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Weaving Sustainability into India's Textile Future

Dear Readers,
Greetings!!

The Indian textile industry has long been a pillar of the nation's economic growth, cultural heritage, and global reputation. Renowned for its craftsmanship, entrepreneurial spirit, and resilience, the sector has consistently adapted to changing market dynamics and technological advancements. Today, however, the industry stands at a defining crossroads. The next phase of its evolution will be determined not only by the products we create but also by the systems we build systems that are sustainable, circular, resource-efficient, and inclusive.

India generates an estimated 70 lakh tonnes of textile waste annually, presenting one of the most pressing environmental challenges of our time.
Yet, this challenge also represents an extraordinary opportunity. What is currently viewed as waste can become a valuable resource, giving rise to new raw materials, innovative products, thriving enterprises, and meaningful employment. By embracing the principles of a circular economy, India has the opportunity to transform textile waste into a catalyst for sustainable industrial growth and enhanced global competitiveness.

The concept of circularity is not new to India. Our traditional textile ecosystem has, for generations, embodied the values of repair, reuse, repurposing, and responsible consumption. These practices, deeply rooted in our culture, provide a strong foundation for building a modern circular textile economy. The challenge before us is to integrate this traditional wisdom with advanced technologies, scientific research, innovative business models, and progressive policy frameworks. Investment in recycling infrastructure, standardized waste collection and segregation systems, advanced fibre recovery technologies, and robust industry-academia collaboration will be critical to accelerating this transition.

Equally important is the recognition that circularity cannot be achieved through technology alone. It demands the collective participation of every stakeholder across the textile value chain from fibre producers, manufacturers, brands, designers, and retailers to waste collectors, recyclers, researchers, policymakers, and consumers. Successful initiatives such as the H&M Foundation-supported Closing the Loop programme demonstrate that textile waste management can simultaneously generate environmental benefits, dignified livelihoods, and sustainable economic value. These examples reinforce the fact that sustainability and economic growth are not competing priorities but mutually reinforcing objectives.

India possesses all the essential ingredients to emerge as a global leader in circular textiles. A rich textile heritage, a robust manufacturing ecosystem, world-class educational and research institutions, a vibrant start-up culture, and one of the world's youngest workforces together provide an unparalleled competitive advantage. The need of the hour is to bring these strengths together through collaborative action and long-term commitment. Circularity must evolve from being a sustainability initiative to becoming a core business strategy that drives innovation, competitiveness, and value creation.

As the global textile industry accelerates its transition towards sustainable production and responsible consumption, India has an opportunity not merely to participate in this transformation but to lead it. Leadership in the coming decade will belong to those who recognise that environmental stewardship, economic prosperity, and social inclusion are inseparable pillars of sustainable development. The decisions we make today will shape the legacy we leave for future generations and determine India's position in the evolving global textile landscape.

As an industry, we have repeatedly demonstrated our ability to adapt, innovate, and emerge stronger from every period of transformation. The journey towards a circular textile economy is another such opportunity one that calls for vision, collaboration, and collective responsibility. Let us work together to ensure that India's textile sector continues to serve not only as a symbol of manufacturing excellence but also as a global benchmark for sustainability, innovation, and inclusive growth. The future of Indian textiles is not merely to weave fabrics it is to weave a more sustainable future for our nation and for the world.

With best wishes,

Dr. Deepa Raisinghani
Chairman – JTA Editorial Board
Journal of the Textile Association

R. K. VIJ, President

HOW TO ACHIEVE USD 350 BILLION TOTAL TEXTILE TRADE BY 2030-31?

How Indian MMF industry can make a substantially larger contribution towards vision of building a USD 350 billion textile economy, including USD 100 billion of exports by 2030-31?

Polyester today accounts for more than half of global fibre consumption and is the principal driver of growth in the textile industry worldwide. India possesses all the fundamental strengths required to emerge as a global leader in this sector a large domestic market, entrepreneurial capability, a skilled workforce, an integrated textile base and growing access to international markets through recently concluded Free Trade Agreements. Yet the industry has not expanded at the pace that these inherent strengths would suggest.

The industry seeks not protection, but the removal of unintended impediments to scale. We believe that if a few structural issues are addressed, India can significantly accelerate investments, expand exports, generate employment and establish itself as a preferred global manufacturing destination for polyester and Man-Made Fibre products.

Among the issues we wish to present are:

- Stable access to key raw materials at internationally competitive prices. PTA and MEG are the principal feedstocks for polyester. Long-term investment decisions require predictable access to these strategic inputs without recurring uncertainty arising from supply disruptions or frequent changes in trade policy.
- Correction of the inverted GST structure. The present structure results in permanent accumulation of Input Tax Credit in a low-margin, capital-intensive industry, locking substantial working capital across the value chain.
- A mechanism for utilisation or refund of GST paid on capital goods. Modern polyester plants require very large investments in polymerisation, spinning, utilities and environmental infrastructure. In the absence of an effective mechanism to realise accumulated capital-goods ITC, GST intended to be a pass-through tax becomes embedded project capital, adversely affecting investment decisions and capacity expansion.
- A review of export competitiveness. Existing remission mechanisms, including RoDTEP, have greatly supported exporters. However, when key raw materials carry duties or additional costs not faced by international competitors, Indian manufacturers are unable to fully realise the advantages created through Free Trade Agreements and growing global market access.
- At present, all the MMF products namely Fