Gazelles :** Symbolizing grace and beauty.	Naturalistic Animals, Inspired by Hunting: Tigers, elephants, peacocks, parrots, and cranes, representing royalty, grace, and Mughal power. Hunting scenes symbolize power and dominion
Bird Iconography	Nightingale and Peacock: Nightingales symbolize divine love, while peacocks represent immortality and beauty. Often rendered symbolically	Peacock, Parrot, Crane: These birds are rendered in a lifelike manner, symboliz ing beauty, wisdom, and grace. Reflect the Mughal admiration for the natural world.
Geometric and Abstract Patterns	Highly Stylized Patterns: Emphasis on abstract geometry, symmetry, and balance, creating a sense of divine harmony. Borders and medallions reinforce cosmic structure.	Less Geometric, More Realistic Forms: Geometric elements are present but secondary to floral and animal patterns. Emphasis is on naturalistic designs, reflecting realism and the Mughal love of nature.
Central Medallion	Unified Focal Point: Large central medallions represent cosmic harmony, with floral and geometric symmetry that embodies the universe's order.	Paradise Garden Layout: Central medallions exist but often take the form of garden -inspired layouts. Carpet interiors may be divided into quadrants filled with florals and animal motifs.
Architectural Influence	Cosmic Medallions and Borders: Medallions represent the center of the universe or paradise garden. Borders are heavily patterned, signifying protection and framing.	Mughal Palace and Garden Elements: Arches, mihrabs, and symmetrical quadrants resemble Mughal architectural styles. Designs often mimic Mughal palaces and chahar bagh gardens.
Religious and Mystical Themes	Islamic and Sufi Influence: The Tree of Life symbolizes the path from earthly life to the divine. The carpet itself represents the cosmos or paradise garden, bridging earth and heaven.	Islamic Paradise with Earthly Elements:Mihrabs on prayer rugs symbolize direction in prayer. Garden layouts emphasize t he earthly paradise, celebrating nature's beauty and Mughal opulence.
Influence of Sufi Mysticism	High: Sufi themes like unity with the divine are prevalent; nightingales, flowers, and trees often represent spiritual concepts such as divine love and the soul's journey.	Moderate: Sufi influence is subtle, seen in harmonious and balanced designs. More focus on earthly beauty and the symbolism of paradise rather than the spiritual journey.
Cultural Fusion	Persian, Zoroastrian, and Islamic Elements: Deeply influenced by ancient Persian mythology, Zoroastrianism, and Islamic spirituality, creating a unique fusion of styles.	Indian, Persian, and Islamic Blending:Combines Persian influences with Indian aesthetics, integrating local fauna, flora, and architectura l elements, creating a distinct Mughal style.
Cultural Fusion	Persian, Zoroastrian, and Islamic Elements: Deeply influenced by ancient Persian mythology, Zoroastrianism, and Islamic spirituality, creating a unique fusion of styles.	Indian, Persian, and Islamic Blending: Combines Persian influences with Indian aesthetics, integrating local fauna, flora, and architectural elements, creating a distinct Mughal style.
Overall Aesthetic	Stylized, Formal, and Symbolic: Emphasis on symmetry, cosmic symbolism, and spiritual depth. Designs often appear structured and idealized.	Naturalistic, Opulent, and Realistic: More lifelike depictions, reflecting the grandeur of Mughal courts and admiration for nature. Designs focus on lush, realistic beauty with rich colors and opulent details.

Persian carpets, which draw inspiration from Islamic art and ancient Persian spirituality, feature geometrical patterns that emphasize cosmic harmony and mysticism. By fusing Persian, Indian, and Islamic themes into a distinctive style, Mughal carpets emphasize opulence and naturalism, reflecting the Mughals' adoration for India's abundant flora and fauna, architectural magnificence, and the idea of an earthly paradise.

5. Conclusion

The artistic evolution of Persian and Mughal carpet designs reflects a rich narrative of cultural exchange, adaptation, and innovation. Persian carpets, renowned for their curvilinear precision, masterful weaving, and symbolic motifs, emphasize structural harmony, symmetry, and elaborate arabesques. Typically centered on medallions or lattice frameworks, they feature scrolling vines, stylized floral motifs, and deep, saturated jewel tones like blues, reds, and golds, enhancing their grandeur. Mughal carpets, initially influenced by Persian aesthetics, evolved as Indian artisans infused indigenous elements, regional craftsmanship, and distinctive color palettes. While sharing common motifs like arabesques and floral patterns, Mughal designs exhibit a shift toward naturalistic floral arrangements, delicate shading, and an open composition. Inspired by Indian miniature paintings and botanical studies, they depict realistic flowers, birds, and fauna, favoring subtle pastels and natural hues over bold Persian contrasts.

This comparative analysis highlights how Persian carpets prioritize order, symmetry, and opulence, whereas Mughal carpets embrace fluidity, realism, and elegance. Despite Persian influence, Mughal carpets developed a unique identity, reflecting a fusion of foreign and local traditions. Their artistic and cultural significance extends beyond aesthetics, serving as historical artifacts that embody the dynamic exchange of design traditions. Understanding these nuances enriches our appreciation of textile heritage and underscores carpets as enduring symbols of artistic mastery and cross-cultural influence.

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Eco-Friendly Alternatives: A Review of the Banana Fiber Resurgence in the Textile Industry

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Abstract:

Banana fiber, a natural and sustainable material, has been utilized for centuries, with origins tracing back to Southeast Asia, particularly the Philippines, where it was first used as early as the 13th century. This fiber, which originates from the pseudo stem of the banana plant, is highly regarded for being environmentally beneficial because it comes from a renewable source that has no effect on the environment. In the textile sector, banana fiber presents a competitive, environmentally friendly substitute for traditional cotton, whose intensive agriculture methods have serious negative impacts on the environment. India, the world's largest banana producer, generates substantial pseudo stem biomass, which can be effectively utilized to produce banana fiber. The paper reviews the potential of banana fiber as a key player in the shift towards more sustainable textile practices, given its rich history and environmental benefits. The review also explores several projects focused on banana fiber applications, identifies major industry players, and evaluates the varied spectrum of products created, emphasizing banana fiber's expanding importance in sustainable textile techniques.

Keywords: *Banana fibre, Ecofriendly, Renewable source, Sustainable, Textile sector*

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1. Introduction

- Brief history of banana fiber in the textile industry, its traditional uses, decline & resurgence

In Indian culture, the banana tree holds sacred significance due to its roots in mythology. In Hindu mythology, when Rishi Durvasa cursed his wife into becoming a banana tree for waking him, she begged for mercy. Rishi Durvasa fulfilled her request by granting the tree special status [1].In Western mythology, Manu, also known as Hazrat Nuh in Islam, sought divine help to restore life on Earth following the great flood. He requested a plant that offered nutritional benefits and God provided the banana tree. Trees with fruit bunches are also commonly displayed at home entrances in southern India, symbolizing abundance, and fertility [2].

Figure 1: Banana fibre plant

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Although it has various uses, it is mainly grown for its nutrient-dense fruit, rich in potassium, magnesium, and vitamin B6. Once the fruit is harvested, a large amount of biomass, especially from the pseudo stem, is left unused, leading to several tons of fibers being underutilized [3]. Each plant bears fruit only once, making banana fibers advantageous, as they are sourced from agricultural residue [4]. These pseudostems can be effectively utilized in production of the banana fibres [5]. India, China, and the Philippines are the top three banana producers in the world, with India leading in production, followed by China and the Philippines [6]. It is currently grown in 129 countries worldwide and ranks as the fourth most significant food crop in the world [7].

Initially, banana fiber had limited textile applications, primarily used for ropes, mats, handicrafts, and composites. In Japan, the use of banana fiber fabric, known as bashōfu, dates to the 13th century in Okinawa's Kijoka region. Bashōfu was categorized into two quality levels: premium bashōfu for fine clothing, such as kimonos for high-class individuals, and rough bashōfu for more affordable garments [8, 9]. The idea of making fabric from banana fiber may have originated from its medicinal uses, as something beneficial for health could also be advantageous when worn [10]. Historically, banana fiber has been used in textiles since ancient times, but its popularity declined with the advent of more convenient fibers like cotton and silk [11]. The early extraction process was labor-intensive and lacked standardized methods, resulting in low productivity of about 200 grams per person per day [12]. Ms. Hitomi Shinzato from the Okinawa Institute of Science and Technology noted that it takes over 23 painstaking steps to produce banana fiber clothing [13]. However, in an era of fast fashion and growing environmental consciousness, banana fiber has emerged as a sustainable solution. It is biomass-derived, provides employment opportunities, and has minimal impact on soil health compared to cotton, requiring less water and no genetic modification. Furthermore, banana plants are perennial, enhancing their sustainability. Because of its environmentally favourable qualities, the market for banana fibre is expanding quickly, with a projected compound annual growth rate (CAGR) of 5.50% from 2023 to 2030 [14]. This revival reflects a global trend toward natural materials and increased awareness of environmental issues.

The objective of this review is to explore

- Origin, properties, and traditional applications of banana fiber in sustainable textiles.
- Production process and recent innovations that enhance the feasibility of banana fiber.
- A comparison of banana fiber with other natural and synthetic fibers in terms of performance.
- The challenges and opportunities for the growth of banana fiber in the textile industry.

2. Methodology

This review is based on an extensive analysis of secondary data sourced from platforms, including peer-reviewed research papers, blogs, YouTube videos, market analysis, and newspaper articles. This paper aims to highlight current knowledge, identify gaps, and lay the groundwork for future research in the field of banana fibre by combining insights from these diverse sources.

3. Basics of Banana Fiber

- What is banana fiber? Origin and botanical source.

Banana plants belong to the Musaceae family [15]. The two wild species that are thought to be the ancestors of cultivated bananas are Musa acuminata and Musa balbisiana. Musa was derived from the Arabic name for the banana as recorded in an Arabic medical encyclopedia by Avicenna [16]. While human-consumed bananas are a member of the Musa acuminata species, Musa textiles are mostly grown for their fibre [17]. Bananas are a tropical crop that thrives in warm, humid weather with temperatures between 15°C and 35°C, fertile soil with a pH of 6 to 7.5, sufficient rainfall (650 to 750 mm during the monsoon season), and shelter from cold and strong winds [18]. Lignocellulose makes about 60% to 85% of the dry weight of banana fibre, with cellulose accounting for roughly 50% and offering structural integrity. Meanwhile, lignin adds mechanical strength and a yellowish hue [19]. The mature outer sheaths of pseudostems have a larger lignin concentration than the inner ones. Fibre composition is influenced by species and extraction techniques, and trace elements [20]. For new plants to sprout, the pseudostem which is made up of closely spaced leaf sheaths must be removed. There is a chance to turn trash into environmentally friendly products because banana plantations produce about 220 tonnes of biomass waste per hectare [21]. Pseudostem of the banana plant produces high-quality fiber with vast potential for diverse industrial applications, including the manufacturing of textiles, sanitary pads, pulp and paper, food items, and reinforced composites used in automotive, construction, aerospace, and other sectors [22].

4. Properties of Banana fibre

Fiber morphology and chemical structure significantly influence fiber properties, leading to extensive research on fiber structures using scanning electron microscopy. Bashofu, the earliest recorded use of banana fiber in fabric production, was studied to understand its popularity. Please check analysis revealed that banana fiber fabric keeps the wearer cool in warm climates and observed various vascular bundles (fig. 2) in the plant sheath even after degumming. These vascular bundles, which transport water and nutrients, enhance the fabric's breathability by facilitating quick sweat evaporation through the pores [23].

In the same study, FTIR (Fourier transform infrared spectrometry) and XRD (X-ray Diffraction) analysis revealed that banana fiber has a crystallinity of 60-70%. Similar findings were reported in another research where internal and external fibers were compared, internal fibers showed a crystallinity index of 61.01%, with 72.81% cellulose and 9.13% lignin, while external fibers showed a crystallinity index of 66.71%, with 61.30% cellulose and 26.70% lignin [24, 25]. The natural diameter of banana fiber averaged 110.5 µm but decreased after alkali degumming due to the removal of lignin and impurities [26, 27]. The treated fiber density was 1.52 g/cm³, comparable to cotton

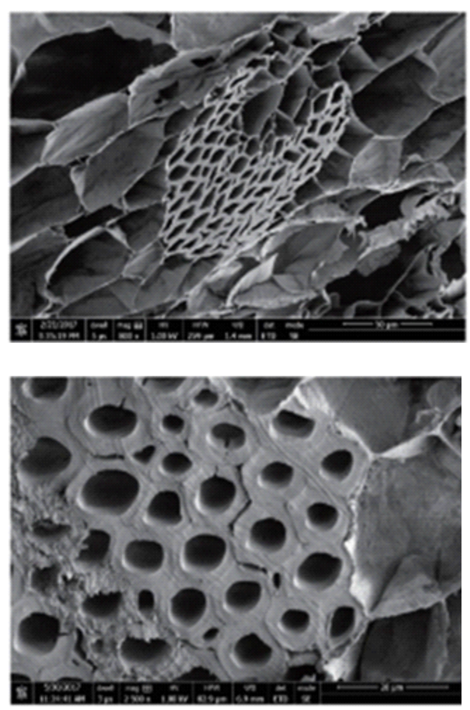
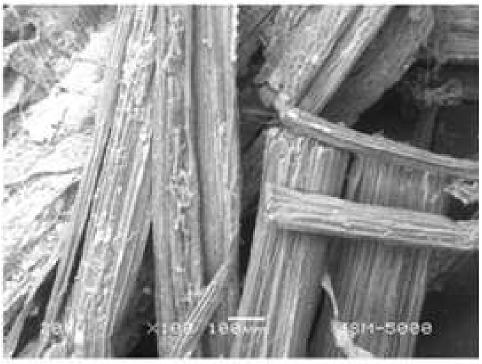
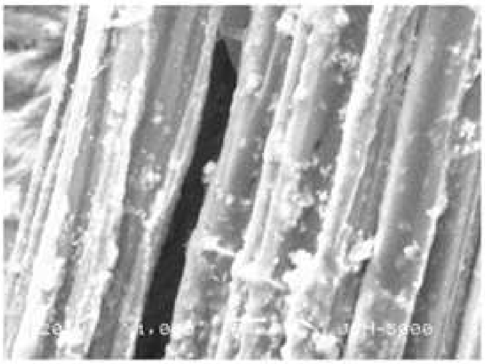


Figure 2: Cross section morphology of degummed banana fibre [23]



Raw Banana fiber (X100)



Raw Banana fiber(X1000)

Figure 3: Scanning electron micrographs of raw banana fibers [26]

while the length-to-breadth ratio for the wild variety ranged from 950 to 1000, lower than cotton's 6000 [28].

Banana fiber consists of helically woven cellulose microfibrils within an amorphous matrix of lignin and hemicelluloses [29, 30]. Research has shown that banana pseudostem fibre along with, jute, and sisal fibers are among the strongest natural fibers, suitable for reinforcing composites and applications like packaging, clothing, and ropes [31]. Additionally, studies have also demonstrated the thermal stability of banana fibers through DSC and TGA analysis [32].

Due to its cellulosic composition and amorphous regions, banana fiber exhibits excellent water absorbency, with a moisture content ranging from 10% to 11.5% [33]. Table 1 covers physical, chemical and mechanical properties of banana fibre.

Banana fiber can be processed into yarn in different ways depending on the spinning system used. When cut and blended with cotton, it can be spun into short-staple yarn, while using a jute-spinning system allows the production of long-staple yarn. Since 100% banana fiber is difficult to card into a web, blending it with cotton in ratios such as 70:30 or 50:50 facilitates successful yarn formation in both ring and rotor spinning, with rotor spinning yielding better yarn quality. Pure banana fiber yarn can also be produced on jute machinery, achieving satisfactory strength, although it tends to exhibit higher hairiness and unevenness [35].

In summary, banana fiber's qualities, including a favorable length-to-breadth (L/B) ratio for spinning, natural shine, good absorbency, strength, and thermal stability, make it suitable for textile applications and promising for further research and a broader range of uses.

5. Traditional applications in textiles and other industries

Although banana fibre is found in abundance in tropical regions and have diverse applications still its potential has not been explored much. The major reason could be its labour-intensive extraction process and low output. There are numerous uses for banana fibre in a variety of sectors. Because of its strength and longevity, it has historically been used to make ropes and cordage for the marine, agricultural, and construction industries. Additionally, it is used in composite boards, soundproofing materials, and filtration systems. Banana fibre has been turned into pulp and used in papermaking since 1944 to make Japanese Yen notes more durable. It is perfect for making filter paper, banknotes, cigarette paper, luxury writing paper, and eco-friendly tea bags with a mesh-like material that lets water pass through while retaining tea leaves because of its strength, durability, and resistance to pests. As a biodegradable substitute, banana fibre is used in packaging to create trays, containers, and inserts [36]. The pseudo stem is used to extract banana fibre, which is then spun into yarn and woven into textiles for apparel and home goods. In South India, banana yarn mixed with cotton or synthetic fibres is used to make lightweight garments, while in the Philippines, fibres from the inner stalk are used to make delicate yet sturdy apparel, headgear, and shoes. Similar to the Philippines, efforts should be undertaken to increase the popularity of banana fibre clothing in India [37]. Banana fibre is also frequently utilised in handicrafts to create mats, baskets, caps, bags, and other

Table 1: Physical/Chemical and Mechanical Properties of Banana Fibres [34]

Physical / Chemical Properties	Range	Mechanical Properties	Range
Diameter (μm)	80 – 250	Tensile Strength (MPa)	529 – 914
Length (mm)	1000 – 5000	Specific Tensile Strength (MPa)	392 – 677
Cellulose (%)	60 – 65	Young's Modulus (GPa)	27 – 32
Hemicellulose (%)	6 – 19	Specific Young's Modulus (GPa)	20 – 24
Lignin (%)	5 – 10	Failure Strain (%)	1 – 3
Pectin (%)	3 – 5	Density (Kg/m³)	750 – 950

ornamental products, demonstrating its versatility and environmental friendliness. Figure 4 shows the craft of banana fiber in Anegundi avillage in koppal district of Karnataka has been thoroughly documented, highlighting traditional methods and contemporary applications [38].

Figure 4: Traditional banana fiber craft of Anegundi [38]

6. Production Process

The pseudo stems of the banana plant are cut in half, and the sheaths are removed layer by layer in order to harvest the fibres. The fibres are separated by removing the sticky cellulose like material. However, the procedure is still difficult because there are no standardised tools or methods. The earliest technique, manual extraction, involves extracting fibres using sharp tools like blades, then drying and cleaning them. Due to precise handling, the manual method yields superior-quality fibres while being labour-intensive and time-consuming, producing only about 4 kg of fibres per day. Mechanical extraction is the ideal method for large-scale production; decorticators or stripping machines can produce 20–30 kg of fibres per day. In order to separate the fibres, a revolving drum beats the sheaths. Then, residues are removed by hand combing, washing, and drying [39]. Another method is retting, which entails dissolving the lignin and hemicellulose. Despite being widespread, water retting is time-consuming, inconsistent, and bad for the environment because its effectiveness depends on factors like bacteria and water pH. Retting time can be shortened by up to 78% with controlled settings [17]. Using chemicals such as sodium carbonate, chemical retting eliminates binding components while maintaining ideal conditions to avoid fibre deterioration. For example, whiter fibres can be produced by combining hydrogen peroxide and sodium hydroxide, then neutralising any remaining alkali with a mildly acidic wash [40]. In anaerobic settings, microbial retting includes bacteria and fungi like Clostridium and Pseudomonas. This technique is less labour-intensive and appropriate for large-scale manufacturing, producing fibres that are comparable to those obtained through hand extraction [19]. Cellulase, pectinase, and lignin peroxidase are among the enzymes used in enzymatic retting to break down lamella and smooth fibre surfaces [41]. Following extraction, the fibres are spun on a spinning wheel and subjected to common textile processing techniques like knitting, weaving, bleaching, and dyeing before the cloth is cleaned, dried, and neutralised.

6.1 Innovations and modern methods

The quality of fibres extracted largely depend on the extraction technique followed, hence, is becomes extremely important choosing the correct technique. Physical extraction techniques are mostly preferred over chemical methods since they do not severely affect the quality and quantity of fibres extracted. A recent innovation is combination of chemical and bacterial treatments which results in finer fibres. Studies have investigated the methods to improve the fineness of fibre for textile applications. The fibers mechanically extracted from the second and third layers of the pseudostem underwent both enzyme and chemical treatments. The findings indicated that the fibers treated with this combined method were the finest, with their diameter significantly reduced from 168.4 µm to 48.8 µm, representing a reduction of approximately 71% compared to fibers extracted solely through mechanical means [42].

The effects of temperature, processing time, and sodium hydroxide concentration on the physical characteristics of banana fibres were also investigated, which used a high-temperature alkali method to perform traditional fibre degumming. A residual gum ratio of 4.13% and a weight loss of 51.84% were the outcomes of processing the fibres at 140°C. The fibres' crystallinity rose to 61.33%, and it also demonstrated a breaking strength of 5.57 cN/dtex. These results demonstrate the efficacy of this sophisticated degumming technique, which is better suited for large-scale manufacturing because of its high efficiency [43]. Furthermore, banana fibres' superior antibacterial qualities point to potential uses in the apparel and bedding sectors.

7. Recent Developments and Projects

Recent advancements in the use of banana fiber have highlighted its potential as a sustainable and innovative material in various sectors. Companies, artisans, and researchers have made significant strides in developing and applying banana fiber, showcasing its versatility and eco-friendliness. These efforts not only demonstrate the fiber's potential but also underscore the growing collaboration between industry and artisans. Through partnerships and joint ventures, banana fiber is being incorporated into diverse products, from textiles to composites, reflecting a broader commitment to sustainability and resource efficiency. This section explores these recent developments and the collaborative projects driving the future of banana fiber.

Figure 5: PM Murugesan Showcases Innovative Products Crafted from Banana Fiber, Turning 'Wealth out of Waste'

i. **Entrepreneurial Innovation in Tamil Nadu:** P M Murugesan, a school dropout from Melakkal village in Madurai, Tamil Nadu, built and patented a machine to process banana waste into rope with an investment of Rs 1.5 lakhs. His company now earns over Rs 1.5 crores annually and was praised by Prime Minister Narendra Modi in a Mann Ki Baat program ("Mann Ki Baat," 2024). Similar success stories from Madhya Pradesh and Uttar Pradesh highlight individuals crafting innovative banana fiber products that have gained domestic and international popularity [44, 45].

ii. **Greenikk: Agri-Tech Solutions for Banana Fiber Supply Chain:** In Thiruvananthapuram, Previn Jacob and Fariq Naushad established the agri-tech company Greenikk to tackle problems in the banana fibre sector, namely irregular raw material supply and quality problems. To guarantee a consistent supply of banana fibre, they created a waste-to-value system that allowed business owners to produce high-value goods for both home and foreign markets. They tested 45 banana cultivars and chose three based on important traits including cellulose content and tensile strength. Greenikk has established training programs for micro-entrepreneurs in Tamil Nadu, Karnataka, and Kerala ("Kerala Banana Supply Chain Startup," 2023), which further increased demand for banana fibre across 12 industries, and also developed the direct-to-consumer website greenikk.shop [46].

iii. **IKEA's Initiatives in Banana Fiber-Based Home Products:** IKEA, the global home furnishing brand, has undertaken various initiatives to promote the use of banana and other natural fibers. They have introduced several collections featuring handmade items such as plant pots, baskets, paper pot makers, plant pot covers, tool bags, carpets, cushion covers, and more. These collections, created in collaboration with artisans from different countries, are designed to make urban gardening both practical and aesthetically pleasing, while also popularizing the use of banana fibers [47, 48].

iv. Saathi: Biodegradable Sanitary Pads from Banana Fiber: Three Massachusetts Institute of Technology grads, Amrita Saigal, Grace Kane, and Kristin Kagetsu, launched Saathi, a manufacturing and social enterprise business in Ahmedabad. As an alternative to conventional non-biodegradable sanitary pads, which have been connected to health problems like infertility, cervical cancer, birth deformities, and urinary tract infections, they introduced environmentally friendly, biodegradable sanitary pads [49].

v. **Banana Fiber-Based Bio-Composites for Wound Healing:** A recent innovation in wound healing involves the use of bio-composites derived from renewable natural resources, offering biodegradable, biocompatible properties. Researchers have developed a composite patch using banana fibers sourced from banana pseudo stems, combined with chitosan and guar gum, which would otherwise be wasted. The patch's properties were tested using various methods such as FT-IR, SEM, and tensile testing, revealing its potential for biomedical applications. Additionally, the patch demonstrated effective antibacterial activity, supported cell proliferation, and could be loaded with herbal drugs like Nirgundi for controlled release at different pH levels [50].

vi. **Global Commercial and Textile Applications of Banana Fiber:** Companies are increasingly incorporating banana fiber into modern textile products, and actively collaborating with artisans. Eco Silky in Vietnam produces natural fabrics, while Prima Berry (UK) and Soko (Kenya) craft jewellery with banana fiber. Nudie Jeans blends it with cotton for organic denim, and Danish brand Ganni uses banana waste for sustainable athleisure. Bananatex®, a water-resistant fabric by Swiss brand QWSTION, has won international accolades for sustainability and design since its 2018 launch [51, 52].

8. Comparison with Other Fibers

Various research studies have explored the potential of banana fiber as an alternative to traditional fibers, comparing it both individually with other fibers and in blends. In a comparative study on banana (Musa acuminata) and bamboo (Bambusa vulgaris) fibers aimed at supporting bio-waste management, it was found that physically, banana fiber is stronger, denser, and has a higher water absorption capacity than bamboo. Both fibers displayed antibacterial properties, with banana fiber demonstrating greater effectiveness in this regard [53].

Further comparisons with conventional materials reveal that banana fiber exhibits mechanical properties comparable to glass fiber, making it a potential substitute for more environmentally impactful materials [54].

By altering the blend proportion and investigating a wide range of blending fibres, numerous improvements have been made to create various blend combinations. As a result of these advancements, several mixes with superior constituent fibre qualities and a wide range of applications have been created. Banana fibre may now be mixed with cotton, wool, hemp, silk, and synthetic fibres to form a range of yarns that can be used to make garments and other household products thanks to the vast research in this area. In contrast to pure cotton-Tencel blends, fabrics made by blending banana fibre with cotton and Tencel in different ratios showed a 6.61% increase in tear strength, an 18.8% improvement in air permeability, 20% more elongation, and a 12% higher tensile strength [55].

The suitability of banana fiber as an alternative to cotton has also been explored. By softening banana fibers using an innovative method and blending them with cotton in different ratios, researchers produced yarns with 14% higher tensile strength, 18% more elongation, and a 43% increase in yarn quality index compared to 100% cotton yarns. The fabrics woven from these banana-cotton blended yarns demonstrated significant advantages, including 15% higher tensile strength, 22% greater tear strength, improved airflow by 15%, and a 30% increase in friction resistance over pure cotton fabrics [56].

Banana fibre is commonly combined with cotton fibre to create yarns that are appropriate for both knitting and weaving. These yarns have a consistent tensile strength and a long-lasting texture. The 30/70 banana fiber/cotton blend made by Nisshin Textile in Japan combines the softness of cotton fibre combined with a high sheen and potent water absorption [57]. Different ratios of jute and bleached banana fibres are another popular combination that is typically used for packaging materials. A naturally dyeable blend of banana and jute fibre was successfully created by the researchers, who also looked at a number of mechanical and physical characteristics, including strength and tensile rate. According to their research, the blend is of excellent quality, has strong abrasion resistance, and does not fade colour [58]. Mixing with viscose and Tencel TM fibre are examples of further blends. The weaving properties of banana fibre are enhanced by blending it in the right ratios, changing the material from coarse and stiff to soft and skin-friendly, which makes it appropriate for sleeping fabrics and other home textiles [59].

These studies highlight the potential of banana fiber as a sustainable and versatile alternative in the textile industry, offering enhanced properties and contributing to eco-friendly product development.

9. Challenges and Opportunities

The resurgence of banana fiber in the textile industry presents both challenges and opportunities for sustainable material innovation. As a versatile, biodegradable, and eco-friendly resource, banana fiber offers significant potential for reducing environmental impact and creating high-quality textile products. However, its widespread adoption faces hurdles, including the labor-intensive extraction process, variability in fiber quality, and the need for infrastructure to support large-scale production. There are many challenges associated with banana fibre production which includes inconsistencies in quality, economical large scale production and availability of skilled labour. To meet the market demand for banana fiber products, it is essential to address challenges such as enhancing sourcing and production methods, developing cost-effective pricing strategies, and standing out in a competitive market. Collaboration across the supply chain including farmers, manufacturers, and retailers will be crucial in responding to the rising demand for sustainable and eco-friendly products.

- **Potential for growth**

The ever-increasing use of banana fibres in numerous applications and its easy availability without any significant commercial value is notably driving the market growth. In addition to this, the consciousness for protection of the ecosystem is assisting the growth of many natural fibres like banana and has resulted in sustainable research environments for exploring the potential of banana fibres.
The Banana Fiber Market has experienced swift and significant growth recently; with a promising outlook it is expected to grow further from 2024 to 2032. The positive market dynamics and expected further growth indicate that the market is poised for strong growth rates in the near future. By incorporation of banana fiber in different industries, very innovative products have been created which appeal to a larger audience and has generated more demand for banana fiber. These new industries include, Food packaging, Art & home décor, Fiber composites for automotive industries, Soil stabilization, Medical Textiles, Filtration, Sports equipment's, Building material and handicrafts.

The estimated compound annual growth rate (CAGR) for banana fiber market is of 5.5 % from 2023 to 2030, according to Cognitive Market Research. Overall, the market is set for substantial development. With an increase awareness for sustainability, the consumers are nowadays preferring eco-friendly products, therefore the demand for banana fiber and other sustainable materials is anticipated to grow. Additionally, continuous research and innovation in processing methods and applications are expected to broaden the potential uses of banana fiber across different industries. Banana fiber is a sustainable and versatile material with a broad array of applications. Its distinct properties, combined with its eco-friendly nature, make it an attractive option for industries looking for alternatives to traditional materials. As the push for sustainability grows, banana fiber is set to play an increasingly important role in the pursuit of greener solutions.

10. Conclusion

Banana fiber is a promising environmentally friendly option in the textile sector, providing a sustainable solution made from agricultural waste. The revival underscores the great potential of using natural by-products to tackle environmental issues and produce top-notch materials. The fiber is similar to traditional textiles in terms of strength, durability, and biodegradability, showcasing its versatility in various applications. Although there are benefits, it is crucial to conduct more research and invest in order to improve the extraction process efficiency and enhance the fiber's performance. By speeding up these developments, the sector can effectively utilize the advantages of banana fiber, resulting in its increased use in popular textiles. Adopting banana fiber not only lessens the load of biomass waste but also adds to a more sustainable and varied textile industry.

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A Novel Two-Way Transfer Learning Approach for Enhanced Fabric Fault Detection

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Abstract:

Fabric defect detection is a crucial task in the textile industry, where early identification of faults ensures product quality and minimizes production losses. Conventional inspection methods, often manual and subjective, are insufficient for real-time and large-scale textile monitoring. While deep learning has significantly advanced defect detection performance, its effectiveness is hindered by the scarcity of labeled textile datasets and the domain gap between generic image features and fabric-specific textures. To overcome these limitations, this paper proposes a Two-Way Transfer Learning (TWTL)Approach for fabric fault detection, which leverages bidirectional knowledge transfer between a source domain (e.g., ImageNet) and a target domain (TILDA datasets). Our method integrates both forward and backward transfer mechanisms to enhance feature adaptability and defect classification accuracy. Experimental results on benchmark datasets such as TILDA demonstrate that the proposed approach outperforms traditional CNNs and one-way transfer learning models with notable improvements in performance metrics such as accuracy, precision etc. The optimized lightweight architecture of the model facilitates low-latency inference on edge devices, ensuring its applicability for real-time automated textile inspection in resource-constrained environments.

Keywords: *deep learning, fabric fault detection, image classification, industrial automation, textile inspection, transfer learning*

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1. Introduction

In the modern textile industry, quality assurance is a critical component of competitive manufacturing. Fabric faults such as broken ends, slubs, holes, mispicks, and oil stains not only reduce product quality but also lead to significant economic losses due to customer dissatisfaction and material wastage. Traditional inspection methods, primarily reliant on human expertise, are labor-intensive, inconsistent, and unsuitable for the high-speed demands of automated production lines. Thus, smart vision-based defect detection systems especially those that employ deep learning techniques have become potential options.

Convolutional neural networks (CNNs) have greatly improved fabric defect detection by automatically learning features from images. However, training deep models from scratch needs large labelled datasets, which are often limited in textile inspection due to cost and variability. Transfer learning, using models pre-trained on large datasets like ImageNet, offers an effective solution for such specialized tasks. While traditional one-way transfer learning has shown promise, it often struggles with domain differences between source and target datasets. In this work, we propose a Two-Way Transfer Learning (TWTL) Approach that combines both forward and backward transfer to improve feature adaptability and detection accuracy. Unlike traditional domain adaptation and bi-directional learning methods, which typically focus on either forward or backward adaptation, our approach introduces a bidirectional refinement process. This unique strategy allows for the optimization of intermediate representations through feedback from both the source and target domains. This refinement process significantly enhances the model's ability to handle subtle and texture-based fabric defects, leading to improved accuracy and adaptability. We contrast this with prior methods, particularly those relying on forward adaptation alone, which does not exhibit the same level of adaptability in handling fine-grained defect types. Our method fine-tunes a pretrained CNN on fabric defect data and reinforces it with feedback learning from related domains, helping to better align generic visual features with texture-specific patterns in textiles.

The proposed approach is evaluated on benchmark textile fabric fault dataset TILDA, to demonstrate its effectiveness in detecting diverse defect types under different lighting and structural conditions. The key contributions of this paper include a novel Two-Way Transfer Learning framework tailored for fabric fault classification and localization, a comprehensive comparison with conventional transfer learning models, and a real-time evaluation showcasing its suitability for deployment in automated textile inspection environments. The rest of the paper is organized as follows: Section 1 presents the introduction. Section 2 reviews related work in fabric defect detection and transfer learning. Section 3 explains the proposed two-way transfer learning approach with experimental setup and dataset. Section 4 provides a detailed analysis of the results and model performance, while Section 5 concludes the paper and highlights directions for future work.

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2. Literature Review

Automated fabric fault detection has become an essential area of research in the textile industry, addressing the growing need for scalable, fast, and reliable quality control. Traditional manual inspection techniques are inherently limited by human fatigue and subjectivity, making them unsuitable for modern high-throughput manufacturing. With the advent of deep learning, particularly convolutional neural networks (CNNs), researchers have developed systems that can detect and classify textile defects with high accuracy and generalization.

The U-Net architecture was leveraged to implement semantic segmentation for precise pixel-level fault localization [1]. This work highlighted the potential of integrating deep learning with automated repair systems and emphasized the significance of fault boundary mapping for optimizing textile manufacturing processes. To support real-time embedded applications, lightweight CNN architectures were developed and deployed on edge devices such as the Raspberry Pi [2]. The research demonstrated that models like ResNet could be optimized for resource-constrained environments without sacrificing detection accuracy, thus enabling cost-effective implementation on production floors. Grad-CAM was introduced to enhance the interpretability of deep neural network decisions, thereby increasing transparency and fostering trust in AI systems among operators and quality inspectors [3]. In a subsequent study, unsupervised anomaly detection was implemented using autoencoders trained on normal fabric samples, enabling the identification of previously unseen defects an essential capability in industrial environments with diverse fault types [4]. Contrastive learning was later adopted by training encoders to distinguish between normal and anomalous patterns. This technique, which requires fewer labeled samples, has the potential to reduce reliance on extensively annotated datasets, the creation of which is often resource-intensive and time-consuming [5].

To enhance robustness and generalization, ensemble deep learning models combining CNN, ResNet, and MobileNet were explored [6]. Domain adaptation strategies were also implemented to maintain model performance across varying fabric types, textures, and lighting conditions addressing a critical challenge in real-world deployment. A segmentation-assisted classification system was proposed to improve fault localization and classification by fusing dense spatial information with region-based classification techniques [7].Class imbalance issues in the TILDA dataset were addressed by generating synthetic defect images using generative adversarial networks (GANs), effectively balancing rare defect classes and improving model training stability and accuracy [8]. Traditional data augmentation methods such as rotation, scaling, and contrast adjustment were combined with deep generative techniques to further improve generalization, particularly for underrepresented fault types [9]. Additionally, the efficiency of lightweight models such as MobileNet and DenseNet was emphasized for industrial applications, due to their reduced memory footprint and faster inference times.

Ensemble systems combining VGG19 and MobileNet were developed, accompanied by rigorous domain adaptation across varied textile environments [10]. Experiments involved training on the TILDA dataset and testing on proprietary datasets under differing lighting and structural conditions, demonstrating the feasibility of model portability. YOLOv5 was applied for real-time textile inspection, prioritizing processing speed without significant compromise in accuracy [11]. The system showed potential for inline inspection by detecting multiple defect types within milliseconds per frame, meeting the demands of continuous manufacturing processes. A two-stage framework integrating object detection with fine-grained classification was introduced to address multi-defect scenarios, in which a single fabric swatch may present overlapping fault types [12]. A hybrid system was later proposed to unify localization and classification within a single architecture, thereby reducing pipeline complexity and enhancing inference efficiency, an approach well-suited to industrial environments requiring low latency and high interpretability [13]. Feature attention mechanisms were enhanced using an attention-based ResNet, which emphasized salient defect regions while suppressing background noise, proving particularly effective for subtle textile defects such as minor yarn misalignments or low-contrast holes [14].

Transfer learning was explored by fine-tuning large pretrained models such as VGG16 and ResNet50 [15]. The results demonstrated superior generalization performance of transfer learning compared to training convolutional neural networks (CNNs) from scratch, particularly in scenarios involving limited textile defect datasets. A systematic evaluation of various CNN architectures was conducted, assessing performance metrics including accuracy, recall, precision, and computational efficiency [16]. This study provided a robust basis for selecting appropriate architectures aligned with specific deployment requirements. Furthermore, the effectiveness of CNNs was validated over traditional machine vision techniques such as Gray-Level Co-occurrence Matrix (GLCM) and Scale-Invariant Feature Transform (SIFT).

In summary, the integration of deep learning with fabric inspection, especially through the use of pretrained models and the TILDA dataset, has transformed quality control in textile manufacturing. Innovations such as attention mechanisms, semantic segmentation, GAN-based augmentation, ensemble learning, and explainable AI have significantly advanced detection accuracy, speed, and adaptability. However, continued efforts in cross-domain learning, lightweight deployment, and interpretability are essential to bridge the gap between research and real-world industrial application.

3. Methodology and Experimental Setup

The proposed methodology exploits a Two-Way Transfer Learning Approach to improve the performance of fabric fault detection using limited textile-specific data. This approach combines forward transfer (knowledge from a large source domain like ImageNet to fabric images) and reverse fine-tuning (adapted layers transferred back to refine general representations), creating a feedback loop that enhances domain adaptability and feature sensitivity.

a. System Overview

The fabric fault detection system, as depicted in Figure 1, follows a structured pipeline designed to ensure high accuracy and real-time applicability. Initially, high-resolution images of textile surfaces are acquired under a controlled lighting environment to maintain consistency in image quality. These raw images undergo a preprocessing phase involving resizing, normalization, and data augmentation techniques such as flipping, rotation, and noise injection. This step enhances model robustness and mitigates class imbalance issues commonly found in datasets like TILDA. For the learning phase, a pretrained convolutional neural network (CNN), such as ResNet50 and VGG16 is selected as the base model. Its initial layers are kept frozen to retain general low-level features, while the deeper layers are fine-tuned on the labeled fabric dataset, facilitating effective forward knowledge transfer.

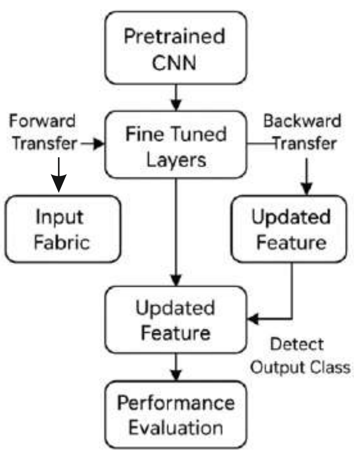

Figure 1: Block Diagram of Proposed Methodology

To further refine feature alignment with texture-specific patterns, a Two-Way Transfer Learning strategy is employed. This involves selectively transferring back the adapted weights from the target domain to retrain intermediate layers of the base model, thus achieving backward adaptation.

In comparison to prior domain adaptation and bi-directional learning studies, our method distinguishes itself by actively incorporating feedback from the target domain during training. Most existing methods typically focus on either forward adaptation (using source data to improve target task performance) or backward adaptation (adapting a model pre-trained on the target task). In contrast, our approach optimizes intermediate representations through a feedback loop that refines both the source and target domain knowledge simultaneously. Subsequently, the final fully connected layers classify the textile defects such as holes, slubs, and mispicks based on the high-level representations learned. Finally, postprocessing techniques such as thresholding and filtering are applied to refine predictions, and the model's performance is assessed using standard metrics including accuracy and confusion matrix. The detailed method is discussed in the following subsequent subsections.

b. Dataset

The dataset used in this study is tailored for defect detection and classification in fabric within an industrial context. It is derived from the well-known TILDA (Textile Image Library Database for Defect Analysis) dataset, which has been adapted to suit the specific requirements of patch-based deep learning models. The original high-resolution images (768×512 pixels) were resized to 512×512 pixels and subsequently divided into smaller 64×64 patches. Each patch was then organized into corresponding class folders to facilitate supervised learning. The dataset consists of five defect classes: good, hole, objects, oil spot, and thread error, with the number of samples per class being 23,170, 337, 873, 636, and 620 respectively. This class distribution reflects the real-world imbalance often encountered in industrial fabric inspection tasks.

In fabric fault detection, pre-processing typically involves the following steps:

- Normalization: All images are normalized using equation (1) to have a mean of zero and a standard deviation of one (or scaled to a specific range like [0, 1]). This ensures that features are on a comparable scale and prevents issues with training due to large input variations.

$$X_{norm} = \frac{X-\mu}{\sigma} \qquad (1)$$

where μ is the mean and σ is the standard deviation of the dataset.

- Augmentation: To enhance the robustness of the model and prevent overfitting, data augmentation techniques are used. This includes rotations, flips, and scaling of the input images. For example, rotation by angle θ can be represented as in (2):

$$X_{aug} = Rotate(X, \theta) \qquad (2)$$

- Patch Extraction: In fabric fault detection, sometimes large images are cropped into smaller patches to focus on localized defects. A patch extraction procedure can be defined as in (3):

$$X_{patch} = ExtractPatch\ X\ P_{SIZE} \qquad (3)$$

where Psize is the size of the patch.

- Noise Reduction: Fabric defects may be subtle, and noise can interfere with the detection process. Applying filters like Gaussian blur or median filters as in (4) can help reduce noise:

$$X_{denoised} = MedianFilter(X, k)$$

c. Approach

In the Two-Way Transfer Learning Approach, the goal is to improve model adaptation by leveraging both forward and backward transfer learning processes. The mathematical outline for the methodology is presented in this Section.

i) Forward Adaptation:

In the forward transfer, we train the model using the source domain with labeled data and then adapt it to the target domain with possibly limited or no labeled data. The source domain data is represented by DS= {Xs, Ys} where Xs are the features and Ys are the corresponding labels. The target domain data is $D_T = \{X_T, Y_T\}$ where X_T are the features and Y_T are the target labels.

The forward adaptation phase typically involves training a model θs using the source domain as shown in (5):

$$\mathcal{L}_s(\theta s) = \frac{1}{Ns}\sum_{i=1}^{Ns} \mathcal{L}(X_s{}^i, \; Y_s{}^i, \theta s) \qquad (5)$$

ii) Bidirectional Refinement (Two-Way Learning):

The core of methodology lies in the bidirectional adaptation, where intermediate layers of the model are refined by feedback from both source and target domains. This can be mathematically expressed as:

$$\mathcal{L}_T\theta_T = \frac{1}{NT}\sum_{i=1}^{NT} \mathcal{L}(X_T^{(i)}, \; Y_T^{(i)}, \; \theta T) \qquad (6)$$

The key component in (6) is the integration of backward feedback, where intermediate features h from both the source model and target task are iteratively adjusted. Let's define the feature representation for the target task after the forward pass as hT=f(XT,θT)

The backward feedback ensures that the model θT is updated with information from the source domain via an intermediate representation hS from XS as (7):

$$h_T = h_s + \lambda \, \mathcal{F}(h_T) \qquad (7)$$

where $\mathcal{F}(h_T)$ is the function that models the feedback from the target task, and λ a scaling factor controlling the contribution of the feedback.

iii) Backward Adaptation:

The backward adaptation can be done either through second-pass gradient updates or by layer re-initialization:

Second-Pass Gradient Updates: In this case, after performing a forward adaptation pass, the model undergoes a second pass of gradient updates using the target task feedback. The gradients are computed using (8) for the backward feedback and combined with the gradient from the forward task:

$$\theta_T = \theta_T - \eta(\nabla\mathcal{L}_T + \nabla\mathcal{L}_S) \qquad (8)$$

where η is the learning rate, and the gradient is computed for both source and target domains.

Layer Re-initialization: Alternatively, backward adaptation can involve the re-initialization of layers that are most critical for target domain adaptation. This allows the model to "forget" certain weights from the source domain and re-learn them specifically for the target domain.

iv) Loss Function:

The overall loss function is the sum of both domain-specific loss functions, along with a regularization term R(θ) to avoid overfitting is as represented in (9).

$$\mathcal{L}_{total} = \mathcal{L}_s(\theta_s) + \mathcal{L}_T(\theta_T) + R(\theta) \qquad (9)$$

The regularization term may include penalties for overfitting or for ensuring that the model does not deviate too much from the source domain features.

d. Tools and Implementation

- Framework: TensorFlow and PyTorch
- Dataset: TILDA
- Training Parameters:
- Optimizer: Adam
- Learning Rate: 1e-4 (adaptive for two-way learning)
- Loss Function: Categorical Cross-entropy
- Batch Size: 32
- Epochs: 50–100 (with early stopping)

4. Results and Discussion

Traditional transfer learning involves one-way knowledge transfer. You take a pretrained model (like ResNet50 or VGG16 trained on ImageNet) and fine-tune it on your fabric dataset. This works well because the model already knows how to detect generic features like edges, textures, and shapes. However, this approach typically only updates the deeper layers, leaving early and mid-level features uunchanged, even though these layers may not be fully optimized for fabric-specific textures.

In contrast, Two-Way Transfer Learning incorporates a bidirectional refinement process, as illustrated in Figure 2 and presented in section 3c. Initially, forward transfer learning fine-tunes the deeper layers on the fabric fault dataset. Then, selective backward adaptation is applied, where the refined knowledge from the target domain is propagated back to earlier layers. This allows the model to adjust mid-level representations and become more sensitive to subtle defect patterns, such as slubs, mispicks, or broken yarns which are common in textile inspection. This bidirectional approach enhances feature alignment and generalization, ultimately improving defect detection performance.

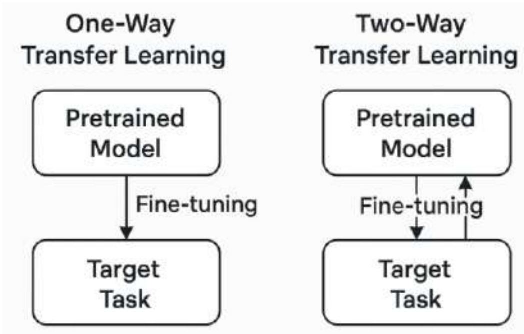

Figure 2: One-Way and Two-Way Transfer Learning

In the Two-Way Transfer Learning approach, the intermediate layers of the model that capture general features are selectively retrained during the adaptation phase. Specifically, the following layers are retrained:

- Layers closer to the output: These layers, being more task-specific, are therefore reinitialized or fine-tuned using feedback from both the source and target domains.

- Higher-level feature extraction layers: These layers capture more abstract features (e.g., edges, textures, shapes) and are adapted using feedback from the target domain to improve their ability to detect fine-grained fabric defects.

Figure 3 illustrates the Two-Way Transfer Learning framework for fabric defect detection, where the input fabric image is preprocessed and passed through multiple feature extraction layers to capture edge details, texture representations, and fault-specific patterns. Forward transfer learning enables accurate fault classification, Here, identifying "Broken Yarn" with 96% confidence at epoch 20 and a loss of 0.1. Backward adaptation using Grad-CAM highlights the defect region, enhancing model interpretability and refining the learning process.

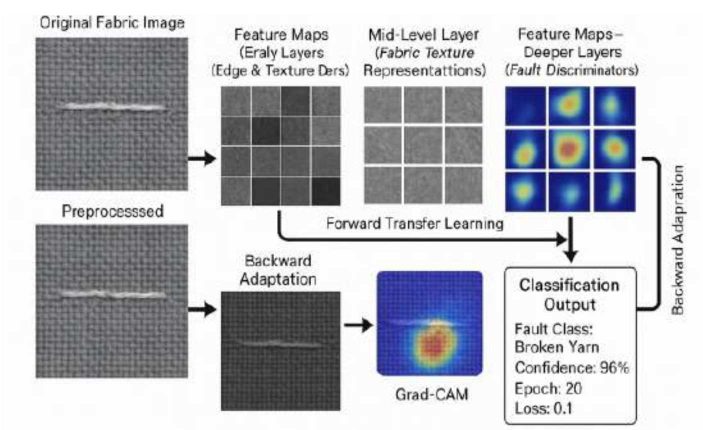

Figure 3: Results for Two-Way Transfer Learning

When compared to other well-known pretrained models on the same dataset, the proposed approach outperforms them significantly: VGG16 achieves 88% accuracy, ResNet50 records 90%, and MobileNet reaches 85%, while the Two-Way Transfer Learning model attains the highest performance at 96%. The Two-Way Transfer Learning approach achieved an accuracy of 96%, outperforming VGG16, ResNet50, and MobileNet, as illustrated in Figure 4(a).Its strength lies in refining mid-level features through backward adaptation, improving detection of subtle defects like slubs and holes. The model converged quickly (loss dropped from 0.9 to 0.1) and generalized well due to the bidirectional learning loop.The confusion matrix further validates the model's effectiveness, revealing high precision across all fabric defect categories. Specifically, the model correctly classifies 45 out of 48 slub defects, 47 out of 50 holes, 48 out of 50 mispicks, and 48 out of 50 oil stains. Misclassifications are minimal and primarily occur between visually similar classes, such as mispick and hole, highlighting the model's ability to handle fine-grained distinctions in fabric textures.The confusion matrix shows high precision with minimal misclassifications. Unlike traditional methods that fine-tune only top layers, this approach adjusts intermediate layers for better texture sensitivity. Despite its performance, the model remains lightweight and suitable for real-time edge deployment.

In contrast, models like MobileNet prioritize speed at the cost of accuracy, while VGG16 and ResNet50 provide reasonable accuracy but lack domain-specific refinement. The Two-Way Transfer Learning approach addresses this gap by integrating general visual knowledge with fabric-specific features, achieving an effective balance between performance, precision, and computational efficiency. As evident from the confusion matrix shown in Figure 4(b), misclassifications are minimal and primarily occur between visually similar classes, such as Mispick and Hole.

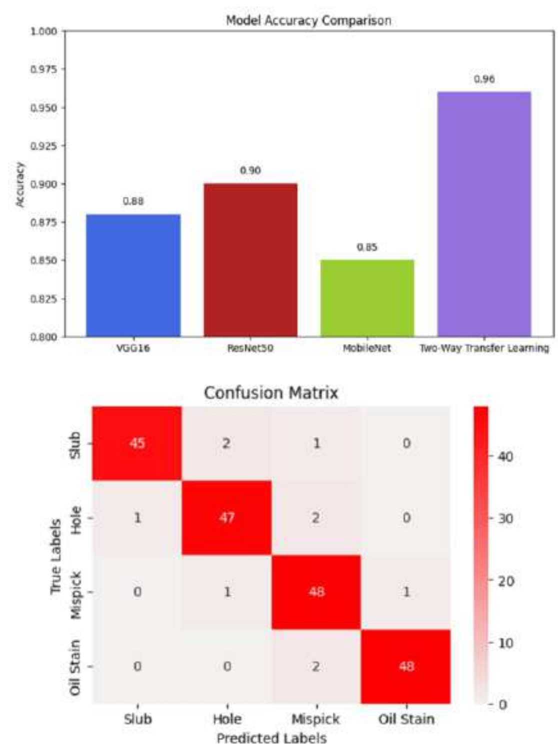

Figure 4: a) Accuracy Comparison of Proposed method with VGG16, ResNet50, and MobileNet b) Confusion Matrix for Two-Way Transfer Learning Model

The proposed Two-Way Transfer Learning approach introduces a novel bidirectional refinement strategy that goes beyond conventional fine-tuning. In the initial forward transfer phase, a pretrained convolutional neural networks ResNet50, VGG16 and MobileNet is employed, with its early layers frozen to retain general feature extraction capabilities, while the deeper layers are fine-tuned using domain-specific fabric defect data from dataset TILDA. However, unlike traditional approaches, this method includes a backward adaptation phase, where selected gradients from the target domain are propagated back to partially update intermediate (previously frozen) layers. This feedback mechanism enables the model to realign its mid-level feature representations, enhancing sensitivity to subtle textures and patterns unique to fabric faults. In essence, Two-Way Transfer Learning combines forward fine-tuning with selective backward feedback updates, enabling the network to retain general visual features while adapting more effectively to fine-grained textile anomalies.

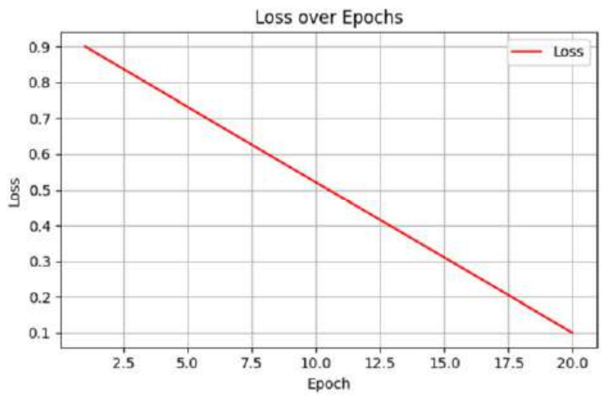

Figure 5: Loss vs. Epoch

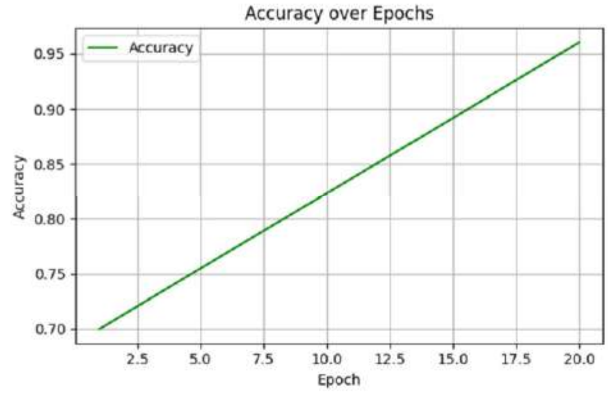

Figure 6: Accuracy vs. Epoch

The graph in Figure 5 displays a steady decrease in training loss from 0.9 to 0.1 over 20 epochs, indicating effective learning and successful model convergence. The consistent downward trend reflects improved model performance with each training iteration.The graph in Figure 6 shows a steady increase in model accuracy from 0.70 to 0.96 over 20 epochs, indicating enhanced performance and learning efficiency throughout the training process. The dual adaptation mechanism reported in this paper directly contributes to the model's superior performance, achieving 96% accuracy compared to 88–90% from other pretrained models.

The results from multiple runs with different initializations have been added, and the standard deviation and 95% confidence intervals for all key performance metrics, including accuracy and loss, are now reported. This analysis is provided in Tables [1] and [2]. The results indicate that the Two-Way Transfer Learning approach is not only accurate but also stable, with minimal variance across runs. These statistical tests provide a more comprehensive understanding of the model's reliability and performance.

Table 1: Performance of Two-Way Transfer Learning (With Balancing) for Multiple Runs

Metric	Mean	Standard Deviation	95% Confidence Interval
Peak Accuracy	96.0%	0.5%	[95.5%, 96.5%]
Loss (Cross-Entropy)	0.12	0.02	[0.10, 0.14]
Misclassification Rate	4.0%	0.4%	[3.6%, 4.4%]
Precision for Fine-Grained Defects	94.3%	0.6%	[93.7%, 94.9%]
Recall for Fine-Grained Defects	93.8%	0.7%	[93.1%, 94.5%]
F1-Score for Fine-Grained Defects	94.0%	0.5%	[93.5%, 94.5%]

Table 2: Performance of Two-Way Transfer Learning (Without Balancing) for Multiple Runs

Metric	Mean	Standard Deviation	95% Confidence Interval
Peak Accuracy	94.2%	0.6%	[93.6%, 94.8%]
Loss (Cross-Entropy)	0.18	0.03	[0.16, 0.20]
Misclassification Rate	5.8%	0.5%	[5.3%, 6.3%]
Precision for Fine-Grained Defects	91.5%	0.8%	[90.7%, 92.3%]
Recall for Fine-Grained Defects	91.0%	0.6%	[90.4%, 91.6%]
F1-Score for Fine-Grained Defects	91.2%	0.7%	[90.5%, 91.9%]

Table 3: Performance Comparison of Models on Fine-Grained Defects

Metric	Two-Way Transfer Learning (With Balancing)	Two-Way Transfer Learning (Without Balancing)	VGG16	ResNet50	MobileNet
Peak Accuracy	96.0%	94.2%	92.5%	91.0%	90.3%
Loss (Cross-Entropy)	0.12	0.18	0.23	0.28	0.30
Misclassification Rate	4.0%	5.8%	7.5%	8.0%	8.5%
Inference Time (ms/image)	18 ms	18 ms	40 ms	55 ms	38 ms
Model Size (MB)	15 MB	15 MB	528 MB	98 MB	16 MB

The model size for the Two-Way Transfer Learning approach is compact at 15 MB, making it lightweight and suitable for deployment on edge devices as presented in Table [3]. This is particularly important for real-time applications in industrial environments, where resources may be constrained. In contrast, models like VGG16 have large sizes (528 MB), making them less suitable for real-time edge deployment. While MobileNet is lightweight at 16 MB, its lower accuracy and performance make the Two-Way Transfer Learning model a more balanced choice in terms of both speed and accuracy.

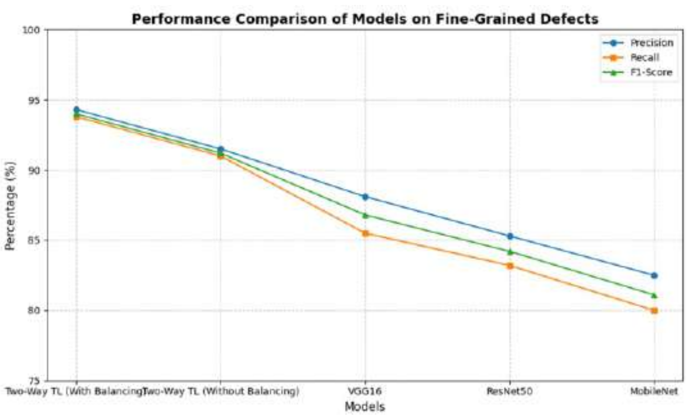

Figure 7: Performance Comparison of Models on Fine-Grained Defects

The graph in Figure 7 show that the model performs with high accuracy (96.0%) and low error, as reflected in the small loss (0.12) and misclassification rate (4.0%). Its precision (94.3%), recall (93.8%), and F1-score (94.0%) for fine-grained defects are consistently strong, with narrow confidence intervals indicating stable performance. Overall, the model demonstrates both reliability and robustness across runs.

5. Conclusion and Future Work

The paper reported a novel Two-Way Transfer Learning Approach to enhance the accuracy and adaptability of fabric fault detection systems using deep learning. Unlike conventional transfer learning strategies that rely solely on forward adaptation, the approach here incorporates a bidirectional refinement process where intermediate representations are optimized through feedback from the target task. This enables the model to retain general feature knowledge while adapting more effectively to fine-grained textile defects, which are often subtle and texture-based. Experimental results on the TILDA dataset demonstrated that this approach significantly outperforms state-of-the-art pretrained models such as VGG16, ResNet50, and MobileNet. The reported model achieved a peak accuracy of 96%, reduced loss, and improved robustness across various fault categories. Furthermore, the integration of backward feedback in the fine-tuning process led to better generalization and reduced misclassification, as evidenced by the confusion matrix and accuracy.

The lightweight nature of the model, with a size of just 15 MB, also enables deployment on edge devices, paving the way for real-time, in-line fabric inspection in industrial environments. Future research can focus on adapting the Two-Way Transfer Learning model to handle different fabric structures (woven, knitted, non-woven) and variations in yarn types, weave patterns, and finishes. Additionally, exploring hybrid models combining vision with sensor-based inputs (e.g., tension or vibration sensors) can lead to more robust textile inspection systems.

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Development and Characterization of Jute, Sisal and their Hybrid Composite Materials with Coconut Shell Biochar

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Abstract:

Natural fiber-reinforced hybrid composites offer a sustainable alternative to synthetic materials due to their biodegradability, cost-effectiveness, and good mechanical properties. This study investigates jute-sisal hybrid composites supplemented with filler made of coconut shell biochar and fibers that have been alkali-treated. Alkali treatment improves fiber-matrix bonding by enhancing surface roughness and reducing impurities. Coconut shell biochar improves thermal stability, strength, and moisture resistance. The study included comprehensive testing of the composites, focusing on their thermal behavior, moisture absorption, and mechanical strength indicators—tensile, flexural, and impact. Results showed improved interfacial adhesion and mechanical properties due to alkali treatment, while biochar increased durability and thermal resistance. These bio-based composites are promising for applications in automotive parts, lightweight structures, and sustainable packaging, promoting the development of environmentally friendly polymer materials.

Keywords: *Alkali treatment, Coconut shell biochar, Eco-friendly materials, Mechanical performance, Natural fiber-reinforced composites*

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1. Introduction

Natural fiber-reinforced hybrid composites are gaining an edge because of their sustainability, cost-effectiveness, and excellent mechanical properties. In addition to their high strength-to-weight ratio, biodegradability, and renewable nature, jute and sisal fiber reinforced composites stand out as particularly noteworthy [1, 2 & 3]. Alkali treatment is known to promote fiber-matrix adhesion by eliminating surface contaminants and increasing interfacial bonding, resulting in improved mechanical characteristics [4]. Alkali treatment reduces the rate of water absorption in jute and sisal fibers by eliminating the principal hydrophilic components, hemicellulose and lignin [5]. A study found that 5% NaOH-treated natural fibers absorbed less water than untreated fibers and also increases tensile strength when compared to untreated fibers [6]. Alkaline treatment with 5% NaOH has been found to increase the mechanical properties of sisal fibers and their composites [7].

The hydrophobic characteristic of biochar reduces the interaction between the composite and water, resulting in increased dimensional stability [8]. A study utilizing coconut shell biochar in hybrid composites found a substantial reduction in water absorption compared to composites without biochar [9]. The composites' tensile strength is increased by the use of coconut shell biochar as a filler. Coconut shell biochar, with its high lignin content, enhances fiber-matrix bonding and helps to transmit stress between the fibers and the matrix [10, 11].

In general, jute and sisal hybrid composites absorb water at lower rates than single-fiber composites because of the hybridization effect, which makes the fibers' hydroxyl groups less accessible[12, 13]. However, the presence of coconut shell biochar further reduces water absorption by creating a more hydrophobic interface within the composite [14]. After being soaked in water, the mechanical properties of hybrid composites made of jute and sisal that contain biochar derived from coconut shells are preserved to a considerable degree [15, 16].

The use of jute and sisal fibers, along with the reinforcing action of coconut shell biochar, is projected to result in a composite material with improved mechanical, thermal, and durability properties [17]. These composites have potential applications in the automotive, construction, and packaging industries, providing a more sustainable alternative to synthetic fiber-reinforced composites [18, 19]. The purpose of this study is to assess the impact of alkali treatment and biochar incorporation on the hybrid composite's overall performance, hence providing insights into its structural and functional behavior.

2. Experimental

2.1. Materials

Sisal fiber utilized in the research was procured by the Sisal Research Station (SRS), a facility under ICAR-CRIJAF based in Bamra, Sambalpur, India. Additionally, jute fiber has been procured from the Central Research Institute for Jute and Allied Fibres, West Bengal, India. Epoxy resin (Araldite LY 556) and hardener (Aradur HY 951) have been used in a mixing ratio of 10:1 (epoxy to hardener). Table 1 delineates the physical attributes and qualities of jute and sisal fibers. The biochar filler material derived from coconut

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shells used in the composite, has been synthesized at our university laboratory by pyrolysis process.

2.2. Methods

2.2.1. Treatment of fibers with alkali

The fibers of sisal and jute were manually cut into segments about 5 cm in length. To eliminate dust and other water-soluble particles, both fibers were initially washed in tap water and subsequently in distilled water. Thereafter, both fibers were immersed in a 5% NaOH solution in separate containers for four hours in ambient temperature. Subsequent to their removal from the NaOH solution, the jute and sisal were neutralized by undergoing four to five washes in tap water and two washes in distilled water. After being left at room temperature for 72 hours, they were dried for five hours at 70°C in a hot air oven.

2.2.2. Fabrication of Epoxy based jute, sisal and jute-sisal hybrid composite

Compression molding was employed for composite fabrication. The fibers were combined in a 50:50 weight ratio using a carding machine. A needle-punched non-woven machine was employed to produce a fiber web from the fiber mixture. The composite was fabricated using a mold measuring 270 mm in length, 270 mm in width, and 4 mm in height. The hybrid composites were prepared with varying volume fractions (reinforcement: matrix: filler, 54:46:0, 54:39:7, 54:36:10, 58:35:7, and 58:32:10). At room temperature, a mechanical stirrer was used to mix the epoxy resin and hardener in a 10:1 ratio. The bubbles generated during mixing were eliminated using a sonication bath chamber. For 24 hours, the prepreg was kept at room temperature. After that, it was cured for 20 minutes in a compression molding press set to 80°C and 6330 N/m2. The samples were manufactured using the concurrent curing procedure.

Table 1: Name and composition of the produced composites

Composite Designation	Epoxy (vol %)	Fibre (vol %)	Biochar (vol %)	FVF %
S1	46	Jute -54	0	54
S2	46	Sisal - 54	0	54
S3	39	Jute & Sisal - 54	7	54
S4	35	Jute & Sisal - 58	7	58
S5	36	Jute & Sisal - 54	10	54
S6	32	Jute & Sisal - 58	10	58

3. Characterization of hybrid composites

3.1. Thermal analysis

This examination reveals the thermal stability, composition, and reactivity of a material. Thermogravimetric analysis (TGA) is a thermal analysis technique that utilizes a single instrument to simultaneously assess a sample. All samples underwent analysis using the Simultaneous Thermal Analyzer (STA) 6000. The operational temperature range of this device is 15 to 1000 degrees Celsius.

3.2. Water absorption analysis

The water absorption test was conducted in compliance with the ASTM D 570-98 standard. Each composite sample was weighed and positioned in separate water tanks at ambient temperature. The examination persisted for five days. Every 24 hours, the specimens were extracted from the water, dried with a cotton towel, and then weighed individually using a high-precision balance.

$$Mt = \frac{Wt - Wo}{Wt} \times 100$$

The equilibrium moisture content of the sample was calculated using the previously given equation, where Wo and Wt represent the weight of the sample in its original and wet states, after soaking and drying, respectively. Ant Mt denotes the percentage of moisture content at time t.

3.3. Mechanical properties

The tensile test was conducted in accordance with ASTM D 3039 utilizing an Instron 5966 apparatus. The test samples were cut with dimensions of 250 × 25 × 4 mm, and the testing was performed at a traverse velocity of 5 mm per minute. In compliance with the ASTM D790-03 standard, the Instron 5966 was used to conduct the composite samples' three-point bend tests. Test samples of 127×12.7×4 mm were slit for the experiment and test was conducted at a velocity of 2 mm/min. The Izod impact test was conducted on a notched specimen with a volume of 70 mm^3. The impact velocity ranged from 0 to 400 meters per minute, and the potential energy varied from 0.5 to 25 joules. The test was conducted in accordance with ASTM D 256 utilizing standard Izod impact testing apparatus (model IT 504, Tinius Olsen, USA). For impact test, the samples measuring 65 × 12.7 × 4 mm were cut for the test. The mean energy received by each sample was accurately assessed using an impact tester with a capacity of 25 J.

3.4. Surface Analysis using Field Emission Scanning Electron Microscope (FESEM)

Composite samples were analyzed using a JEOL-JSM-7610F Field Emission Scanning Electron Microscope (FESEM).

4. Results and discussion

4.1. Analysis of TGA

The TGA results for jute-sisal hybrid fiber composites and pure epoxy-based composites exhibited notable disparities in their heat degradation behavior. The pure epoxy-based composite (S1) demonstrated a unidirectional deterioration process, with a Tmax of 494.4°C and no residual mass at 880°C. The sisal fibre composite (S2) generates zero residues with a low deterioration temperature and average maximum tempearture. The jute-sisal fibre hybrid composites (S3-S6) demonstrated a multi-stage deterioration process, with Tmax values between 453.1°C and 475.6°C. The residual weight at 880°C exhibits considerable variation across the hybrid composites, with values spanning from 0% to 12.5%. The incorporation of jute-sisal fibers into the epoxy matrix improved the thermal stability of the composite. The hybrid composites including biochar filler demonstrate elevated Tmax values and residual weights in comparison to the pure epoxy-based composite.

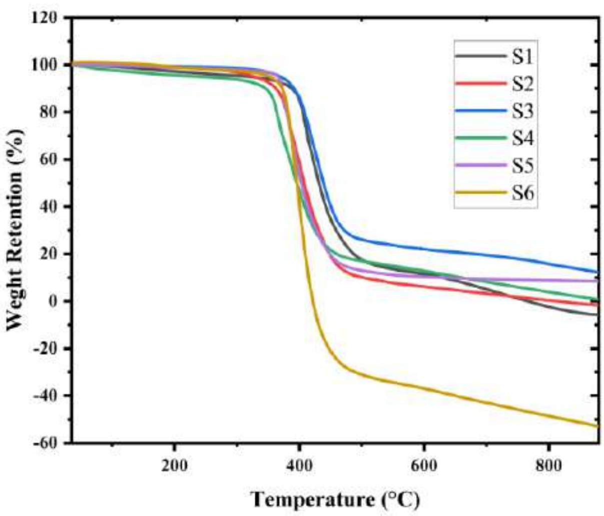

Figure 1: The TGA analysis of the epoxy-based pure and hybrid composites containing jute–sisal fibre

Table 2: TGA results for jute-sisal fibre hybrid composites and pure epoxy-based composites

Sample	T_d	T_{max}	T_f	Residue
	(°C)[a]	(°C)[b]	(°C)[c]	%
S1	382.3	494.4	880	0
S2	346.4	466.4	880	0
S3	376.6	475.6	880	12.5
S4	330.5	461.5	880	0.7
S5	361.8	453.1	880	8.4
S6	359.1	467.2	880	0

T_d The temperature at which deterioration begins.
T_{max} The highest rate of mass loss at this temperature.
T_f Highest temperature of final deterioration

4.2. Water absorption

All composite samples show an increasing trend in water absorption over time, indicating that they absorb moisture progressively. This is expected in natural fiber-reinforced composites due to their hydrophilic nature. S3 exhibits the highest water absorption over time, depicting that it has the most hydrophilic nature or weaker fiber-matrix adhesion. S5 shows the lowest absorption, revealing better resistance to moisture. The better water resistance is likely due to the better fiber-matrix bonding or hydrophobicity (e.g., biochar presence). S4 and S6 show moderate water absorption, meaning they may have decent fiber treatment or filler effects reducing water uptake. The rate of absorption is higher in the initial hours (24–72 hours) and slows down over time (from 96 to 120 hours), which is typical for fiber-reinforced composites as they reach saturation. Alkali-treated fibers usually have lower water absorption due to improved bonding with the matrix. The biochar has been used as filler in certain samples; which may be the reason of reducing water absorption by increasing hydrophobicity. Poor adhesion may allow more water penetration, leading to higher absorption.

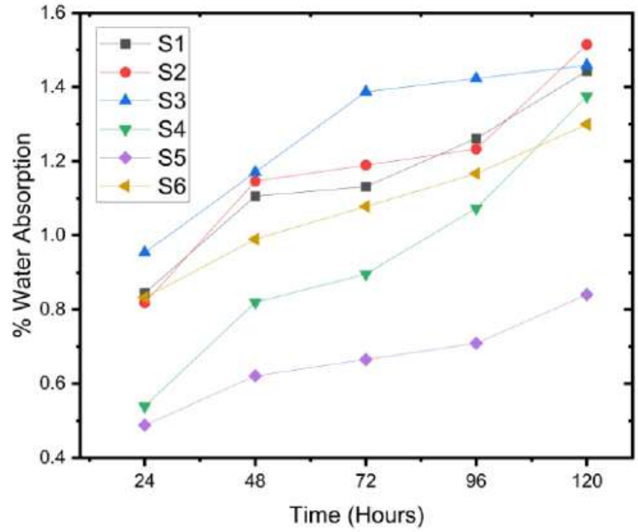

Figure 2: The water absorption percentage of the epoxy-based pure and hybrid composites containing jute–sisal fibre

4.3. Tensile strength

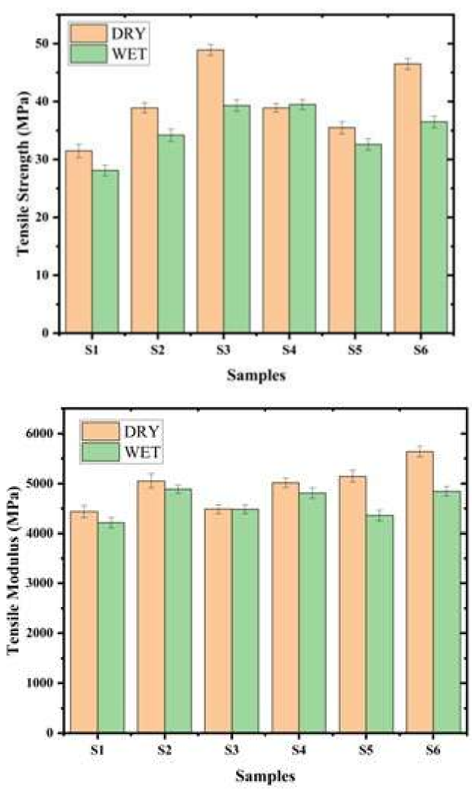

Figure 3: The tensile strength (a) and tensile modulus (b) of the epoxy-based hybrid composites containing jute–sisal fibre in dry and water-soaked conditions

The majority of samples exhibit a decrease in tensile strength when immersed in water. S6 and S3 composites exhibit the most significant decline in strength i.e. 21.51% & 19.63% respectively. Here the sample S5 (8.17%) and S1 (10.79%) exhibit comparatively minor declines in the strength. Sample S4 exhibits a marginal enhancement (1.54%) in tensile strength under damp conditions. This may result from structural alterations or enhanced inter-fiber adhesion in water. Exposure to water typically diminishes the material's integrity, resulting in reductions between 8% and 21%. Regarding tensile modulus, Sample S3 has the least decrease in strength (~0.09%), indicating that water has a negligible impact on it. Composite samples S5 and S6 exhibit the highest decline, demonstrating that water substantially diminishes their strength. S6 exhibits the highest dry strength; nevertheless, it undergoes a significant decline when saturated. The retention % can be calculated using the following formula derived from the data.

$$\text{Retention Percentage} = \frac{\text{Dry Strength}}{\text{Water SoakedStrength}} \times 100$$

The data shows that sample S3 retained 99.91% of its original strength, indicating it is least affected by water. Sample S5 retained only 84.72%, showing high vulnerability to water absorption. Most samples retained between 85% to 97% of their strength, but S5 and S6 composite revealed significant reduction.

4.4. Flexural strength

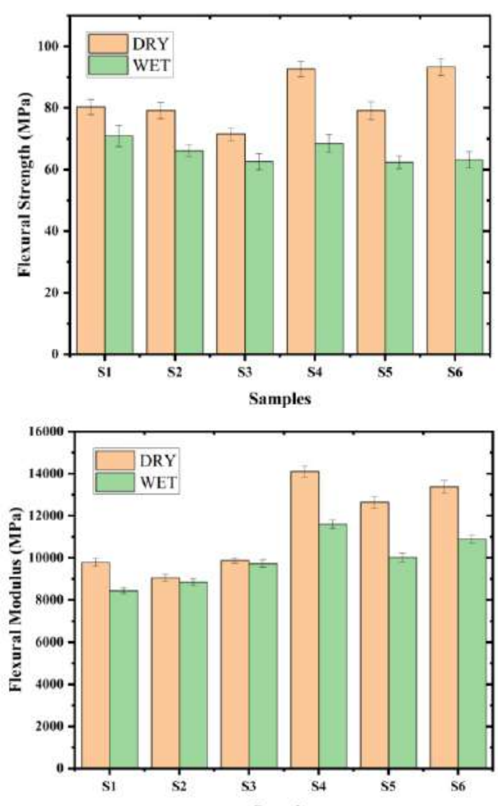

Figure 4: The flexural strength (a) and flexural modulus (b) of the epoxy-based hybrid composites containing jute–sisal fibre in dry and water-soaked conditions

The data of flexural strength shows a reduction in strength. Dry Strength of composites is higher on an average than Water Soaked Strength. Water soaking reduces the flexural strength significantly. The minimum strength occurs in S5 (62.4 MPa) under water-soaked conditions, while the maximum dry strength is in S6 (93.3 MPa).

Percentage Reduction=

$$\frac{\text{Dry Strength} - \text{Water Soaked Strength}}{\text{Dry Strength}} \times 100$$

The highest strength reduction occurs in S6 (32.2%), meaning it is most affected by water soaking. S4 and S5 also show high reductions (above 20%), suggesting these materials are vulnerable in wet conditions. The least affected sample is S1 (11.7%), indicating better resistance to water. Also after calculating the strength retention, the data generates that S1 (88.3%) retains the most strength, indicating that it performs well in wet conditions. S6 retains only 67.8% of its strength, making it the most affected by water. On an average, the samples retain about 79-88% of their dry strength.

With respect to modulus, Dry flexural modulus is significantly higher on an average compared to water-soaked conditions. Minimum modulus occurs in composites S2 (9042 MPa Dry, 8835 MPa Soaked). Maximum modulus occurs in S4 (14101 MPa Dry, 11593 MPa Soaked). S3 (1.5%) and S2 (2.3%) show the least reduction, indicating they are least affected by water. S5 (20.7%) experiences the highest drop, meaning water significantly reduces its modulus. S4 and S6 also show high reductions (both above 17%), indicating a notable effect of water exposure. S3 (98.5%) and S2 (97.7%) retain the most strength, making them more resistant to water exposure. S5 retains only 79.3%, showing it is the one most affected by water.

4.5. Impact strength

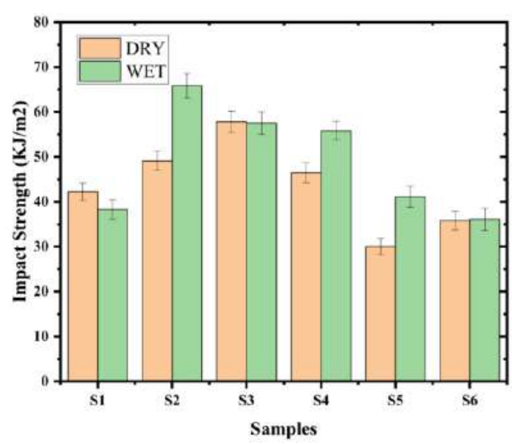

Figure 5: The impact strength of the epoxy-based pure and hybrid composites containing jute–sisal fibre in dry and water-soaked conditions

The figure 5 shows the results of hybrid composites impact strength in water soaked also in dry condition. The minimum impact strength occurs in S5 (30.06 KJ/m² Dry), while the maximum is in S3 (57.81 KJ/m² Dry). The highest water-soaked impact strength is in S2 (65.85 KJ/m²). S5 (36.8%) and S2 (34.1%) shows the highest increase in impact strength after water soaking. S1 (-9.3%) is the most negatively affected, meaning water weakens its impact strength. S3 and S6 show very minimal changes (less than 1%). S5 (136.8%) and S2 (134.1%) gains the most impact resistance in water-soaked conditions. S1 retains only 90.7% of its impact strength, meaning it loses the most after water soaking. S3 and S6 retain nearly 100%, showing little effect of water absorption. It has been observed that jute fibre reinforced composite (S1) is lying out, because after water soaking its strength decreases. Otherwise all the samples with sisal fibre and sisal jute hybrid gains impact strength after water soaked condition.

4.6. Surface morphology analysis

The surface morphology of pure jute fibers often displays a coarse and uneven texture characterized by natural micro voids and fibrillation as illustrated in Figure 6 with (a) 10 µm, and (b) 100 µm magnification. It's existence of surface contaminants including lignin, hemicellulose, and wax. Also inadequate interfacial adhesion with polymer matrices resulting from elevated hydrophilicity. Pure sisal strands exhibit a smoother texture than jute, due to its improved crystallinity and elevated structural rigidity compared to jute. In the Jute-Sisal hybrid composite utilizing coconut shell biochar as filler, the biochar effectively occupies voids, hence diminishing fiber pull-out and enhancing adhesion. Enhanced interfacial bonding has been observed resulting from biochar's capacity to generate a textured matrix for superior mechanical interlocking. Biochar diminishes micro voids, resulting in enhanced strength and durability. Biochar boosts thermal resistance and diminishes deterioration.

5. Conclusion

The comprehensive characterization of pure jute (S1), pure sisal (S2), and hybrid jute–sisal (S3–S6) composites reinforced with coconut shell biochar reveals significant improvements in mechanical, thermal, and moisture resistance properties. Pure jute offered greater flexibility, while pure sisal contributed higher stiffness. The hybridization of jute and sisal effectively combined these properties, resulting in composites with superior tensile, flexural, and impact performance. The incorporation of coconut shell biochar played a critical role in enhancing fiber–matrix adhesion, reducing void content, and improving thermal stability by delaying degradation. FESEM analysis confirmed better interfacial bonding and minimized fiber pullout in biochar-reinforced composites. Additionally, biochar significantly reduced water absorption, enhancing the long-term durability of the composites under both dry and water-soaked conditions. Overall, hybrid jute–sisal composites with coconut shell biochar present a sustainable and high-performance alternative for applications demanding moisture resistance and mechanical strength, particularly in the automotive, marine, construction, and eco-friendly packaging industries.

6. Funding

For doing the research, writing, and/or publishing this work, the authors did not get any funding.

7. Data availability

Data validating the results of this study are available from the corresponding author upon reasonable inquiry.

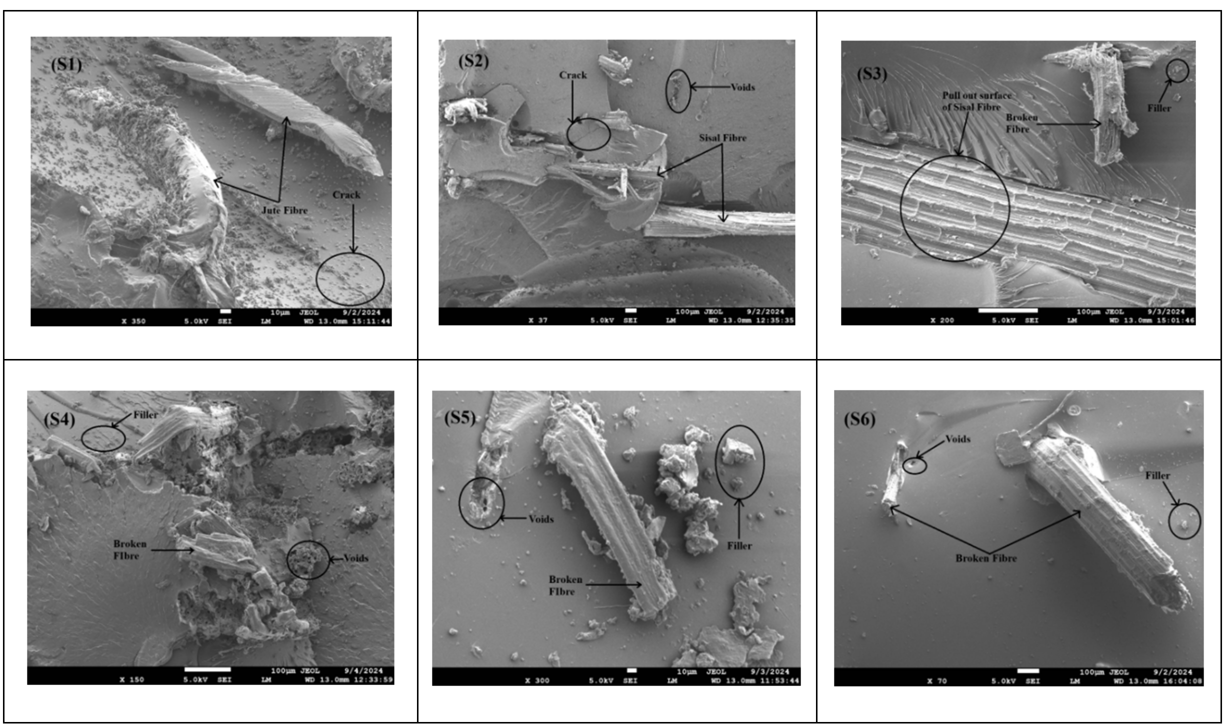

Figure 6: These are the FESEM micrographs of the pure and hybrid composites made with epoxy that comprise jute–sisal fibre

8. Declarations

All authors have accepted and agreed to submit this paper to the Journal of Textile Association; it has not been published and is not being considered for publication elsewhere.

9. Conflict of interest

The authors affirm that there are no conflicts of interest related to this research.

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Development of Recycled Fabric using Different Blend Ratio and their Comfort Properties Analysis

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Abstract:

More businesses are increasingly embracing the idea of supply chain to boost their total profitability as a response to the shortening product life cycles and to remain competitive by managing the business effectively. The rate of returns and their disposals has increased due to the popularity of e-commerce, quicker technological advancements, a shorter life cycle, and increased customer interest in and preference for what is in style. In this research study, in comparison to polyester-cotton and polyester-wool blended fabrics, recycled polyester blended fabrics have slightly reduced air permeability since they are hairier. In comparison to polyester-cotton and polyester-wool blended fabrics, recycled polyester blended fabrics have a higher water vapour permeability and vertical wicking due to microstructure and moisture recovery. When the fabric's GSM increases from the 126 to 138 gram range, its feel factor value decreases as a result of an increase in frictional qualities brought on by the GSM increase. The recycled polyester blend also contributes to an increase in the fabric feel factor and hairiness level. But there is a trend of slightly altering recycled cloth that is all-blend. In comparison to the comparably soft polyester/wool/recycled polyester blend textiles, polyester/cotton/recycled polyester blend fabrics have a soft feel (excellent fabric feel factor). Nearly identical knitted fabrics are available that use recycled polyester fibres. When we used P70C30R00 and P70W30R00 mixed yarn and fabrics, we discovered that up to 7% to 14% recycled polyester fibre was slightly different. Recycled polyester has positive effects on the environment and the economy.

Keywords: *Fabric feel factor, Knit Fabric, Recycled polyester, vertical wicking, Water vapour permeability*

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1. Introduction

More businesses are now embracing the idea of supply chains to boost their overall profitability and ecological advantages in response to growing competition, shortened product life cycles, and effective business management. Product returns and disposals have risen as a result of reduced life cycle. Businesses have come to realize how much value they can recover by recycling or remanufacturing returned or discarded goods. The reverse supply chain is an instrument to simplify and optimize this process of gathering used products, refurbishing them, and then selling them. This academic study aims to list the primary problems associated with creating the reverse chain and the cost concentrations for doing so. The reverse chain and the conventional forward chain are contrasted to show their differences. The conventional forward supply chain manufactures materials, components, and finished goods. Consumers use or consume end items. In addition to the forward flow of items, most businesses also have reverse flows of products that are either actively taken back by the business or actively returned by consumers, frequently for reuse or resale. The reverse supply chain (RSC) of the company is the collection of systems that manage these reverse flows and is the central idea of this study. When it comes to disposal, waste reduction has already grown to be a significant issue for human society. Recycling products or materials appears inevitable to displace the typical one-way economy, and customers now demand that businesses take steps to minimise their negative effects on the environment throughout the entire production process. Companies were aware of the need to integrate environmental concerns with their expanding economic understanding. Global fiber production increased once more to a record 113 million tonnes in 2021, following a little decline in output caused by COVID-19 in 2020. From 58 million tonnes in 2000 to 113 million tonnes in 2021, the production of fibre on a global scale has nearly doubled during the last two decades. If current trends continue, this production will reach 149 million tons in 2030. The percentage of recycled fibres increased slightly from 8.4% in 2020 to 8.9% in 2021, according to the non-profit Textile Exchange's Preferred Fibre & Materials Market Report, mostly because of a rise in polyester fibre generated from recycled bottles. Nevertheless, less than 1% of the global fibre market in 2021 was made up of recycled pre- and post-consumer textiles. The production of synthetic materials produced from fossil fuels increased from 60 million tonnes in 2020 to 63 million tonnes in 2021. Global sales of recycled textiles are anticipated to reach $7.6 billion by 2027, up from an estimated $5.6 billion in 2019. According to the report Global Textile Recycling industry 2021 to 2026, the industry is projected to grow at a CAGR of 3.6% from 2020 to 2027. Utilizing a variety of methods, used clothing and waste fibres are recycled and recovered to generate recycled textile. Municipal garbage, which includes things like used or abandoned clothing, tyres, shoes, carpets, furniture, and non-durable items like sheets and towels, contains the majority of

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recyclable textiles. Recycling textiles reduces demand for virgin resources like wool and cotton as well as pollution, water use, and energy use. The second most polluting industry in the world, behind oil, is the textile and clothing (T&C) sector. It generates more than $450 billion in yearly sales and employs an estimated 60 million people worldwide. Despite the wide range of products offered, 60% of the T&C market is made up of clothing. Fast fashion is defined as readily available and low-cost clothing. Globally, there will be an apparent consumption of 168.4 billion pieces of clothing in 2021. The Statista Consumer Market Outlook predicts that its value will rise over the next few years, reaching 197.3 billion pieces in 2026.Clothing sales are predicted to quadruple from their current level by 2050.Numerous non-renewable resources are needed and consumed in the manufacture, supply, and use of textile products. The usage of energy, water, and dangerous substances, as well as the production of solid waste and carbon dioxide emissions, are among the environmental issues. Various garment producers claim that businesses are becoming more worried about the forward supply chain for clothing.

2. Material and Methods

2.1. Material

The different aspects of textile material have been considered in the present study. Four types of fibers i.e., Recycled polyester, Virgin Polyester, Cotton and wool are used to prepare the blended fabric samples.

Table 1 - Specification of fibers

Fiber	Length (mm)	Fineness
Recycled polyester	38	1.5 D
Fresh Polyester	38	1.6 D
Wool	38	1.6 D
Cotton	32(Avg. effective)	3.8 mic

From above blended yarns, six different fabric samples, using same yarn count 22 Ne and different blend on Knit fabric produced by circular knitting machine with interlock structure.

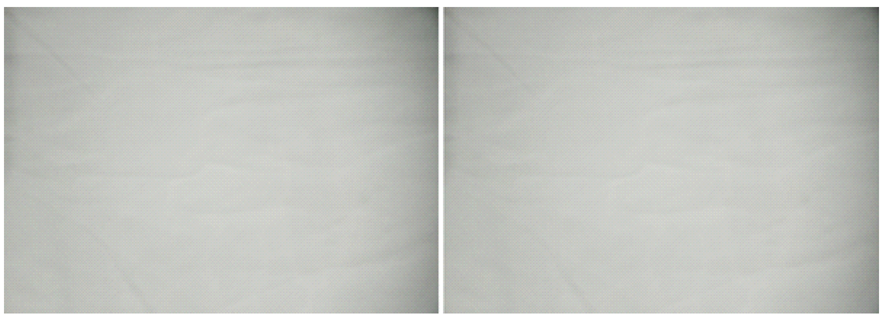
(a)  (b)

Figure 1 - (a) Polyester/Cotton/ Recycle Polyester (b) Polyester/Wool/ Recycle Polyester (70/30/00 blend ratio)

(a)  (b)

Figure 2 - (a) Polyester/Cotton/ Recycle Polyester (b) Polyester/Wool/ Recycle Polyester (67/30/07 blend ratio)

(a)  (b)

Figure 3 - (a) Polyester/Cotton/ Recycle Polyester (b) Polyester/Wool/ Recycle Polyester (56/30/14 blend ratio)

2.2. Methods

All-recycled fabrics were preconditioned for 24 hours before testing under typical atmospheric conditions of 65+/-2% RH and 27+/-2oC temperature. The air permeability test, vertical wicking, water vapour permeability tester, and drying rate tester were used to examine the comfort properties.

2.2.1. Fabric particulars

The fabric details measured were: wales per inch (WPI), course per inch (CPI), linear density of yarn (denier), fabric mass per unit area (g/m2) and fabric thickness (mm). The WPI and CPI were measured according to the ASTM D-3887 Standard. Yarn linear density and fabric mass per unit area were measured according to ASTM D 1059- 01 and ASTM D 3776M -09a standard respectively by using an electronic weighing balance.

2.2.2. Thickness testing

Thickness testing was carried out as per BS EN ISO 9073-2: 1995 using the electronic thickness tester at 0.25 KPa pressure. For each sample 30 readings were taken to get the result at 95% confidence level.

2.2.3. Air permeability testing

The construction properties of the yarns and textiles, in which huge volumes are occupied by air, have a direct bearing on a fabric's air permeability. The volume of air travelled through 100 square millimetres of fabric in one second at a pressure difference of 10 millimetres of water is the definition of a fabric's air permeability, which measures how well it permits the passage of air through it. The FX 3300 air permeability tester was used to measure air permeability in accordance with ASTM D737-04. At a test pressure of 98 Pa, testing was conducted inside a 15.07-inch-diameter circular test head. The amount of air passing through the fabric per second was measured in cm3/cm2/s.

2.2.4. Water vapour permeability testing

To determine how resistant textiles and textile composites (particularly active wear fabrics) are to water vapour penetration, the testing standard BS 3424 is used. A water vapour permeability tester was used for this, which contains eight containers with water reservoirs, a typical permeable fabric cover, a sample holder ring, and a precision driving mechanism.

The fabric's water vapour permeability (WVP) was calculated in grammes per square meter per day using equation (I).

$$WVP = \frac{24\,M}{A_t} g/m^2/day \quad \ldots. (i)$$

Where,

M = Loss of water (g) through fabric, A = Internal area of the fabric (m2)

t = Time oftesting (24 hours)

2.2.5. Vertical wicking

Fabric wicking was assessed using the strip test method, with the results expressed as wicking height in centimeters. In this experiment, a cloth strip was suspended vertically, its lower edge resting in a container filled with distilled water. Then, the rate at which water rose through the leading edge was observed. A dye was applied to water in order to identify the location of the waterline. The test fabric's ability to wick moisture was determined by measuring the height of rise over time. The fabric's vertical wicking test was conducted in accordance with DIN 53924 standard using a sample size of 20 cm 2.5 cm. On these fabric structures, measurements with periods of 5, 10 and so forth were established with an eye towards wales.

2.2.6. Fabric Feel Factor or (Soft and Harsh feel test)

Only a few tools, such as the Fabric feel tester and the Kawabata evaluation method for fabrics, are now available for objectively assessing fabric handle. A fabric feel tester (Figure 3.10) was utilised to obtain an impartial assessment of the fabric's feel for this investigation.

The test uses a sample that has a 24 cm diameter. Equation (i) was used to determine the fabric feel factor for the fabrics submitted to the test. When the feel factor value is low, the fabric will be softer; however, when it is high, the opposite will be true, making the cloth harsher.

$$\text{Feel factor (f)} = 26.58 + 20.65 * P_E - 0.436 * WE - 0.131 * a + 5.064 * P_R - 0.361 * DR(i)$$

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 and Discussions

Table 2 - Knit fabric basic characteristics

Types of Knit fabric	WPI	CPI	Stitch density	Loop Length (mm)	Thic kness (mm)	GSM
P/C/RP (70/30/00)	28.12	19.22	540.46	2.9	0.37	128
P/C/RP (63/30/07)	28.14	19.35	544.50	2.9	0.37	130
P/C/RP (56/30/14)	30.66	20.85	639.26	2.8	0.38	135
P/W/RP (70/30/00)	28.14	19.24	541.42	2.9	0.37	128
P/W/RP (63/30/07)	28.15	19.38	545.54	2.9	0.37	130
P/W/RP (56/30/014)	31.04	20.86	645.34	2.8	0.38	135

Table 3 - Air permeability and Water vapour permeability results

Types of knit fabric	Air Permeability ($cm^3/cm^2.sec$)	Water Vapour Permeability ($gm/m^2/day$)
P/C/RP (70/30/00)	585	1537 ± 22
P/C/RP (63/30/07)	574	1558 ± 18
P/C/RP (56/30/14)	562	1586 ± 13
P/W/RP (70/30/00)	572	1476 ± 13
P/W/RP (63/30/07)	564	1484 ± 12
P/W/RP (56/30/014)	543	1508 ± 08

Table 4 - Vertical wicking test and fabric feel factor value results

Types of knit fabric	Vertical wicking(cm) (Wale wise)	Vertical wicking(cm) (Coarse wise)	Fabric feel factor value (%)
P/C/RP (70/30/00)	7.83	6.21	32.67
P/C/RP (63/30/07)	8.26	6.45	35.08
P/C/RP (56/30/14)	8.73	6.67	39.55
P/W/RP (70/30/00)	5.11	4.52	34.76
P/W/RP (63/30/07)	5.42	4.74	38.27
P/W/RP (56/30/014)	5.76	5.34	42.05

3.1 Water Vapour Permeability

The micro porosity structure and moisture recovery of the fibres affect the fabrics' water vapour permeability. The fabric's ability to absorb moisture will rise if the recycled polyester content is slightly increased, leading to greater diffusion.

Tables 2 & 3 and Figure 4 demonstrate the differences in fabric water vapour permeability with polyester, cotton, recycled polyester, and wool blend factors. The microstructure and moisture recovery are the key factors that influence an increase in water vapour permeability. When compared to polyester fibres, recycled polyester regains moisture a little bit more. Increased water vapour permeability P56C30R14 in comparison to P70C30R00 was discovered on the fabric's surface as a result. Increased water vapour permeability results from an increase in recycled polyester content. Additionally, it saw an increase in the amount of recycled polyester fibre in blends of polyester, cotton, and recycled polyester as well as an improvement in the fabric's water permeability. As a result, the observed rise in recycled polyester fibre content in blends of polyester, wool, and recycled polyester causes an increase in the materials' water vapour permeability. P56W30R14 blended fabrics, for example, are more permeable to water vapour than P70W30R00 blended fabrics.

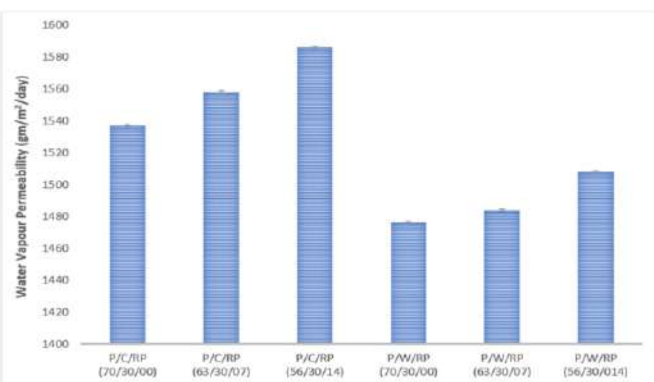


Figure 4 - Water Vapour Permeability of recycled polyester with different blend ratio fibres

3.2 Air permeability

Tables 2&3 and Figure 5 demonstrate the differences in fabric air permeability with polyester, cotton, recycled polyester, and wool blend factors. The main cause of the reduced air permeability is the fabric's surface, which is somewhat more hairy in P56C30R14 than P70C30R00. Air permeability decreases as recycled polyester content increases. Additionally, it has been noted that when recycled polyester fibre content in mixes of polyester, cotton, and recycled polyester increases, the fabric's air permeability decreases. In comparison to polyester, recycled polyester has a little bit more hairiness. Thus, it can be shown that the amount of recycled polyester fibre in mixes of polyester, wool, and recycled polyester increases or decreases air permeability. P56W30R14 blended fabrics, compared to P70W30R00 blended fabrics, have less air permeability.

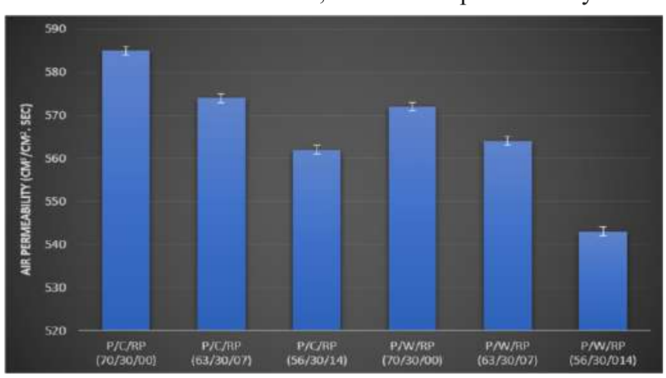


Figure 5 - Air Permeability of recycled polyester with different blend ratio fibres

3.3 Vertical wicking performance

Tables 2 and4 show the effects of blend and fabric type on the vertical wicking of the fabrics (wale- and course-wise).

According to Figure6, the P56C30R14 blended textiles have a higher wicking rate in the wale-wise wicking direction than the P70C30R00 mixed fabrics. Additionally, it was noted that the influence of the recycled polyester fibre in mixes of polyester, cotton, and recycled polyester increased the vertical wicking of the fabric. P56C30R14 mixed fabric has greater wicking along the wale than along the course. This is because stronger capillary action in the wale wise direction makes the transfer of water simpler in that direction. Because recycled polyester fibres retain their ability to absorb water, wicking increases as recycled polyester content does. With P70C30R00 & P70W30R00 blended knitted fabric, we discover that up to 7% recycled polyester is slightly different. Additionally, P56W30R14 blended fabrics have a higher wicking direction in both the wale wise and coarse wise directions than P70W30R00 blended fabrics.

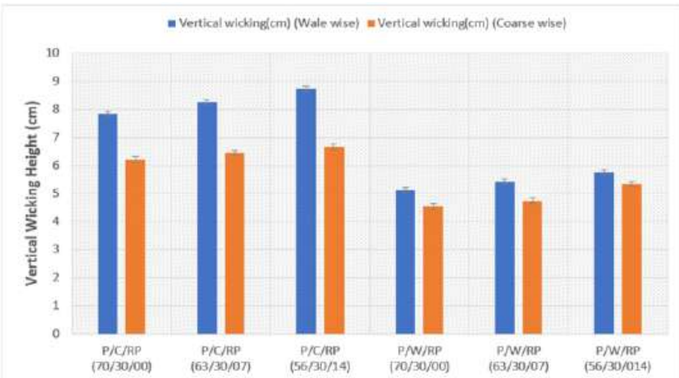


Figure 6 - Vertical wicking performance of recycled polyester with different blend ratio fibres

3.4 Fabric feel factor value (%)

Knit materials are utilised for recycled polyester with various blends of cotton and wool for clothing, as can be seen in tables 2 to 4 and Figure7. P/C/RP 70/30/00, P/C/RP 63/30/07, P/C/RP 56/30/14, P/W/RP 70/30/00, P/W/RP 63/30/07, and P/W/RP 56/30/14 blend garment wear are some examples of these materials. To put it another way, Tables 2 and4show that when the fabric's GSM increases from the 128 to 135 gramme range, its feel factor value decreases as a result of an increase in frictional qualities brought on by the GSM increase. The recycled polyester blend also contributes to an increase in the fabric feel factor and hairiness level. But there is a trend of slightly altering recycled cloth that is all-blend. Figure shows that the fabric feels factor value of the P56C30R14 blended textiles is higher than that of the P70C30R00 mixed fabrics. Additionally, it was observed that the presence of some hairiness in recycled fabric raised the fabric feel factor value when recycled polyester fibre was added to blends of polyester, cotton, and recycled polyester. Blended textiles P56W30R14 to P70W30R00 showed comparable patterns. In comparison to the comparably soft polyester / wool /recycled polyester blend textiles, polyester/cotton/recycled polyester blend fabrics have a soft feel (excellent fabric feel factor)

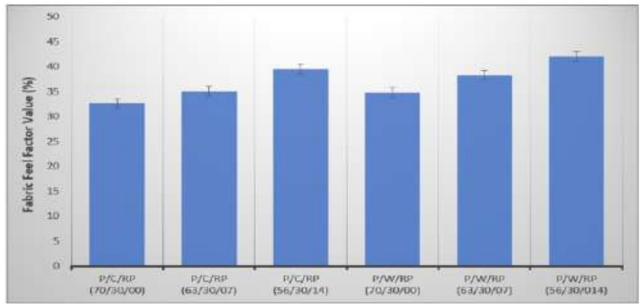


Figure 7 - Fabric feel factor value of recycled polyester with different blend ratio fibres

4. Conclusions

In this study, we looked at how ecological factors affected how effective the reverse supply chain was in the recycled fabric fashion sector. Then, after creating recycled polyester fibre with added natural fibre to create sustainable fashion wear products and lower the cost of the products, we assessed the comfort performance of the finished knit garment fabric to come to the conclusions that are presented below.

- In comparison to polyester-cotton and polyester-wool blended fabrics, recycled polyester blended fabrics have slightly reduced air permeability since they are hairier.
- In comparison to polyester-cotton and polyester-wool blended fabrics, recycled polyester blended fabrics have a higher water vapour permeability and vertical wicking. due to microstructure and moisture recovery.
- When the fabric's GSM increases from the 126 to 138 gramme range, its feel factor value decreases as a result of an increase in frictional qualities brought on by the GSM increase. The recycled polyester blend also contributes to an increase in the fabric feel factor and hairiness level. But there is a trend of slightly altering recycled cloth that is all-blend. In comparison to the comparably soft polyester/wool/recycled polyester blend textiles, polyester/cotton/recycled polyester blend fabrics have a soft feel (excellent fabric feel factor).
- Nearly identical knitted fabrics are available that use recycled polyester fibres. When we used P70C30R00 and P70W30R00 mixed yarn and fabrics, we discovered that up to 7% to 14% recycled polyester fibre was slightly different. Recycled polyester has positive effects on the environment and the economy. .

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Phulkari as Heritage: Exploring Female Awareness of Traditional Needlework

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Abstract:
The rich and diverse heritage of Indian culture finds expressive embodiment not only in its music, dance, and rituals but also in its intricate embroidery traditions. These embroidery patterns—each regionally distinct and historically embedded—serve as living symbols of cultural identity, gendered labor, and aesthetic expression. This study was designed to assess the level of awareness and cultural familiarity regarding traditional embroidery styles among female participants from the states of Punjab and Haryana, two regions with particularly vibrant needlework legacies.

A structured survey methodology was employed to collect quantitative data from a stratified sample of women belonging to various age groups and socio-economic backgrounds. The instrument included questions aimed at evaluating participants' recognition, understanding, and cultural association with prominent embroidery.

The data was analyzed using descriptive statistics and cross-tabulation to identify patterns of awareness across demographics. The results revealed that respondents across all age categories exhibited a moderate to high level of awareness regarding traditional embroidery forms. Notably, Phulkari emerged as the most widely recognized and culturally resonant embroidery type among participants, signifying its enduring popularity and strong regional identity, particularly in Punjab. These findings underscore the persistent relevance of traditional textile arts among contemporary women, while also highlighting the potential for cultural preservation and revival through targeted educational and promotional initiatives.

Keywords: *Embroidery Patterns, Frequency, Motif applications, Repeat and Regional Embroidery, Thread Work, Traditional, Zardozi*

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1. Introduction

Embroidery, or thread work, represents one of the oldest and most celebrated textile art forms, extensively employed for the surface embellishment of fabrics and garments. India stands as a global leader in the production of embroidered textiles, with region-specific styles such as Phulkari from Punjab, Ari and Kutch embroidery from Gujarat, and Chikankari and Zardozi from Uttar Pradesh gaining both domestic and international recognition. Each form holds cultural distinctiveness and aesthetic significance, contributing substantially to the livelihood of artisans and the growth of regional craft economies.

The essence of Indian cultural identity is prominently reflected through these embroidery traditions, which encapsulate not only artistic expertise but also intangible cultural heritage passed down across generations. India's folk and traditional arts, encompassing festivals, music, oral traditions, and textile practices, represent a complex network of expressions, providing deep insights into its socio-cultural and historical evolution. Embroidery, in particular, emerges as a key connotation of regional identity and heritage preservation. Traditional Indian embroidery is characterized by remarkable diversity in technique, motifs, thread type, stitch forms, and symbolic representations. From the narrative Kantha of Bengal to the floral vibrancy of Phulkari in Punjab, and the intricate Kasida of Kashmir, each style embodies the geographical and cultural ethos of its region. These patterns not only enrich the fabric aesthetically but also act as markers of social identity, occasion-based wear, and craftsmanship lineage.

Despite the popularity and use of such embroidered textiles in contemporary fashion and interior decor, a gap persists between consumption and conscious recognition. Many consumers, particularly younger generations, demonstrate limited awareness regarding the specific names, origins, and cultural contexts of the embroidery styles they wear or purchase. This study, therefore, aims to analyse the level of awareness among female consumers in Punjab and Haryana concerning traditional embroidery patterns. A quantitative approach was adopted using a structured survey administered across varied age groups. The findings reveal a significant level of appreciation for traditional embroidery among respondents, with Phulkari being the most recognized and favoured style. The study underscores the need for continued promotion, documentation, and education about traditional textile arts to bridge the cultural knowledge gap and support craft sustainability.

2. Literature review

Embroidery, a timeless and culturally rooted art form, utilizes needle, thread, and fabric to convey intricate designs imbued with emotional and aesthetic expressions [1]. Embroidery has flourished in the Indian subcontinent for

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centuries, adorning not only garments but also household textiles, temple hangings, and even the coverings of domesticated animals. They emphasized that this form of embellishment served both decorative and symbolic purposes, often reflecting community narratives, personal emotions, and seasonal inspirations through the hands of women artists.

Embroidery techniques are classified based on the characteristics of the base material and the stitch placement in relation to the fabric [2]. Explain that embroidery generally falls into three categories: surface embroidery, counted-thread embroidery, and needlepoint or canvas work. Counted-thread embroidery requires a precise count of the threads within an even-weave fabric like cotton or linen, enabling highly symmetrical patterns and designs.

In her study on traditional attire, described how embroidery was applied to various garments worn by both men and women. A wide range of stitches was used, predominantly floral and avian motifs. Her research observed that embroidery practices evolved over time in design aesthetics, stitch quality, color palette, and thread material, indicating a dynamic blend of tradition and innovation [3].

Hand embroidery served as a form of self-expression, particularly among women, capturing lived experiences and emotions in their textiles. These practices extended beyond mere adornment, playing roles in religious, familial, and social contexts. Traditional embroidery thus emerged as both a utilitarian and spiritual craft, encoding symbols of flora, fauna, and daily life across different regions [4].

The dichotomy between traditional hand embroidery and modern machine embroidery in their research. They highlighted that while machine embroidery caters to fast, affordable fashion demands, hand embroidery remains prominent in couture and designer apparel due to its intricacy, customizability, and aesthetic depth. Despite the decline in everyday use due to its cost and slow process, hand embroidery continues to thrive in high-end fashion and bespoke wear. They further emphasized the regional diversity of Indian embroidery, naming examples such as Phulkari (Punjab), Kutch (Gujarat), Chamba Rumal (Himachal Pradesh), Kantha (West Bengal), Kasuti (Karnataka), Chikankari (Uttar Pradesh), Gota Patti (Rajasthan), and Kasida (Kashmir), each rooted in unique cultural and historical narratives [5, 6].

3. Materials and Methods

This descriptive research study comprises a field investigation and extensive literature survey tailored to meet the objectives. Techniques and methods of data collection and their execution were designed in line with the chosen methodology and goals. The methodology is scientific and logical in nature, aimed at exploring new dimensions in Phulkari traditional embroidery through creative innovation. Evaluate their relevance and acceptance through qualitative methods. For this purpose, jury-based evaluation was conducted, involving ten artists and five academic experts. Each motif was rated on a five-point scale considering its precision, finesse, and overall suitability. Out of 63 developed motifs (evaluated in 3 phases), the best three were selected for advancement into final products.

3.1 Selection of Variables

Dependent Phulkari, Cultural segments and independent variables Threads, embellishment techniques and respondent age were identified to meet the study's analytical objectives.

3.2 Data Collection

Data was gathered from both primary and secondary sources. The absence of new motifs and modern embellishments in traditional embroidery indicated a gap in innovation and appeal. Therefore, a comprehensive field survey was undertaken in selected districts of Punjab. Primary data was collected via interviews, observations, and photographic documentation includes motif structure, color schemes, traditional processes, and socio-cultural contexts. Personal visits were made to artisans' homes and local markets. Some data was also collected through telephonic interviews with traditional artisans. Secondary data Sourced from archives, libraries, academic records, museum collections, and government reports documenting Phulkari's origin, evolution, and techniques.

3.3 Sampling Size and Selection

A random sampling technique was applied to select 400 respondents from six key cities. Respondents included artisans, designers, experts, students, and consumers. Artisans, Designer, Experts, Students and consumers were selected 25- 25 from each category.

3.4 Criteria for Selection

Phulkari being female-dominated, women involved in Phulkari embroidery were selected via chain sampling, based on experience and willingness to share knowledge.

3.5 Tools and Techniques

Observation and interviews were used for artisans and consumers alike. A mix of open- and close-ended questions addressed demographic details, professional background, design preferences, color choices, and cultural relevance.

3.6 Questionnaire Design The questionnaire had three sections according to research structure:

Figure 1: Research Design Stage

3.6.1 Demographics and professional information

3.6.2 Views on Phulkari motifs and material combinations

3.6.3 Application and market potential for newly designed Phulkari

3.7 Develop Sample for analysis Research Design

Figure 2: Research Design Stage

3.8 Statistical Analysis and Interpretation

For data analysis, statistical tools such as mean, percentage, standard deviation, t-test, and ANOVA were applied wherever relevant. Data was analyzed both qualitatively and quantitatively. Results were compiled into tables, charts, and photographic evidence. Respondent preferences were recorded to assess motif popularity and design acceptance [7].

$$\text{Preference Index Phase} = \frac{\text{Preference frequency of motif category wise}}{\text{Total Respondents}} \times 100$$

3.9 Documentation of Historical Literature

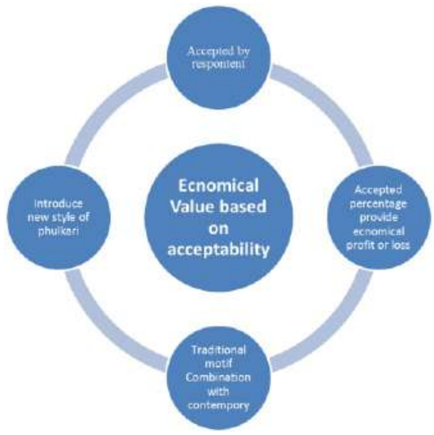
In-depth documentation of Phulkari's historical and cultural significance was undertaken. The study included the evolution of motifs, their symbolic meanings, color, regional variants, and traditional uses.

3.10 Design Forecasting / Thread Techniques & Contemporary Work

Fashion trend analysis was conducted to position Phulkari within modern market dynamics. A mood board was developed to visualize the transformation of traditional motifs into wearable designs across different fashion categories. New embroidery techniques such as Zardozi, Aari, pipe, and beadwork were fused with traditional thread work to elevate aesthetic appeal and expand usage in high-end markets.

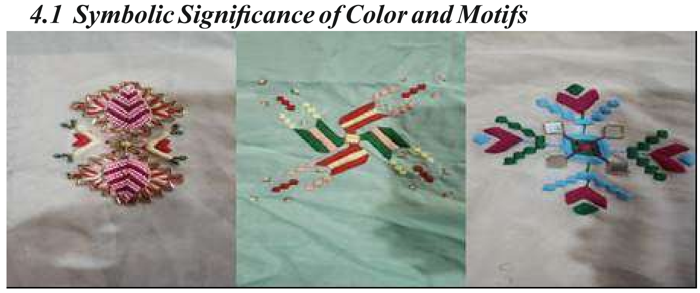
3.11 Acceptance and Economic Viability

Economic analysis of newly developed motifs included cost estimation, marketability, and labor intensity. The study provided actionable insights for artisans to integrate modern design thinking while preserving heritage.



4. Result and Discursion

4.1 Symbolic Significance of Color and Motifs



Sample No. A ***Sample No. B*** ***Sample No. C***

4.2 Symbolic Significance of Color and Motifs

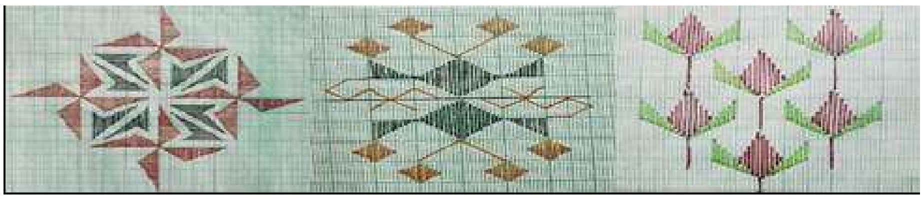
This section analyses and interprets the symbolic relevance of color and motifs observed in Sample A, Sample B, and Sample C. Each sample reflects cultural, emotional, and traditional meanings embedded in the design elements of the phulkari [8, 9] Shown in table no 1.

Table 1: Design elements of the phulkari

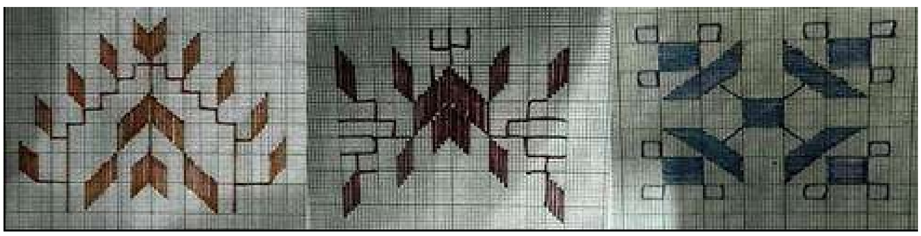
Sample No.	Colors Used	Symbolic Meaning of Colors	Motifs Used	Symbolic Meaning of Motifs
A	Maroon, Cream, Golden	Red signifies power and fertility; symbolizes protection, Red Orange symbolism of Baisakhi	Geometrical shapes	Like Sun waves symbolizes life and divinity; Peacocks represent beauty; or unity
B	Yellow, Green, Maroon, Pitch	Yellow symbolizes joy and prosperity; Green indicates growth; Maroon reflects wealth	Swastika , Zigzag lines	Lotus denotes spiritual Fish abundance; Zigzag lines represent water/energy
C	Blue, Red, Green, Pink, White	Blue symbolizes calmness and spirituality; Orange denotes courage; Pink implies love, White denotes purity	Geometric patterns	Elephant represents strength and wisdom; symbolize continuity; Geometry reflects balance

4.3 Illustration of the Traditional Motifs for Phulkari

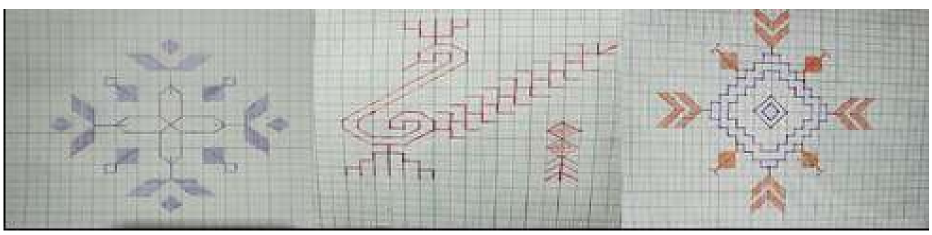
Selection of phulkari motifs for designing based on the existing designs available from different most popular motifs, the samples for apparels with combination of different techniques and styles of thread work [10, 11, & 12]. Hence, researcher selected different combination of fabrics for transferring traditional motifs of phulkari. The investigator collected various types of motifs of various occasion from selected different sources. Motifs were collected with the help of photographs, literature, artisans and videos. Collected motifs were shown to textile experts, and professionals to know their opinion regarding which motifs would be feasible. The selected motif converts in geometrical form by the help of graph papers there were varieties of motifs of phulkari embroidery which has been presented in this section mention below for references, designs were selected on the basis of expert advice.



Motif No.: 1 ***Motif No.: 2*** ***Motif No.: 3***



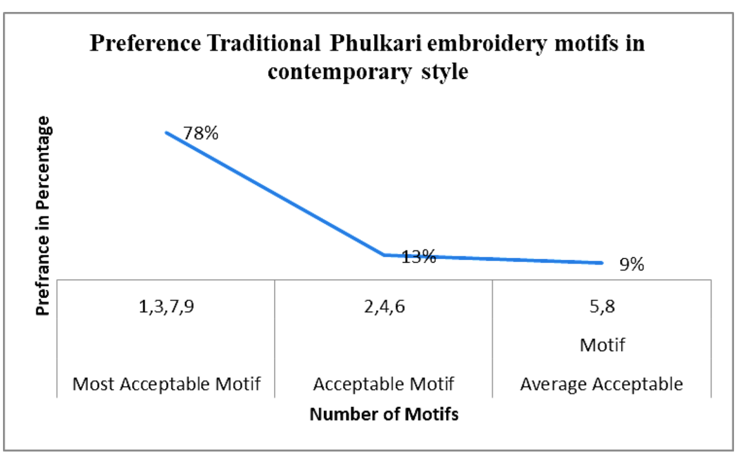
Motif No.: 4 ***Motif No.: 5*** ***Motif No.: 6***



Motif No.: 7 ***Motif No.: 8*** ***Motif No.: 9***

Table 2: Preference Traditional Phulkari embroidery motifs in contemporary style

Finding Details	Most Acceptable Motif	Acceptable Motif	Average Acceptable Motif
Motif No.	1,3,7,9	2,4,6	5,8
Preference	78%	13%	09%



Graph 1: Preference Traditional Phulkari embroidery motifs in contemporary style

Out of Total 400 respondent 302 rating for most acceptable motif was (1, 3, 7 & 9) were in contemporary use in the different products develop by phulkari.52 respondent accepted in second category design number (2, 4 & 6) and in last category only 36 respondent response for design number (5, 8), respectively new styles of phulkari motifs were mostly found in markets in different apparels like Kurtis, suits, sarees, shirts, tops, dupattas for women's wear products.

4.4 Selection of fabric Sourcing

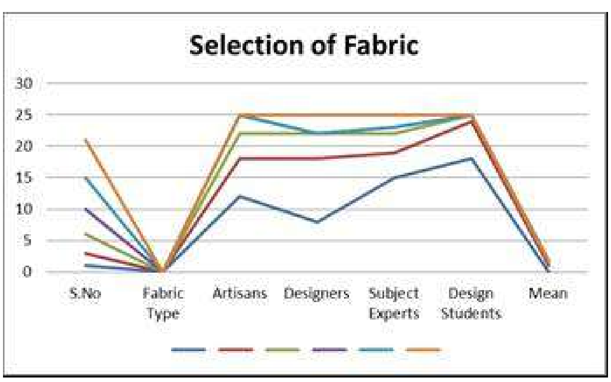
Basically, in traditional Phulkari was developing on the Khaddar in texture like rough cotton Fabric was used in Punjab and it was a traditionally part of the trousseau of a bride [13, 14]. The numbers of Phulkari given at the time of the daughter wedding it is the socioeconomic status of the family in one shawl approximate used 5 to fifty motifs Numbers as well as heaviness/ intricacy of the design of Phulkari and bagh were considered important in the social prestige of the family. Hand spun, hand woven khaddar was used in Phulkari making as suggested earlier because of its ready availability and cost effectiveness. Five types of the fabric as mentioned below with data regarding the preference of respondents.

Table 3: Selection of Fabric Material

Fabric Type	Artisans	Designers	Subject Experts	Design Students
Fine Cotton	12	08	15	18
Crape	06	10	04	06
Synthetic Blended	04	04	03	01
Khaddar	03	-	01	-
Blended Georgette	-	-	-	-
Fine Leather	-	03	02	-

Maximum acceptance for various material for Phulkari, 48 % artisans were preferring Fine Cotton and second preference was Satin, case of designer's 40% prefer satin due to highly rich status and 325 like fine cotton in same preference was analysis 60% Subject expert and design student's was preferring fine cotton due to easy to handle.

Formula for mean Frequency/N = (∑fixi)/ ∑fi



Graph 2: Selection of Fabric Sourcing

The table indicate that for cotton was the most preferred fabric scoring highest 2.12 and F1 (4.2) ranked satin ranked second with score 1.04 ranked III, 0.24 ranked IV, 0.02 ranked, First, Second and third preference fabric was used for final sample.

4.5 Inclusion of new motif with Thread Work

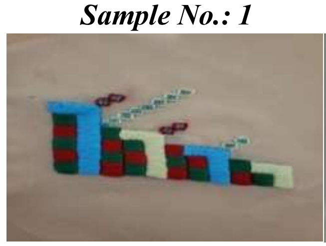
From selected thirty motifs [14, 15], fifteen designs were developed from the application of thread variation and another fifteen for different styles and finally thirty designs had been decided on for placement on distinct apparels. In order to quantify the data regarding preferential selection of experts weighted mean score was calculated. Acceptability of the products by the consumer was converted into percentage using the formula mentioned below

(Thread work preference analysis by Artisans, Designers, Subject Experts and Concern Students)

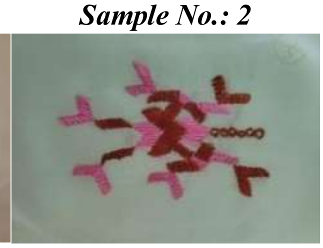
$$\text{Acceptability Index} = \frac{\text{Max accepting frequency of design}}{\text{Total score}} \times 100$$

Sample No.: 1

Sample No.: 2

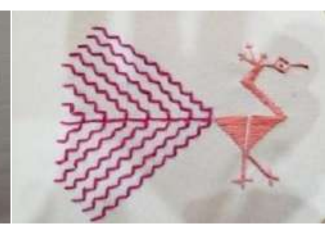


Sample No.: 3



Sample No.: 4

Sample No.: 5



Sample No.: 6

4.6 Application of Contemporary thread work with Phulkari-benefits to society

4.7 Inclusion of new motif with contemporary Work

Acceptability of developed Contemporary motifs prepared by thread work, results indicated, highest preferences for sample 1a, 2b and 5e, up to 100% respondents indicated their preference for sample number 6f more than 95% respondents preferred 4b and 3c sample number motifs preferred by 90-95% respondents.

Sample No.: 1a

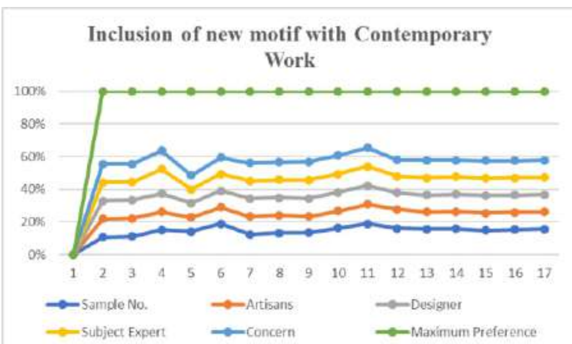
Sample No.: 2b

Sample No.: 3c

Sample No.: 4d

Sample No.: 5e

Sample No.: 6f



Graph No. 3: Incusion of new motif with contemporary work

Maximum acceptance for various material for Phulkari, 48 % artisans were preferring Fine Cotton and second preference was Satin, case of designer's 40% prefer satin due to highly rich status and 325 like fine cotton in same preference was analysis 60% Subject expert and design students was preferring fine cotton due to easy to handle. The table indicate that for cotton was the most preferred fabrics coring highest 2.12 and satin ranked second with score 1.04 ranked third, 0.24 ranked fourth, 0.02 ranked, First, Second and third preference fabric was used for final sample.

Illustrations No. 1 to 4: Inclusion of new motif with Contemporary Work-Acceptance

Illustrations No.: 1, 2

4.8 Analysis the Acceptability of the Developed Range of Women's Wear-Cotemporary

A survey was conducted in order to test the accept ability of the developed range of digitally design Indo-Western collection. Women's western wear were evaluated for acceptability from the common consumer responses obtained from 300 common consumers on five point self-develop rating scale out of 300, 240 common consumer response on all informal common parameters like and dislike on preference. The developed sets were then shown to the consumers. The final feedback of consumers was collected through opinion based on utilization. All application acceptable by common consumes more than 90 to 95 %. (Final Collections-1-6)

Illustration No.: 3, 4

Illustration No. : 5, 6

A survey was conducted in order to test the acceptability of the developed range of digitally design Indo-western collection. Women's western wear were evaluated for acceptability from the common consumer responses obtained from 300 common consumers on five point self-develop rating scale out of 300, 240 common consumer response on all informal common parameters like and dislike on preference. The Illustration no 5,6. Developed sets were then shown to the consumers. The final feedback of consumers was collected through opinion based on utilization. All application was accepted by common consumers more than 90 to 95 %.

5. Conclusion

The study comes to the conclusion Traditional Textile reveal the artistic creativity of a region's people producing a traditional masterpiece that has been shaped by the winds of time. These crafts serve as the foundation for ethnic fashions that shape future trends and innovations. The Phulkari craft comes from the land of Punjab, which has seen such transformations as a result of changing times and trends. The arctic fact, which is an important part of Punjab's cultural heritage, needs to be revitalized. To review all transformations, the various traditional aspects of the craft must be compared to their modern form. To study the traditional style, aspects and modifications, documentation of both traditional and contemporary articles worked with Phulkari embroidery was undertaken.

The current study demonstrates that a sense of accomplishment and the capacity to regulate their wages has given craftsmen in Punjab's rural and semi-urban areas increased confidence. Crafts men who continue to work as crafts men or product designers are aggressively working with the current period in Phulkari to preserve the identity of phulkari. Designers and artisans respect and control of masculine power masculinity tend to be considerably happier and capable of making some autonomous judgments. And because the local economy requires such a mix, demand for work is increasing for the peoples. Numerous companies valuing their talents have also assisted them in realizing their own potential in generating new designs for the market.

Phulkari demand is constantly strong, but labor costs are too high, therefore scholar invention is more advantageous for all those who cannot afford to buy pure phulkari items. This had an impact on many parts of Phulkari, including not only the themes, colors, designs, and patterns employed, but also the material on which the embroidery was done, as well as the thread used. Commercialization has resulted in adjustments to the embroidery method and technique in order to make it more cost efficient and minimize the time required to complete it. In truth, the alterations in the fabric and threads utilized were also intended to reduce the overall cost of the product.

As a result, the report allows the reader to comprehend all of the ways in which commercialization has impacted the original traditional work form. Furthermore, an essential aim of this paper is to illustrate each distinct difference between the traditional labor form and the modern commercialized product supplied in marketplaces. Finally, the report includes a review of the evolution of the marketable product throughout various time frames; beginning with the moment commercialization progressively began. Phulkari is the outcome of a fusion of many motifs, thread work, and needle work styles on the integration of Punjabi state from Punjab memories. Throughout the process, the work has expanded in terms of creativity and talents, with the initial concept of economically producing and generating a new catalogue for the fashion industry.

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Textile Wastewater: High-Impact Zero Liquid Discharge for Sustainable Effluent Treatment

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Abstract:

The textile industry is a vital contributor to India's economy, but it is also one of the largest consumers of water and a significant source of industrial wastewater. Dyeing, finishing, and washing processes release effluents laden with dyes, salts, heavy metals, and other chemicals, contributing to high chemical oxygen demand (COD), biological oxygen demand (BOD), and non-biodegradable pollutants. Conventional wastewater treatment technologies such as reverse osmosis (RO), multiple-effect evaporators (MEE), and advanced oxidation processes (AOPs) are effective but highly capital- and energy-intensive, making them unsuitable for small- and medium-scale industries. This paper explores the use of coagulation–flocculation (C–F) as a cost-effective and scalable method to achieve Zero Liquid Discharge (ZLD) in the textile industry. By optimizing coagulant type, dosage, and process conditions, this approach significantly reduces COD and color at a fraction of the cost of advanced methods. A detailed comparison of ZLD technologies demonstrates that C–F is an effective pre-treatment or standalone option, providing an economical solution to wastewater recycling and reuse, supporting both environmental compliance and water conservation.

Keywords: *Coagulation–flocculation process, Cost-effective wastewater management, Effluent reuse and recycling, Textile wastewater treatment, Zero Liquid Discharge (ZLD)*

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1. Introduction

India's textile industry is one of the largest in the world, contributing substantially to the country's GDP and employment, particularly in states like Gujarat, Tamil Nadu, and Maharashtra. However, its heavy reliance on water and chemical-intensive processes presents severe environmental challenges. Textile manufacturing consumes vast volumes of water, approximately 425 million gallons daily, and generates highly contaminated wastewater containing dyes, salts, heavy metals, alkalis, acids, and other pollutants [1, 2 & 3]. Cotton cultivation, a key raw material source, adds to this water footprint, requiring up to 10,000 liters of water per kilogram [4].

The dyeing and finishing processes alone account for nearly 20% of global industrial water pollution. This wastewater, if untreated, leads to ecological degradation, harming aquatic ecosystems and posing risks to human health. The complexity of textile effluents, characterized by high salinity, alkalinity, and color, makes treatment challenging, requiring innovative and sustainable solutions.

Zero Liquid Discharge (ZLD) has emerged as a promising approach to address these issues, ensuring that no wastewater is discharged into the environment. Importantly, ZLD directly supports the United Nations Sustainable Development Goals (SDGs), specifically Goal 6 (ensuring access to clean water and sanitation), Goal 12 (fostering responsible production and consumption), Goal 14 (conserving marine ecosystems), and Goal 15 (protecting terrestrial ecosystems by minimizing pollution). However, most ZLD technologies, such as RO, MEE, and membrane filtration, are prohibitively expensive and energy-intensive for small and medium enterprises (SMEs). This research investigates the potential of coagulation–flocculation as a low-cost, high-impact technology for ZLD in the textile sector.[5-10].

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2. Textile Industry Wastewater Characteristics

Textile wastewater is highly variable, depending on the type of fabric, dyeing methods, and chemicals used. It typically contains, Dyes and pigments, and Azo dyes, which account for over 50% of dyes used, are persistent, carcinogenic, and resistant to biodegradation. Salts and alkalis: Sodium chloride and sodium sulfate are extensively used during dyeing, leading to high salinity that inhibits biological treatment. Heavy metals: Chromium, copper, and iron compounds are used as mordants and dye fixatives. Other additives: Starch, formaldehyde, surfactants, and various finishing agents. All stages in the textile industry generate heavily contaminated wastewater, as shown in Figure 1.

These pollutants collectively contribute to high COD and BOD levels, color, turbidity, and toxicity, making textile wastewater among the most challenging industrial effluents to treat [11].

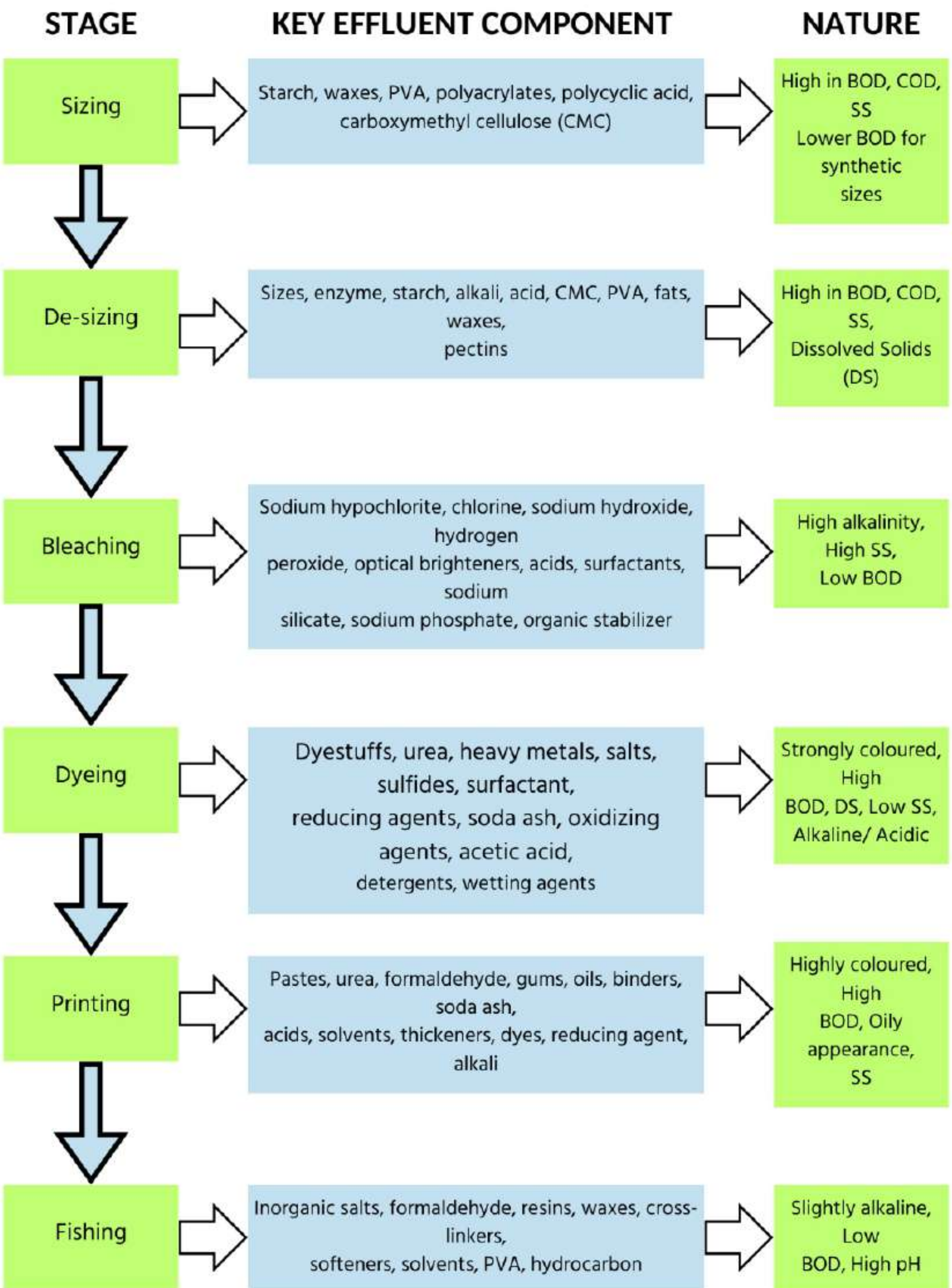

Figure 1: wastewater generation in the textile industry

3. Challenges in Textile Wastewater Treatment

The persistence of dyes and other synthetic chemicals limits the effectiveness of conventional biological treatment methods. High salt concentrations, heavy metals, and toxic compounds further inhibit microbial activity. Advanced treatment technologies like ozonation, Fenton's reagent, and photocatalysis can break down complex molecules but involve high costs, intensive energy requirements, and specialized infrastructure.

Moreover, small and medium enterprises, which constitute a significant portion of India's textile industry, often lack the capital and space for installing sophisticated wastewater treatment plants. There is, therefore, an urgent need for simple, affordable, and effective treatment solutions [12].

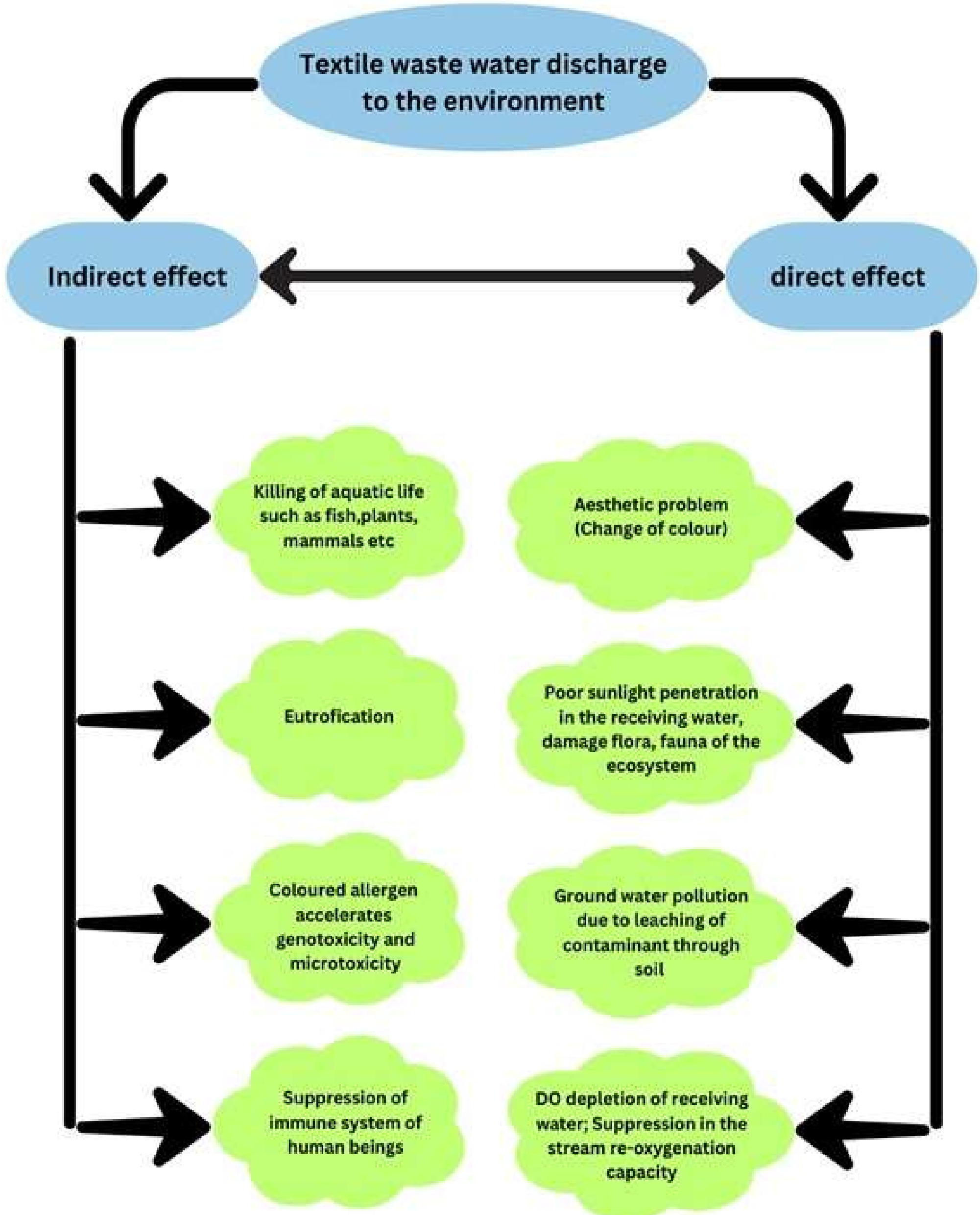

Figure 2: Effects of wastewater from the textile industry

4. Overview of Textile Wastewater Treatment Technologies [13]

To achieve effective treatment and water reuse, industries often employ a combination of physical, chemical, and biological methods. The main approaches include:

i. **Coagulation–Flocculation (C–F):** A chemical process that uses coagulants such as alum, ferric chloride, or polyaluminum chloride to destabilize particles and dyes, forming flocs that can be removed via sedimentation or filtration. C–F is highly effective for color and COD removal and can reduce treatment costs when optimized.

ii. **Membrane Filtration:** Ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) separate pollutants based on molecular size. These methods are effective for desalination and dye removal but are hindered by high costs and membrane fouling.

iii. **Advanced Oxidation Processes (AOPs):** Techniques like ozonation and photocatalysis generate hydroxyl radicals to oxidize non-biodegradable compounds. These methods are powerful but energy-intensive.

iv. **Biological Treatment:** Conventional activated sludge systems are widely used but fail to degrade synthetic dyes effectively. They are best employed as part of a hybrid system.

v. **Electrocoagulation:** An electrochemical process that destabilizes pollutants using an electric current. While effective, it is energy-intensive and less feasible for small-scale plants.

Table 1: Summary of Wastewater Treatment Methods

Method	Description	Advantages	Disadvantages
Coagulation–Flocculation	Uses chemicals to destabilize and aggregate particles.	Effective at reducing COD and color; simple setup.	Sludge generation; chemical cost.
Membrane Filtration	Uses semi-permeable membranes for separation.	Removes salts and dyes effectively.	High cost; fouling issues.
AOPs	Oxidizes organic pollutants with radicals.	Effective for persistent compounds.	Expensive; energy-intensive.
Biological Treatment	Uses microbes to degrade organics.	Low cost; effective for BOD.	Ineffective for dyes.
Electrocoagulation	Electric current destabilizes pollutants.	Works on various pollutants.	High energy demand.

5. Zero Liquid Discharge (ZLD) Implementation

The Indian textile industry is among the largest consumers of water globally, with dyeing, finishing, and washing processes contributing significantly to both water usage and industrial wastewater generation. It is estimated that the industry consumes over 425 million gallons of water per day, making water sustainability a critical concern, especially in water-stressed regions. Specific water consumption varies by process type, ranging from 28 L/kg for denim dyeing to 285 L/kg for knit composite units. Even upstream, cotton cultivation demands up to 10,000 liters per kilogram, contributing further to the industry's overall water footprint [14].

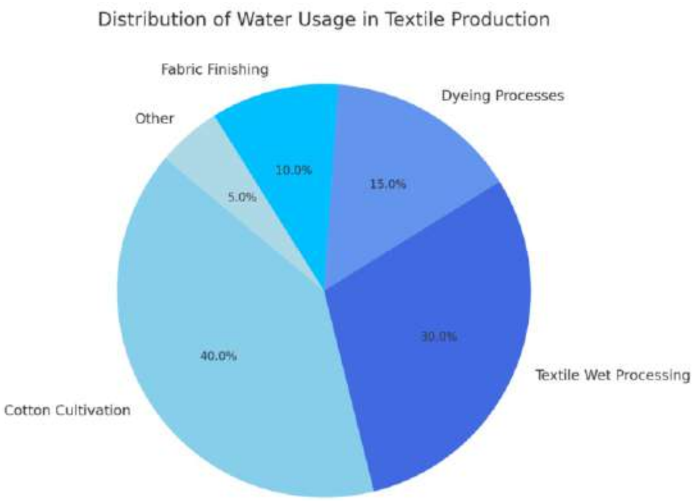

Figure 3: Textile industry's overall water footprint [15]

This extensive water use leads to equally large volumes of wastewater, which often contains dyes, heavy metals (e.g., chromium), alkalis (NaOH), starch, acids, and other hazardous chemicals. Dyeing and finishing processes alone account for approximately 17–20% of the total industrial wastewater. If not adequately treated, this wastewater can contaminate water bodies, posing serious risks to ecosystems and human health [14].

To address these issues, Effluent Treatment Plants (ETPs) are mandated for all textile units under government regulation. However, conventional treatment systems often fall short of achieving complete water reuse. In response, the concept of Zero Liquid Discharge (ZLD) has emerged as a sustainable solution. ZLD aims to eliminate any discharge of liquid waste from industrial premises by recovering, recycling, and reusing the entire wastewater stream. There are some zero liquid discharge (ZLD) Methods in use, such as Reverse Osmosis (RO), Multiple Effect Evaporator (MEE), Membrane Filtration, Advanced Oxydation Processes (AOPs), Spray Dryer, Constructed Wetlands, etc. These methods are compared in Table 2 [16-19].

5.1 Criteria for Effectiveness Rating (★ system)

Figure 2: Process flowchart of Yarn Manufacture from Recycled Cotton Fiber

ZLD Method	Mechanism	Effectiveness	Energy Use	Capital Cost	Operating Cost	Suitability
RO	Membrane separation	★★★★☆	High	Very High	High	Low
MEE	Thermal evaporation	★★★★★	Very High	Extremely High	Very High	Low
Membrane Filtration	Size-based separation	★★★★☆	Moderat e	High	Moderate	Moderate
AOPs	Oxidation with radicals	★★★★☆	High	High	High	Low
Spray Dryer	Thermal drying	★★★★★	Extremel y High	Very High	Very High	Low
Constructed Wetlands	Natural filtration	★★☆☆☆	Low	Moderate	Low	Moderate
Coagulation – Flocculation	Particle destabilization	★★★☆☆	Low	Very Low	Very Low	High

The **effectiveness rating** (from ★☆☆☆☆ to ★★★★★) is based on four key performance parameters in textile/dye wastewater treatment:

Pollutant Removal Efficiency
Ability to reduce COD, BOD, color, TDS, and toxic dyes.
High efficiency (>90%) earns higher stars.

Water Recovery Rate
The extent to which treated water can be reused in industrial processes.

Higher water recovery (>80%) increases rating.

Robustness & Reliability
Consistency of performance across variable wastewater quality (pH, salinity, dye type).
Technologies less prone to failure/fouling rank higher.

Scalability & Industrial Applicability
Suitable for both large and small-scale industries.
Adaptability to existing effluent treatment infrastructure.

Star Rating Explanation
★☆☆☆☆ – Very low effectiveness (removes <40% pollutants, low water recovery, highly inconsistent).
★★☆☆☆ – Limited effectiveness (40–60% removal, suitable only for specific pollutants, poor scalability).
★★★☆☆ – Moderate effectiveness (60–75% removal, can handle mixed effluents but with limitations).
★★★★☆ – High effectiveness (75–90% removal, reliable under varied conditions, industrially applicable).
★★★★★ – Excellent effectiveness (>90% removal, high water recovery, robust and scalable).

So in the **Table of ZLD Methods**, the ★★★☆☆ rating for **Coagulation–Flocculation** reflects:

Strengths: Good COD and color removal (60–80%), very low cost, easy for SMEs.

Limitations: Does not remove dissolved salts effectively, has a sludge disposal issue, and has lower long-term water recovery than RO or MEE.

5.2 Economic comparison of ZLD methods

a. Define Cost Categories

Capital Cost (CAPEX): Infrastructure, equipment, installation.

Operating Cost (OPEX): Chemicals, energy, labor, membrane replacement, and sludge handling.

Cost per m³ of Treated Water: A normalized figure for direct comparison across methods.

b. Typical Cost Ranges (from literature & industry reports)

(Values are indicative, vary with plant size, effluent load, and region; all in USD per m³ wastewater treated)

c. Interpretation

Coagulation–Flocculation (C–F) is by far the cheapest option (~$0.2–0.3/m³) due to low chemical and infrastructure costs.

MEE and Spray Dryers are the most expensive (~$3–5/m³) and are only used where complete ZLD is mandated.

RO and Membrane Systems fall in the middle but require frequent maintenance and high electricity use.

Combining C–F as a pre-treatment with RO or AOPs significantly reduces total costs by lowering the pollutant load before high-end polishing steps.

All ZLD is typically implemented using energy-intensive and capital-heavy technologies such as Reverse Osmosis (RO), Multiple Effect Evaporators (MEE), membrane filtration, and advanced oxidation processes. These technologies, while effective, are financially out of reach for many small and medium enterprises (SMEs) due to their high cost and space requirements.

6. Materials and Methods

Analytical grade alum, lime, ferric chloride ($FeCl_3$), and ferrous sulfate ($FeSO_4$) were sourced from Sisco Research Laboratories Pvt. Ltd. (SRL), India. Commercially available anionic (A), cationic (B), and nonionic (C) polymers were obtained from local distributors and used as flocculants. Standard reagents required for COD estimation were freshly

Table 3: Typical Cost Ranges for different ZLD methods

Method	Capital Cost (CAPEX)	Operating Cost (OPEX)	Typical Cost per m³	Remarks
Reverse Osmosis (RO)	$300–500/m³ installed capacity	$0.70–1.00/m³	$1.0–1.5	High brine reject, membranes need frequent replacement
Multiple Effect Evaporator (MEE)	$600–800/m³ capacity	$2.0–3.5/m³	$3.0–4.5	Very energy-intensive (steam), viable for high-salinity brines
Nanofiltration / UF	$250–400/m³ capacity	$0.50–0.90/m³	$0.8–1.2	Good for color and partial COD removal, prone to fouling
Advanced Oxidation (AOPs)	$200–350/m³ capacity	$1.5–2.5/m³	$2.0–3.0	High chemical and energy demand, good for recalcitrant dyes
Spray Dryer (brine drying)	$800–1200/m³ capacity	$3.0–4.0/m³	$4.0–5.0	Used only as a final ZLD step for concentrated brines
Constructed Wetlands	$50–100/m³ capacity	$0.10–0.30/m³	$0.2–0.4	Land-intensive, not suitable for high-strength textile effluents
Coagulation–Flocculation (C–F)	$50–150/m³ capacity	$0.10–0.20/m³	$0.2–0.3	Cheapest method, effective for COD/color, but limited for TDS removal

prepared in the laboratory, following the procedures outlined in the American Public Health Association (APHA) guidelines.

Case study: Wastewater treatment with said method was carried out for many dyes and dye intermediate industries around Ahmedabad. One case is discussed here of M/s Varahi Intermediates, G.I.D.C. Naroda, Gujarat, a facility engaged in the production of metaphenylene diamine-4-sulphonic acid (MPDSA). MPDSA serves as a key intermediate in the synthesis of mordant and reactive dyes widely used by textile industries and process houses. The wastewater generated from textile industries using these dyes will have similar characteristics to wastewater generated from Ms Varahi intermediates. The untreated effluent was characterized by a COD of ~32,000 mg/L and a TDS concentration of 566 mg/L.

Jar test experiments were conducted for coagulation –flocculation trials, following standard APHA procedures. Stock solutions of coagulants and flocculants were prepared in distilled water. For each run, 10 mL of coagulant solution was added to 100 mL of wastewater and mixed for 60–70s. This was followed by the addition of 1 mL of flocculant solution with slow mixing (30–40 rpm) and subsequent settling. The clarified supernatant was separated by filtration. For further polishing, 1.0g of activated carbon was added per 100 mL of partially treated water, stirred for 10 min at 50–60 rpm, and filtered to obtain a colorless, clear effluent.

Initially, conventional single-stage trials were performed using one coagulant paired with one flocculant (alum–A/B/C, lime–A/B/C, etc.). Later, combined coagulant approaches were tested to enhance efficiency, particularly lime–alum and lime–$FeCl_3$ systems, each applied with different flocculants (A/B/C). For all cases, 10% coagulant solutions and 1% flocculant solutions were prepared in distilled water.

7. Results and Discussion

Analyses of COD and TDS were conducted according to the APHA standard methods.

In conventional single-stage treatment with individual coagulants, reductions in TDS were negligible. While COD levels decreased moderately, sludge generation was significant, and overall performance was unsatisfactory. To address this, a two-stage treatment strategy was adopted. This modification led to marked reductions in both COD and TDS.

When coagulants were paired and applied in two stages, a substantial improvement was observed. For example, lime–alum treatment reduced TDS to ~450 ppm with anionic flocculant and 370 ppm with cationic flocculant. However, nonionic flocculants were less effective, failing to reduce TDS below 450 ppm. By contrast, lime–$FeCl_3$ combinations did not yield appreciable improvements in TDS removal.

COD analysis revealed more promising outcomes. In Stage 1, COD decreased from 32,000 mg/L to ~25,000 mg/L, while Stage 2 further reduced it to ~10,000 mg/L. Among the combinations, lime–$FeCl_3$ outperformed lime–alum in COD reduction. Subsequent activated carbon treatment polished the effluent to below 50 mg/L COD and <150 mg/L TDS. These final values fall well below statutory discharge limits (200 mg/L COD, 500 mg/L TDS), rendering the water suitable for reuse within the plant. Table 4 shows all results and is compared in Figure 4. Although color intensity decreased after the coagulation–flocculation process, complete decolorization was only achieved following activated carbon adsorption. This highlights the importance of combining physico-chemical treatment with adsorptive polishing for high-strength dye intermediate effluents.

Table 4: Results of experiments

Treatment Method	Flocculant Type	TDS (ppm)	COD (mg/L)	Remarks
Untreated Wastewater	–	545	32,000	Highly colored, turbid
Lime (single coagulant)	Anionic	510	29,000	Minimal TDS reduction, slight COD drop
	Cationic	520	2850	–
	Nonionic	526	28,800	Ineffective
Alum (single coagulant)	Anionic	525	27,000	Some COD removal, weak TDS effect
	Cationic	410	2450	Significant COD reduction
	Nonionic	390	25,000	Best TDS reduction in a single stage
$FeCl_3$ (single coagulant)	Anionic	540	28,800	No major effect
	Cationic	542	29,200	–
	Nonionic	538	29,000	–
Lime & Alum (two - stage)	Anionic	450	20,000	Improved reduction
	Cationic	370	1800	Strong TDS + COD reduction
	Nonionic	460	21,000	Less effective
Lime & $FeCl_3$ (two-stage)	Anionic	520	17,000	Effective COD reduction
	Cationic	515	15,000	Better COD removal than Lime–Alum
	Nonionic	525	18,500	Weak TDS impact

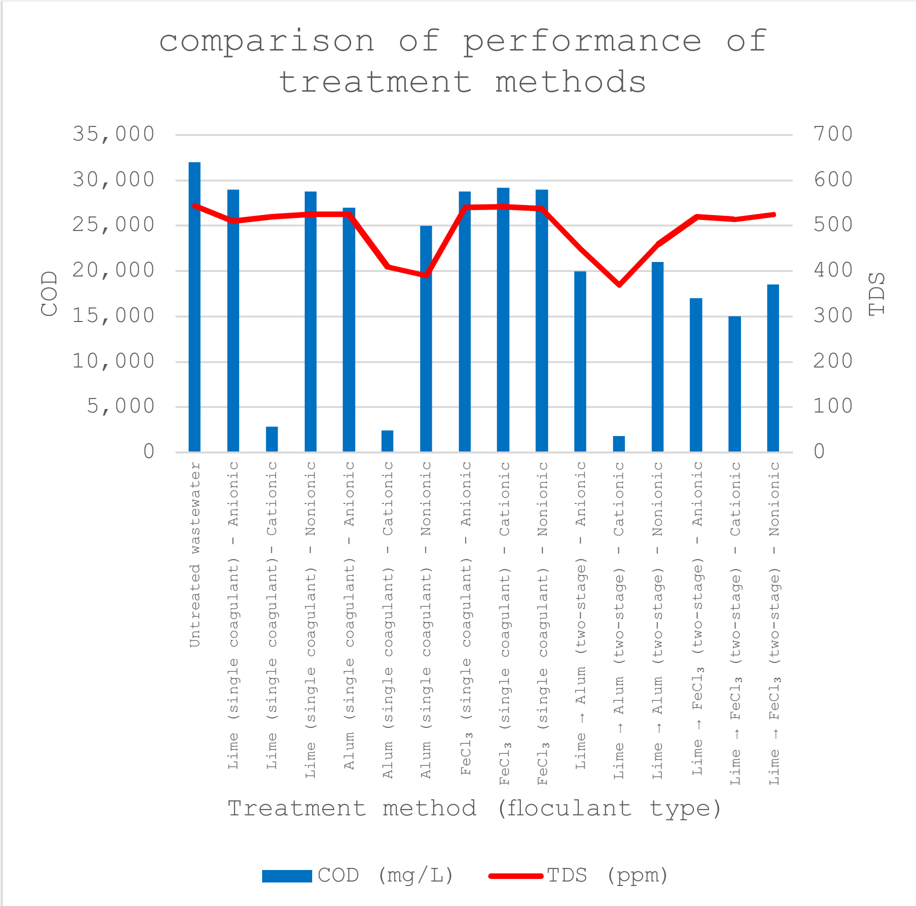

Figure 4: Comparison of experimental results

Treatment with activated charcoal resulted in a significant reduction in both color and COD and produced clear, colorless water. Final COD levels dropped to 30 mg/L, and in several cases, values were observed to be as low as 10 mg/L. The treated effluent thus became suitable for reuse within the process, eliminating the need for external discharge of water from the plant. In the primary treatment stage, the use of coagulants such as ferric chloride, alum, and polyelectrolytes effectively facilitated the separation of colloidal matter from wastewater. However, this process generated a considerable volume of sludge, which requires safe disposal through a Treatment, Storage, and Disposal Facility (TSDF). All the pollutants removed by the C-F method will be carried away by the sludge generated by it to clean the water.

The use of alternative coagulants, such as pre-hydrolyzed metallic salts, is often more effective than the hydrolyzing metallic salts, such as ferric chloride, aluminum sulfate (alum), and ferric sulfate, which are readily soluble in water. Pre-hydrolyzed coagulants such as poly-aluminum chloride (PACl), polyaluminum ferric chloride (PAFCl), polyferrous sulfate (PFS), and polyferric chloride (PFCl) seem to exhibit better color removal even at low temperatures and may also produce a lower volume of sludge. The effectiveness of PACl products gives more rapid flocculation and stronger flocs compared to alum at an equivalent dosage. This can be attributed to the fact that these coagulants are pre-neutralized, have a smaller effect on the pH of the water, and so reduce the need for pH adjustment.

Commonly used textile dyes are ionic, mostly anionic, and hence, the cationic polymer can be preferred as it exhibits better dye removal performance, due to its opposite surface charge attraction. Different coagulants affect different degrees of destabilization. The higher the valence of the counter ion, the more its destabilizing effect and the less the dose needed for coagulation. Alum, ferric chloride, and ferric sulfate are the most widely used chemical coagulants with varying dose amounts in textile wastewater treatment.

8. Advantages of Coagulation–Flocculation

i. Low Capital Investment: Requires only simple tanks and settling chambers.

ii. Minimal Energy Requirements: No need for high-pressure pumps or thermal units.

iii. Cost-Effective Chemicals: Readily available coagulants like lime, alum, and PAC.

iv. Space Efficiency: Ideal for SMEs and decentralized plants.

v. Integration Capability: Can serve as a pre-treatment for RO or MEE to reduce costs.

9. Government Initiatives and Industry Adoption

Government schemes like the Integrated Processing Development Scheme (IPDS) encourage water conservation through funding support for effluent treatment plants. Many companies are adopting closed-loop systems, digital printing, enzyme-based processes, and organic cotton cultivation to lower their water footprint.

Coagulation–flocculation fits into this ecosystem as a scalable, low-barrier solution.

10. Conclusion

Zero Liquid Discharge is both an environmental and economic necessity for India's textile industry. High-cost ZLD technologies are often inaccessible for SMEs, making it imperative to adopt low-cost yet effective alternatives. This study demonstrates that coagulation–flocculation, when optimized, is a viable, scalable, and economical method for wastewater treatment, reducing COD, color, and other contaminants to levels suitable for reuse. Future research should focus on innovative coagulants, hybrid treatment systems, and sludge minimization to further enhance the sustainability of this approach.

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Shushk Engineering

Klydo Colourimeter - Colour Identification Systems

Introduction

One starts appreciating the World of Colours, as school student, in form of 48-colour set of crayons, to the day one opens the shade book to decide on the colour on the walls. Colours are creativity, colours are creation. And going from creativity to creation involves skill and precision.

Shushk Engineering, may not be skilled craftsmen, but are obsessed with precision. Thermometers can precisely measure temperature. Delhi's traffic can very well measure a driver's patience. So why can't one precisely measure and communicate colour?

Klydo is the sum total of our efforts to measure colour, put a definitive name and number to it.

Colour Identification

Colour identification systems were necessary as soon as mass manufacturing of consumer goods started across the world. Two scooters standing side by side at a showroom, couldn't afford to have even a slightly differing shade in the eyes of the customers walking in. Though several systems, endorse by different nations and companies, still exist to this day, Pantone has emerged as the clear victor.

Pantone's "Colour Matching System" was developed in 1950s. Since then, they have taken over industry after industry: print media, textiles, interior design, just to name a few. Any industry that has an eye for colour consistency, employs Pantone colour coding for its products. The system is very simple: each colour has a unique code. In case of textiles, it's a 6-digit code.

So the designer only has to specify the colour code to the manufacturer and then it's up to the manufacturer to create that exact shade and maintain it the entire time it's in production.

Need for improvement

The existing matching process has several gaps which Klydo aims to solve:

1. 8% of men and 0.5% of women are colourblind. These people can't rely on their eyes to match product colour with the pantone colour cards at all! An even greater percentage of population has low sensitivity for colour as well.

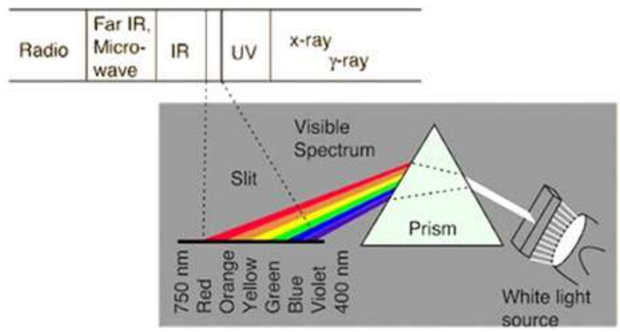
2. If the floor worker is correctly able to spot a difference between the product shade and the pantone shade, he/she still doesn't know how to remedy it. Which dyes need to be added? In what quantity? In order to reach the right shade.

3. Finally, Pantone reference guides are not the easiest objects to carry around. Moreover, one requires time and patience to sift through all the shades and find the closest match.

Physics behind Klydo

Klydo is designed to address all of these core issues with using the Pantone matching system. To understand how, one must first understand the physics behind the operation of Klydo.

All light is not same. It may look homogenous, but a glass prism reveals that it is composed of several "colours". Those colours are actually light waves of different wavelengths.



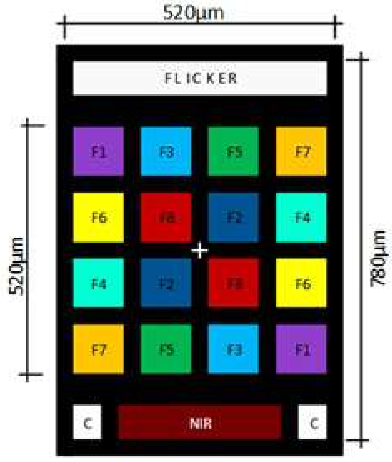
White light (or sunlight) going through the prism reveals

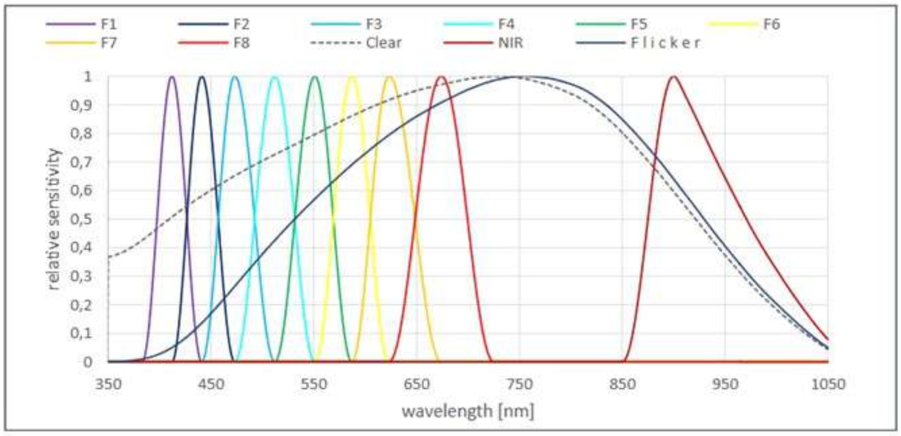
Human beings have evolved to distinguish between lights of different wavelengths. The red deer hiding in the green grasses is revealed because the light coming from the two excite different type of cells in the human eyes. This way, colour is nothing but a proxy for wavelength of light reflected by an object. A bright red apple absorbs all wavelengths falling on it except those in the 'Red' region.

Thus, it can be concluded that all objects must have colour, even the ones that reflect no light (black objects) or all light (white objects). So, all objects must have a "Spectral Signature". It is the symphony of light reflected by an object; to which human eyes are the audience. In order to read this symphony, Klydo uses a state-of-the-art Spectroscopy sensor.

Spectroscopy sensors work on a principal not too dissimilar from solar panels. Light hits them, they produce electric current. The only difference being that these sensors have multiple cells in them, each sensitive to only a specific part of the spectrum. So you could say that each cell is sensitive to a single colour. As depicted in the figure below, the sensor used in the Klydo reads light in 8 "bands" in the visible region. So a bright Green object would produce a strong signal in the F5 band and some signal in the adjacent F4 and F6 bands.

The story doesn't end here. There is complex maths worked out by team Shushk Engineering that turns the signal given by the sensor into a Spectral Signature and then into CMYK or RGB colour outputs. In addition, the software also



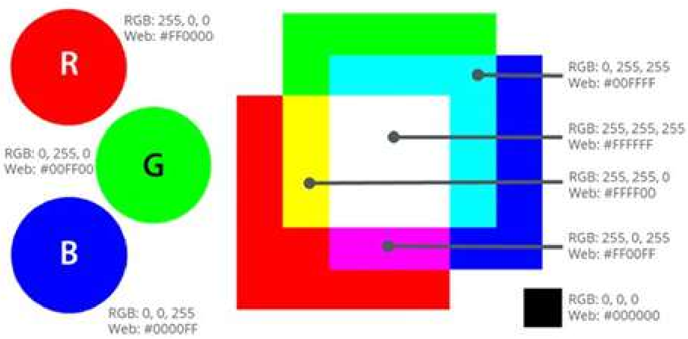


compares it to our repository of Pantone colour signatures, which will be discussed in the next section.

Let's briefly describe the RGB and CMYK colour systems:

- **RGB – Red Green Blue**

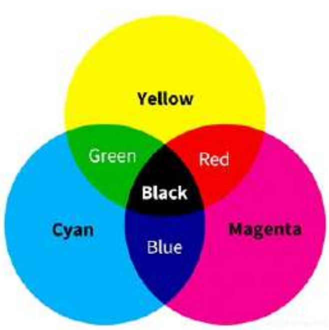
This system is more "natural" of the two. That is because human eyes have special cells called Cones that are sensitive to red, green and blue colour light. This system is extensively used by the digital world. Any screen around you operates by receiving the RGB value of each pixel from a digital source.



From the figure above it is evident how mixture of different lights produces different colours. This way, a modern LED display can create a very life-like image. Conversely, Klydo can scan any colour and break it down into its R, G and B components.

- **CMYK – Cyan Magenta Yellow Black**

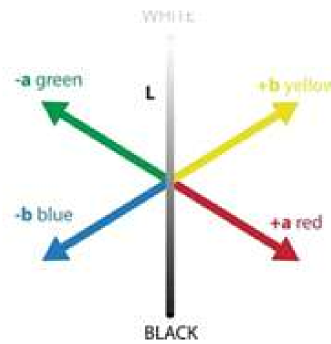
This colour system was developed by the print industry and continues to be universally used by all publications. You can even see 3 narrow bands of CMY at the edge of your newspaper. RGB cannot be used for print or dyeing because when two dyes are mixed, they tend to absorb most of the light, leaving us with very dull shades.



For example:
Red (light) + Green (light) = Yellow (light)
Red (dye) + Green (dye) = Brown (dye)

- **CIELAB colour space**

The CIELAB colour space, also referred to as L*a*b*, is a colour space defined by the International Commission on Illumination (abbreviated CIE) in 1976. It expresses colour as three values: L* for perceptual lightness and a* and b* for the four unique colours of human vision: red, green, blue and yellow. CIELAB was intended as a perceptually uniform space, where a given numerical change corresponds to a similar perceived change in colour. While the LAB space is not truly perceptually uniform, it nevertheless is useful in industry for detecting small differences in colour.



- **Device Operation**

Have a look at the device first:

Image 1. Scanning mode

Image 2. Reference mode

The device is a battery operated, stand-alone unit with no need for any internet connection, WiFi, Bluetooth, no App on your smartphone. Isn't it refreshing in this day and age? Just a nifty hand-held device that works for about 6 hours that can then be charged with any C-type USB cable!

Here are the basic steps of how to operate the device:

a) Turn on the device with the power switch at the top (see Image 2).

b) Place the device on the surface or fabric or page whose colour you want to inspect.

c) Press down the nose (see Image 1) on the surface such that it forms a seal. This is important because any light from outside can pollute the readings.

d) Now simply press the button on the top right (see Image 2). A quick press scans the image and a long press (more than half a second) takes you to the reference mode.

e) In case of scanning, keep the nose pressed until fresh values appear on the screen.

The scan reveals two distinct pieces of information.
Firstly it matches with the entire database of Pantone or RAL colours and reveals the closest match (see Image 1). Secondly, Klydo calculates the L*a*b* composition of the colour you've scanned (see Image 1). These values are display on a scale of 0 to 100 for L and -100 to +100 for a* and b*.

Image 3. Top face of Klydo

Besides this, the device displays battery level at the upper right corner (see Image 2). When the battery gets low, please charge with the standard C-type charger provided with the device, or any other mobile charger.

There's a communication port provided as well for Serial communication. This is mainly for any device updates or modification as discussed with the client.
Reference Mode
When you press the button for longer than half a second, you enter the reference mode (see Image 2). The goal of this mode is twofold:

Either the reference colour you want is on a sample you have. So you scan the reference sample and long press the button to store its colour values. Every subsequent scan will compare the scan's value with the reference value. Thus, the L*a*b* values will be compared with those of the stored reference.

Or the reference colour you want is in the form of a Pantone/RAL code. To implement this, you can input the six-digit/four-digit code of the colour and press the enter button on the touch screen. This would set that particular Pantone/RAL shade as the reference colour and all subsequent scans will be compared with set Pantone shade, until a new reference is set by long pressing the button.

Once the reference is set, any new scan will reveal ΔE* value at the bottom of the screen (see image 1). The delta we calculate is as per the 3-page formula published by CIE in 2000. This is the most accurate way to calculate the colour difference between 2 shades. ΔE* of 1 and below is the same colour and above 10 is a substantially different colour. Based on this, the Grayscale difference between the two shades is also calculated. This ranges from 1 to 5. 5 is the exact same colour and 1 is a different shade altogether.

KLYDO

For more details, please contact:

Website: www.shushk.in
Mob.: +91-8447727837; +91-9971162233

Zapper Filterless Air purifier

Canary AQI monitor

The Textile Association (India), Ahmedabad Unit

April 2025

The Textile Association (India) Ahmedabad Unit started distribution of nutrition kits to the pregnant ladies who are under malnutrition during the pregnancy. Every month approx. 150 kits are distributed. And the said activity will be carried out by the association for the next six months starting from April 2025 in association with the AMC health department.

16th May 2025

TAI-Ahmedabad Unit arranged a motivational program “Chalo Jivi Laiye” for the members and their family members. The speaker was Mr. Maulik Pandya. He expressed during his deliberation how to maintain your life style after 60 years or a certain age. More than 500 members were present in the function. It was really informative towards the audience.

6th June 2025

TAI-Ahmedabad Unit arranged a family drama “Powerful Patidar” for the members and their family. The said drama is directed by the Vipul Shah. The drama provided a strong social message.

2nd – 8th July 2025

TAI-Ahmedabad Unit arranged an internship textile training program for the student of BE Sem-6 of Textile Technology, L. D. College of Engg, Ahmedabad. During the training program lecturers were Prof. Ashwin Thakkar, Mr. K. J. Shah, Mr. Vikram Jain, Mr. Parth Parmar, Mr. Rajendra Suthar & Mr. Sanjeev Singh. Topics covered were Advanced Textile, Weaving, Technology of Denim, CAD & New Frontiers in Textile, Advance Spinning & Textile Product Development.

12th July 2025

A half day technical program was organized on Circularity in Textile Industry. Speakers from industry delivered lectures on various aspects of sustainability, circularity, Life cycle analysis, GHG and Carbon foot prints with reference to growing export obligations. The program was widely acclaimed by the audience.

24th – 30th August 2025

Committee members of The Textile Association (India), Ahmedabad Unit visited Vietnam from 24.08.2025 to 30.08.2025 to study some of the latest developments in textile.

19 committee members visited LUA VIET company near Ho Chi Minh city of Vietnam. The company specializes in various products using bamboo fibre. Products for apparel and home use were explained. A full demonstration of products belonging to few categories of Technical textile was given also. A demonstration of these products was given by experts from the company. A live demo was also given to TAI committee members.

15th Sept 2025

A half day technical program was organized on Textile Start Up Ecosystem. About 10 textile startups were invited and they made presentation in front of investors who were invited from industry. Two startups were given assurance about mentoring. The startups were in the areas of product design, technical textile, smart textiles, wearable electronics, waste recycling etc.

19th Sept 2025

TAI-Ahmedabad Unit arranged one-day seminar on "Investor Conclave on Comprehensive Sportswear Manufacturing Projects in India" in its meeting room. The knowledge partner was Unified Knowledge Services Pvt Ltd., (UKS), Delhi. All the experts were invited by the UKS and during the deliberation the subjects were covered: Comprehensive Project Portfolio, Market Intelligence, Ecosystem Access and panel discussion. Around 55 registered members were attended this important seminar from the area of sportswear/technical textiles.

25th Sept 2025

A half day technical program was organized on Impact of Geopolitical Issues and Tariff Restructuring on Textile Industry. Mr. Eishiro Takeishi, Asia Editor of The Asahi Shimbun, Japan deliberated on various issues with reference to current geopolitical issues and its impact on South Asian Countries especially India. He also talked about tariff restructuring across various trade blocks and its impact on textile trade between India and Japan. The program was well accepted by the audience.

27th Sept 2025

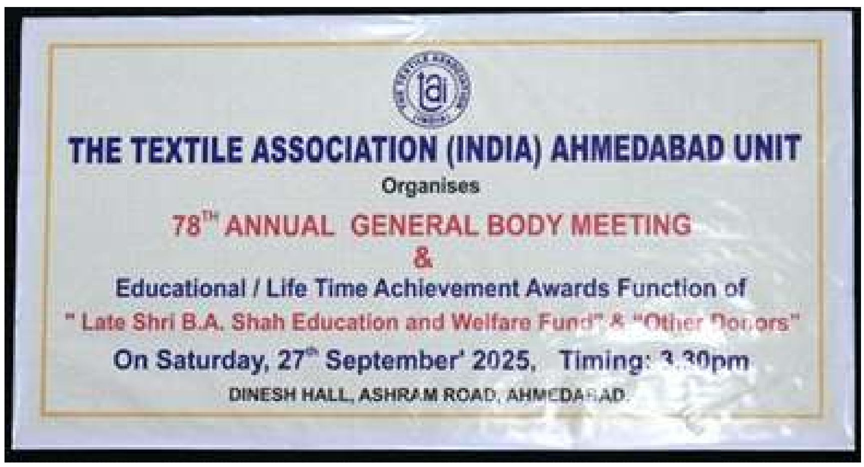
Prize distribution function to the Bright Students:

The Textile Association (India) Ahmedabad Unit arranged a prize distribution function to the bright students from donors of "Late Shri B. A. Shah Educational & Welfare Fund; Hirabhai J. Patel Textile students diploma/degree fund and other funds" held on 27th September' 2025 at Dinesh Hall, Ashram Road, Ahmedabad. During the prize distribution function the association distributed total 28 Mementoes and 40 certificates to the selected qualified students of SSC/CBSE, HSC-Science & Commerce, PhD in Textile Engineering, Bachelor & Master of Pharmacy, LLB, BDS & other Engineers (Computer, Electrical etc). Shri Hirabhai J. Patel, Vice President handed over the certificates & mementoes to the Textile Manufacturing, Textile Technology & Textile Engineering rankers' student of LDCE & RCTI, Ahmedabad. Every year association has been organizing this function to encourage the students. One memento with certificate handed over to a student who successfully completed ATA diploma on Textile Yarm Manufacturing group through TAI-Ahmedabad unit in the year 2024 from the T. L. Patel, ATA prize fund.

Life Time Achievement awards 2025:

As a part of the prize distribution function The Textile Association-Ahmedabad Unit also handed over Lifetime Achievement Awards to the most senior and honorable members Shri Kanaiyalal J. Patel & Shri Gaurang J. Dwivedi who rendered their valuable services towards the association & Textile Industries for almost 40 years in different way. Their contributions were memorable to the association. This lifetime achievement award was donated by Late Shri B. R. Shah, Past President and Trustee of the TAI-Ahmedabad Unit.

78th Annual General Body Meeting of The Textile Association (India) Ahmedabad Unit



The Textile Association (India) Ahmedabad Unit arranged its 78th Annual General Body Meeting on 27th September 2025 at its premises Dinesh Hall, Ashram Road, Ahmedabad. The AGM was conducted as per the agenda, and Shri Haishchandra C. Shah, Hon. Secretary welcomed the meeting and presented the association's activities from 1st April,2024 to 31st March 2025. Shri Hasmukhbhai S. Patel, President remarked in his speech that the association organized regular technical programs and also carried out activities for member's welfare and now association is also working towards the society activities. Not only that association also arranged Internship textile training program for the textile engineering students of L. D. College of Engineering and RCTI, Ahmedabad.

AD' from the House of Arvind announces Raghav Juyal as its Brand Ambassador

Championing Comfort, Style & Everyday Fashion

AD', the contemporary ready-to-wear brand from the house of Arvind, proudly announces the appointment of Raghav Juyal, celebrated actor and youth icon, as its new brand ambassador. Known for his authentic personality, effortless charm and distinctive sense of style, Raghav perfectly embodies the spirit of AD – comfortable, breathable and fashionable everyday wear that resonates with today's generation.

Commenting on the announcement, Pranav Dave, Chief Business Officer – Retail & Knits, Arvind Limited said, "Raghav Juyal's individuality and effortless style align seamlessly with our brand ethos. 'AD' from the house of Arvind is about creating versatile, easy-to-wear fashion that fits into the everyday lives of our consumers, while making them look and feel confident. Raghav brings that spirit alive with his relatable and charismatic personality."

Raghav Juyal, known for his individuality and creative energy, shared his excitement, "I am excited to associate with 'AD' from the House of Arvind. The brand represents fashion that is relaxed yet stylish – something I personally relate to. For me, comfort is non-negotiable, and the brand delivers exactly that while still keeping it trendy. I look forward to this partnership and connecting with people who enjoy fashion that feels as good as it looks."

'AD' redefines everyday fashion by offering stylish, breathable, and versatile apparel designed for the modern lifestyle. With a focus on balancing comfort and fashion, the brand is fast becoming a preferred choice for those who seek clothing that transitions effortlessly from work to leisure.

With Raghav on board, the brand will soon unveil a new campaign across digital platforms, retail stores, and marketplaces, celebrating the idea of everyday fashion that is effortless, confident, and in tune with today's lifestyle. The collection is available across The Arvind Store, Myntra, and other leading e-commerce platforms, ensuring easy access for today's fashion-forward consumers.

About AD:
AD is a modern menswear label redefining wardrobe essentials through premium fabrics, technical construction, and versatile designs. Focusing on innovation, resilience, and timeless appeal, the brand caters to men who equally value comfort and confidence.

For further information, please contact:
Namita Naik
9867818259
namita@itwplayworx.com

BASF and LEMON sign Memorandum of Understanding to Co-develop New Material Solutions for Apparel

BASF and LEMON Co., Ltd. (LEMON) have signed a Memorandum of Understanding (MoU) to jointly develop new material solutions using Freeflex®, a fiber made from BASF's Elastollan® thermoplastic polyurethane (TPU).

LEMON, a leading producer of functional Nano membranes, will incorporate Freeflex into the production of its waterproof and windproof apparel. The agreement also outlines future opportunities for collaboration in technology development and business expansion.

"This partnership with BASF allows us to expand the application of our electrospinning technology and deliver high-performance nanofiber materials to global brands," said Lee Jong-il, Chief Executive Officer, LEMON. "By combining our expertise in Nano membrane development with BASF's material innovation, we aim to set new standards in functional textiles."

Freeflex is a high-performance BASF material engineered for fabricating Nano-mem branes with a reticular structure via electrospinning. This material offers high water repellency, improved air permeability, and is ultralight weight. It is designed to perform reliably under extreme environmental conditions while maintaining comfort and durability.

"Freeflex demonstrates how material science can contribute to the future of high performance and more sustainable clothing," said Rohit Ghosh, Vice President, Business Management TPU, Performance Materials Asia Pacific, BASF. "We are excited to introduce advanced TPU fiber technology to the South Korea's apparel industry through the partnership with LEMON."

In addition to its functional benefits, Freeflex is made without the intentional use of Per- and poly-fluoroalkyl substances (PFAS) and is fully recyclable. These attributes align with both companies' commitment to more sustainable innovation.

Heading to the Future in the Name of Quality

Uster presents novelties at ITMA Asia + CITME 2025

There's news from Uster Technologies to be announced for the industry's upcoming event in Singapore. The Uster 360Q universe is growing with new products, solutions and services. Innovation developments can also be recorded in the fields of man-made fiber testing and fabric inspection. Uster innovations address the industry's trending topics as mill management and process control, optimization of delivered fabric quality and yield.

Presented for the first time two years ago at ITMA in Milan, Uster 360Q has attracted considerable interest, and FiberQ has proven itself in practice as a raw material management solution with profit potential. Under 360Q – and with the goal to empower spinners to achieve Think quality at the next level – Uster developed a further solution and tools.

Uster Fiber2Yarn for the great picture

Newly combining and correlating data of FiberQ – measured with Uster HVI – with data from Uster Quantum yarn clearers, spinners can learn about the influence of different raw material parameters on the end product quality. This highly sought-after information offers a great opportunity to optimize mixings and continuously achieve a higher level of quality consistency besides better control of the production process. The Uster Fiber2Yarn solution is available in two different views, like the correlations over time and the correlations over different mixings.

A wide range of valuable features and information can be found on the Uster 360Q Platform. Uster services are hosted on the cloud-based platform with a technology architecture that makes businesses more agile and cost-effective. Additionally, the cloud solutions enable businesses to leverage AI and machine learning capabilities. The integration of Uster Intelligence – combining artificial intelligence with Uster's expertise – is opening up new possibilities for spinners. Additional benefits include further advancements in the Uster Academy, such as the introduction of the Uster Chatbot and Wiki, providing direct and easy

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access to Uster know-how. The Academy's e-learning portfolio has been expanded to serve a broader range of users.

Furthermore, the platform serves as a central access point for notifications and alerts. The Uster 360Q Platform is also where users – free of charge and with no license needed – find Uster news and the latest application literature. Also, the content provided earlier via the Uster Insights App will be integrated into the platform. And of course, the new Uster Statistics web app is part with all well-known functionality in a new format.

The simplicity of fabric quality control

Uster presents at ITMA Asia + CITME 2025 the brand-new Uster Fabriq Vision 2. The next generation fabric inspection system stands for reliable performance – also in challenging environments – and shows enhanced detection capabilities. Both advantages result from the Smart Vision Camera 3 for high-performance in-camera image processing. Uster's real-time process monitoring and quality inspection solution further convinces by simplified operation through Uster Intelligence-supported style creations as well as by image-based and supported visual setting adjustment for easier adaption.

Fabric producers need to ensure a consistently high rate of defect detection by automated control during final inspection. Uster Fabriq Vision 2 offers advanced process safety through the Super Inspection Mode for increased security, even after production, and consistent Uster Intelligence-supported quality decisions. The system's ability finally allows fabric yield to be optimized and prevents claims – quickly set up and easy handled when fine tuning.

Fiber process control for cotton, synthetics and blends

Uster AFIS 6 has been launched earlier this year but will be presented at ITMA Asia + CITME in Singapore first time to an audience in Asia. The next-generation AFIS stands out by uniquely testing man-made fiber properties in addition to cotton in the same unit. It provides critical data to optimize fiber process control in spinning, paving the way for superior yarn quality and reduced waste.

AFIS 6 can be seamlessly integrated in the mills quality management regime by connecting to Uster Quality Expert and the integration of the Uster Statistics. The enhanced user experience result from the new user interface and its various languages available is a key highlight. Another plus is simplified data analysis through the integral reporting functionality.

Not to be missed

Uster looks forward to the upcoming opportunity to shake hands with customers and friends at ITMA Asia + CITME 2025. At the Uster booth in Hall 3, B301 – visitors find the Uster experts to discuss hot subjects as sustainability and making yarn of recycled fibers and they receive the latest Uster Sustainability Bulletin to dive deeper into these subjects.

The occasion also offers the opportunity to gain first-hand insights into the new features of the market-leading Uster yarn clearer. Quantum 4.0 introduces hairiness monitoring at an unmatched level. It will also be interesting to hear about the latest cooperations for ring spinning optimization (RSO). Besides the seamless integration of the Pinter Monitoring System, the Uster RSO 3D compatibility has been expanded and includes now Rieter and Savio winders, alongside continued support for Murata winders.

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ITMA 2027 Stand Space Application Now Opens

Stand space application is now open for ITMA 2027. The 7-day exhibition will be held at Messegelaende Hannover, Germany from 16 to 22 September 2027. Featuring the theme Co-creating the Future of Textiles, the exhibition is expected to bring together global leaders and innovators to shape the industry's future.

Following the success of ITMA 2023 in Milan, leading textile and garment machinery manufacturers are invited to secure their presence early at the industry's most influential platform to launch their technologies, forge partnerships and grow their businesses worldwide.

Alex Zucchi, President of CEMATEX, owner of ITMA, said: "In 2027, ITMA returns to Hanover after 36 years. More than a platform for the promotion of innovative technologies, it is a turning point in the textile industry. As we evolve from Industry 4.0 to 5.0, we're not just automating, we're humanising technology. Together, we'll accelerate the shift towards a circular economy – one that is built on collaboration, innovation and regeneration."

Dr. Janpeter Horn, Chairperson of VDMA Textile Machinery Association, said: "We expect to have a strong presence of VDMA companies as our members are excited that ITMA will be staged in Germany after a long break. Supported by Hanover's best-in-class exhibition infrastructure, ITMA 2027 will be an excellent platform for them to launch their latest innovations, focusing on efficiency, automation, digitalisation and sustainability."

The exhibition is expected to gross 200,000 square metres and draw over 1,500 exhibitors. Well known as the Olympics of textile machinery exhibitions, the upcoming edition prepares the industry to meet new challenges and opportunities amidst tighter sustainability regulations and rapidly evolving technological developments. To apply for space, visit www.itma.com.

CEMATEX grants

ITMA 2027 will feature 20 product sectors, encompassing the entire textile and garment manufacturing value chain. One of the sectors is Research and Innovation. Research and educational institutions applying to exhibit in this sector will be able to leverage a CEMATEX grant to defray 50 per cent of their participation costs.

CEMATEX will also be providing a grant to fully subsidise the participation of up to 20 young companies with innovative products and services for the textile industry. Launched in 2023, 15 companies were selected to participate in the Start-Up Valley.

One of the exhibitors, TreeToTextile - a Swedish-based cellulose fibre producer - was delighted with the outcome of their participation. Ida Alnemo, Head of Application & Sustainability, enthused: "ITMA has been a great platform for future collaboration needed to scale breakthrough innovations like ours, to make a positive change in the textile industry in offering better fibres to all."

Information on the two grants can be found on the exhibition website.

More information on ITMA 2027 is also available at the upcoming ITMA ASIA + CITME, Singapore 2025 exhibition which will be held at Singapore Expo from 28 to 31 October 2025. Visit stand H5- D304 to learn more about the exhibition, venue, accommodation options and Hanover city from the ITMA Services team and partners.

The last ITMA exhibition was held in Milan in 2023. It featured the participation of 1,709 exhibitors from 47 countries, and visitorship of over 111,000 from 143 countries.

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FICCI TAG 2025 – Post Event Report

State working towards establishing Six Technical Textile Parks to make Maharashtra a hub for Technical Textiles: Textiles Minister, Govt. of Maharashtra.

Garment-Led Investments Poised to Drive Indian Textile Industry's Growth: FICCI - Wazir Advisor.

Mr. Sanjay Savkare, Minister of Textiles, Government of Maharashtra today released the annual FICCI -Wazir Advisors Textile industry report 'Catalysing Textile & Apparel Growth: Leveraging Global Opportunities' during TAG 2025 Annual Textile Conference organised by FICCI on 12-09-2025 at Hotel Trident, Mumbai.

Mr. Savkare said that Maharashtra Government through its policy measures is focusing on attracting domestic and foreign investment and providing support on skilling, R&D and infrastructure development to build globally competitive textile & apparel industry in Maharashtra. He informed that state is working towards establishing Six Technical Textile Parks, one in each of the revenue divisions, to make Maharashtra a hub for Technical Textiles.

L to R: Mr. Deepak Mukhi, Director, FICCI MSC, Mr. Dinesh Joshi, Co-Chair, FICCI MSC, Shri Sanjay Savkare, Hon'ble Minister of Textile, Govt. of Maharashtra, Smt. Anshu Sinha, Principal Secretary (Textile), Govt. of Maharashtra, Mr. Prashant Agarwal, Jt. MD, Wazir Advisors

L to R: Jyoti Prakash Mohapatra, Joint President-Marketing & Business Development, Grasim Industries Ltd. Prashant Agarwal, Jt. MD, Wazir Advisors, R.K. Mishra, Additional DGFT, Directorate General of Foreign Trade, Shaleen Toshniwal, MD, Banswara Syntex, Kapil Pathare, Jt. M D, VIP Clothing

He further added that state has set up a task force to seek suggestions from the stakeholders to enhance the export competitiveness of Maharashtra and support to Textile Industry will be extended as per the suggestions of the Task Force.

Ms. Anshu Sinha, Principal Secretary (Textile), Government of Maharashtra stressed about the need for collaboration and collective efforts of Industry, Academia and Government to further strengthen Maharashtra's position as leading manufacturing hub for the Textile Industry and sought support of the industry in the areas of Skilling, R&D and Sustainable practices.

Mr. Prashant Agarwal, Joint MD, Wazir Advisors shared a brief overview of FICCI – Wazir Advisors Report, which takes stock of the global and Indian textile & apparel (T&A) landscape in a year marked by geopolitical uncertainty, shifting trade flows, rapid advances in sustainability and innovation, and the challenges arising from the US reciprocal tariff scenario. The report also talks about what strategies can India adopt to fully realize its potential and position itself as a leading global hub.

The report states that Global textile & apparel trade reached ~US$ 893 billion in 2024, reflecting 5% growth over the previous year, with China retaining one-third share. The global apparel market, now at US$ 1.8 trillion, is projected to touch US$ 2.3 trillion by 2030. India, with a US$ 184 billion domestic T&A market and US$ 37 billion in exports (FY25), continues to hold strong fundamentals but faces challenges from newly imposed US tariffs of 50%, compared to lower rates for competitors like Bangladesh and Vietnam.

The report identifies garmenting investments as the central lever for India's next phase of growth, supported by FDI inflows, global alliances, and government schemes like PLI and PM MITRA Parks. It highlights how forward integration into apparel manufacturing can enhance value addition, create large-scale employment, and improve India's competitiveness as an end-to-end sourcing hub.

The study emphasizes innovation and sustainability as twin imperatives ranging from smart textiles, eco-friendly materials, and digitalized supply chains to scalable adoption of green manufacturing practices. It further underlines India's factor cost advantages over peers, while cautioning that weak R&D and lack of FTAs with key markets remain bottlenecks.

The way forward, according to the whitepaper, rests on market diversification beyond the US, policy stability, infrastructure development, R&D and skilling, and embedding sustainability across the value chain. By combining investment-led growth with innovation and global partnerships, India can not only withstand tariff headwinds but also position itself as a leading global sourcing destination by 2030.

There were three session after the inagural, the first session was on Investment in End Use Product as the Key Engine for Growth supported by FTAs were key discussion points made on the role of garmenting as the anchor for T&A value chain development, Opportunities in technical textiles & home textiles through product innovation, R&D support, and development of specialized manufacturing ecosystems, Capital requirements and role of automation and digitalization outlook for large-scale apparel clusters, Policy levers and infrastructure enablers to attract private investment, Strategies to compete with global competitors such as China, Bangladesh, Vietnam, etc. through infrastructure development, skill enhancement and labour retention, How FTAs can enhance the investment case for backward integration and Developing strategies for workforce retention. The session Moderator was Mr. Prashant Agarwal, Joint Managing Director, Wazir Advisors and the panellists were Mr. R.K. Mishra, Additional DGFT, Directorate General of Foreign Trade, Mr. Shaleen Toshniwal, Managing Director, Banswara Syntex Ltd, Mr. Kapil Pathare, Joint Managing Director, VIP Clothing, and Mr. Jyoti Prakash Mohapatra, Joint President- Marketing & Business Development, Grasim Industries Ltd.

L to R: Mr. Kushal Motiani, Head – BD & Marketing, Brandix Apparel India, Mr. Narendra Dalmia, CEO, Strata Geosystems (India) Pvt. Ltd, Dr. G. V. Aras, Strategic Advisor and Independent Director, Mr. Birendranath Bandyopadhyay, Executive Director, Orbit Exports, Mr. Navin Agrawal, Sr. Vice President, A.T.E. Enterprises Pvt. Ltd.

L to R: Mr. Amit Mittal, Managing Director, MADASKY Consulting, Mr. V. R. Sai Ganesh, COO – Textiles, Zydex Industries Pvt. Ltd, Mr. Avinash Mayekar, Managing Director, Suvin Expo LLP, Mr. Shyamlal Patnaik, Jt. President & Global Business Head - Specialty Business, Grasim Industries Ltd, , Mr. R. Sabhari Girish, Chief Sustainability

The next session was on Broadening the Investment Lens: FDI, Expansions & Strategic Alliances for T&A Growth in which deliberations made on Greenfield Investments: Assessing India's attractiveness for end-to-end manufacturing setups, Brownfield Expansions: Understanding investment outlook among domestic players scaling for exports, FDI: Strategic entry points for global players across synthetic, technical, and sustainable textiles, Joint Ventures & Strategic Partnerships: Initiatives enabling global partnerships and related challenges, Policy Enablers: P M Mitra parks, PLI schemes, and FTA-aligned incentives to boost investor confidence. The Session moderator was Dr. G. V. Aras, Strategic Advisor and Independent Director and the panellists were Mr. Narendra Dalmia, CEO, Strata Geosystems (India) Pvt Ltd, Mr. Birendranath Bandyopadhyay, Executive Director, Orbit Exports, Mr. Kushal Motiani, Head, Business Development & Marketing, Brandix Apparel India Pvt Ltd, Mr. Navin Agrawal, Sr. Vice President, A.T.E. Enterprises Pvt. Ltd.

The final session was on Global Sourcing: Driving Innovation and Sustainability and the deliberations were made on how ESG regulations are shaping export opportunities and acting as trade requirements, how FTAs are including sustainability conditions and what it means for India, the growing need for certifications, audits, and traceability in supply chains, what changes factories must make towards sustainability and innovation to retain global buyers and stay competitive. The session moderator was Mr. Avinash Mayekar, Managing Director, Suvin Expo LLP and the panellists were Mr. Shyamlal Patnaik, Jt. President & Global Business Head - Specialty Business, Grasim Industries Ltd, Mr. V. R. Sai Ganesh, COO – Textiles, Zydex Industries Pvt. Ltd, Mr. R. Sabhari Girish, Chief Sustainability Officer, Sulochana Cotton Spinning Mills P. Ltd, Mr. Amit Mittal, Managing Director, MADASKY Consulting Pvt. Ltd, Mr. Sudipto Mandal, Regional Sales Director, Oerlikon Textile India Pvt. Ltd.

ITAMMA conducted its 82nd AGM

ITAMMA focused on 'Packaging Aspects' during its 82nd AGM on 24th Sept 25 at ITME Centre, Mumbai
On 24th September, 2025.

Mr. N. D. Mhatre, Director General (Tech), ITAMMA in his opening remarks mentioned that the many of our members complain that their goods are rejected at their user end due to poor packaging. Also considering today's era of digitalization most of the automations involve electronic gadgets/attachments on the textile machines which have to be taken care in packaging during logistics. ITAMMA has always focused its activities depending on the need and the developing trends of the Textile Industry Globally. So during this AGM we will be focusing on importance of packaging and so we have invited Dr. Babu Rao Guduri, Additional Director, and Professor HOD, T & E and Laboratory Departments, Indian Institute of Packaging, Mumbai.

He informed that a stalwart consultant Mr. Avinash Mayekar, Managing Director, and Suvin Expo LLP will speak on Expectations from Indian Textile Engineering Industry to be prepared for 'Viksit Bharat 2047.

Mr. Omprakash Mantry, President, ITAMMA in his

Welcome Speech said that The Indian textile machinery industry is a vital component of the nation's economy, comprising approximately 3,000 manufacturing units and a market size expected to reach USD 2.02 billion by 2033. The packaging aspects of the Indian textile engineering industry involve diverse materials like woven sacks, Flexible Intermediate Bulk Containers (FIBCs), jute hessian, and synthetic bags, fulfilling needs for protection, storage, and transport of industrial and agricultural goods.

Key trends driving innovation include a focus on sustainable and smart solutions, with the government encouraging the reduction of single-use plastics in favour of biodegradable and paper-based alternatives to reduce polymer dependence. Emerging opportunities lie in the development of innovative, eco-friendly packaging materials and smart packaging to meet growing consumer demand and support the broader Indian packaging sector's sustainable transition. Knowing that the Indian Institute of Packaging (IIP) a national apex body, set up in 1966 by the packaging and allied industries and the Ministry of Commerce, Government of India, with the specific objective of improving the packaging standards in the country, it will be beneficial to the stakeholders of the textile engineering industry in promotion of exports and create infrastructural facilities for overall packaging improvement in India.

We all are aware about India's vision for its textile industry by 2047 is to become a global powerhouse, achieving $600 billion in textile exports and a domestic market of $1.8 trillion, and so the presentations on the share of Textile Engineering Industry in this target and Expectations from this Industry in the contribution for ' Viksit Bharat 2047' will further enrich our knowledge in this aspect.

Mr. Avinash Mayekar, Managing Director, Suvin Expo LLP made presentations as Guest Speaker on “Expectations from Indian Textile Engineering Industry to be prepared for ' Vikasit Bharat 2047”.

Vikasit Bharat – The key to success lies in the growth of individual sectors. India's rise as a superpower will be possible only when the technology sector is the strongest and for textiles, this is the only way forward for maximising their share in the global market.

Mr. Avinash Mayekar, Managing Director, Suvin Expo LLP made presentations as Guest Speaker on “Expectations from Indian Textile Engineering Industry to be prepared for ' Vikasit Bharat 2047”.

Vikasit Bharat – The key to success lies in the growth of individual sectors. India's rise as a superpower will be possible only when the technology sector is the strongest and for textiles, this is the only way forward for maximising their share in the global market. We all know the success of yarn business and how the presence of Indian brand in spinning machinery as today seen all the reputed global spinning machinery brands having their manufacturing base in India the scenario can be replicated to all other segments of textiles if India truly wants to achieve the textile vision of Exports Target: US$ 600 billion, Domestic Market: US$ 1.8 Trillion& Technical Textiles Market: US$ 309 Billion. In a nutshell, we need to strategize.

Our way forward:
India's Strategy for Vikasit Bharat

- Import Substitution: Target import reduction
- Initiate Auxiliary business for sectors having zero to nil production in India
- Collaboration: Build partnership for Technology Exchange and offer operational excellence.
- OEM Development: Partner with renowned international brands
- Supply Chain Improvisation: Raw material and crucial parts production base development

- Infrastructure Creation: Textile Parks, Cluster Development, Textile Engineering Park and R&D Centers, Center of excellence for technology development.

Technology to target

Manmade spinning	Open end spinning, Airjet spinning, Cone Winding, TFO Twisters
Weaving	High speed Rapier Looms, High speed Airjet Looms, Waterjet Looms. Spares & Accessories
Knitting	Circular knitting, Warp knitting, Spares & Accessories
Processing	State-of-the-art Continuous bleaching & dyeing range, Knit processing range, Denim range, Spares & Accessories
Garmenting	Sewing Machines, Embroidery Machines, Robotics, Spares & Accessories
Technical Textiles	Converting Machines, Needle punched Technology, spun bond Technology, Spun lace Technology, Spares & Accessories

Dr. Babu Rao Guduri, Additional Director, and Professor HOD, T & E and Laboratory Departments, Indian Institute of Packaging, Mumbai in his Guest of Honour Speech gave detailed insight on activities of IIP along with some case studies justifying the importance of packaging especially while exporting the goods. He also informed on presently observed sustainable practices in this activity.

ITAMMA also felicitated Dr. Seema Srivastava, Executive Director, India ITME Society, for completing the Doctorate Program in Management Studies successfully and being awarded Doctorate at A Grade by the Indian Institute of Business Management and Studies, during the AGM

Mr. Vishal Masand, Hon' Treasurer (2025-26), ITAMMA thanked Guest of Honour and Guest Speaker for their valuable presentations, India ITME Society for offering the premises on complimentary basis, PRESS and the audience..

AGM of Indian Technical Textile Association

The Indian Technical Textile Association (ITTA) successfully concluded its 15th Annual General Meeting (AGM) on 19th September 2025 at the Orchid Hotel, Mumbai. The meeting was conducted under the Chairmanship of Shri. Avinash Misar, with a large presence of ITTA members, special invitees, and press media representatives. Dr. Anup Rakshit, Executive Director of ITTA, warmly welcomed the distinguished guests, members, and press representatives to the event. Shri. Mahesh Kudav, Vice Chairman conducted the Business Session. The AGM was honoured by the presence of Shri. Kartikay Dhanda, Secretary, Textile Committee, as the Chief Guest and Dr. T. V. Sreekumar, Director, The Bombay Textile Research Association (BTRA) as a Guest of Honour.

Shri Kartikay Dhanda addressed the ITTA members, highlighting the critical role that ITTA has played over the years as a dedicated association in uplifting the technical textile sector and serving as a vital link between the industry and the government. He acknowledged ITTA's significant contributions in driving innovation, sustainability, and growth within India's textile industry and appreciated the Ministry of Textiles, through NTTM and PLI schemes, for working towards the sector's development by implementing such initiatives.

He further emphasized the vast growth potential of technical textiles and commended ITTA for fostering industry interactions. Addressing the delegates, he also underlined the need to reduce bottlenecks, enhance facilitation processes to make exports more competitive, and seize opportunities for joint ventures and innovations to bridge technological gaps in the sector.

Dr. T. V. Sreekumar expressed his gratitude to ITTA for the invitation and acknowledged BTRA's close association with the technical textiles sector. He highlighted the strong collaboration between ITTA and BTRA, noting that ITTA's presence on the BTRA campus has fostered knowledge exchange, research collaborations, and industry outreach, benefiting stakeholders. He shared that BTRA is engaged in major projects such as Carbon Fibre precursors and emphasized the importance of innovation, capacity building, and continuous awareness to strengthen India's global competitiveness.

Appreciating ITTA's efforts in conducting seminars, workshops, and training programs, he reaffirmed BTRA's commitment to supporting ITTA and the industry through research, testing, training, and technology development, and encouraged members to actively participate in ITTA's initiatives.

Shri Avinash Misar, Chairman, ITTA, thanked Shri Kartikay Dhanda, Secretary, Textiles Committee; Dr. T. V. Sreekumar, Director, BTRA; and other dignitaries for their gracious presence. He highlighted ITTA's steady growth over the past 15 years, noting that the industry has achieved a 12% CAGR since 2021, with turnover reaching USD 27 billion and exports rising to USD 2.4 billion in 2024–25. With projections of USD 45 billion by 2030, he expressed confidence in the sector's strong future while acknowledging challenges such as raw material imports, GST anomalies, QCO issues, and the need for greater MSME support under schemes like PLI.

He appreciated the Ministry of Textiles' initiatives - NTTM, PM MITRA, and sustainability programs which have positioned technical textiles at the forefront. He also underlined ITTA's role in developing BIS standards, representing industry on key committees, promoting training and skill development, evaluating NTTM projects, and driving awareness across India. With over 400 members, ITTA remains committed to supporting the sector in close collaboration with the government to overcome challenges and achieve sustained growth.

Dr. Anup Rakshit highlighted that since last year, ITTA has introduced the Innovation Awards to recognize members who are doing outstanding work in developing innovative products and machinery. This year, the jury selected 4 awardees from 6 applications, whose names will be announced during the ceremony. He further shared that ITTA's Executive Development Programs and Train-the-Trainer programs on key segments of technical textiles have gained popularity, with over 400 participants from industry, academia, and management benefiting so far.

Dr. Rakshit also announced the launch of ITTA's new quarterly magazine, Technical Textile Today, published with the support of TVC Media. He noted these as some of ITTA's recent noteworthy initiatives.

The AGM concluded with the formation of the new Board wherein Shri. Mahesh Kudav, Managing Director, Venus Safety & Health Pvt. Ltd., formally took over as the Chairman of ITTA and Dr. Nandan Kumar, Managing Director, High Performance Textiles Pvt. Ltd. was unanimously elected as the Vice Chairman of ITTA.

Shri. Mahesh Kudav, Chairman, ITTA

Dr. Nandan Kumar, Vice Chairman, ITTA

Shri. Avinash Misar continues to be the ex-member of the Board and will be a guiding force of the association along with Shri. Amit Agarwal (Ex- Officio Member).

A notable moment during the meeting was the presentation of the "Lifetime Achievement Award" to Shri. Pankaj Kapoor, Managing Director of Park Non-Woven Pvt. Ltd., for his outstanding contributions to the technical textile industry and his lasting impact on the field. Shri. Kapoor was inducted into the 'ITTA Hall of Fame', in addition to Shri. Pramod Khosla of Khosla Profil, Shri. Yogesh Kusumgar of Kusumgar Corporates and Shri. Mohan Kavrie of Supreme.

The Innovation Awards on outstanding contributions and advancements in the Technical Textile industry, introduced by ITTA, were presented to the following Five companies -

1. Prashant West Point Machinery Pvt. Ltd. - Shri. Apurva Kapadia and Ms. Amoli Shah, Director on the "Intelligent Direct Warper for Fibre Glass Yarn".

2. Tarasafe International Pvt. Ltd. + High Performance Textiles Pvt. Ltd. - Shri. Anaveer B. Telasang, Vice President & Business Head - Marketing and Merchandising & Shri. Mahendra Kushwaha, Manager-New Product Development, Tarasafe and Dr. Nandan Kumar, Managing Director, HPT on the two innovations i.e., "Light Weight & Breathable Multi-Functional Protective Wear Sleeve, Apron, Bib-Trouser and Chap-Trouser and TaraHeal - Reduce: Reuse: Recycle! Now in FR!".

Shri. Pankaj Kapoor was honoured with The Lifetime Achievement Award

3. Garware Technical Fibres Ltd. - Shri. Yogesh Padule, Assistant Manager - R&D on the "Bio Aqua Rock Bag - An Eco-Friendly Solution for Erosion Control".

4. Northern India Textile Research Association (NITRA) - Dr. M. S. Parmar, Director General on the "Development of Fire Entry Suit".

The AGM also featured a Knowledge Sharing Session aimed at providing valuable insights and industry expertise with insightful presentation on "Recent Advances in Carbon Fibre Precursor development under NTTM" by Dr. T. V. Sreekumar, Director, BTRA.

Shri Anil Kumar Vasupillai, Additional Executive Director, ITTA, extended a heartfelt vote of thanks to all members, guests, participants, and dignitaries for their presence and for making the ITTA AGM a success.

He reaffirmed ITTA's commitment to being the voice of the Indian technical textile industry and to working closely with the government on policy initiatives. He further emphasized that ITTA remains dedicated to facilitating the needs and aspirations of its members and supporting them in achieving higher growth and business development.

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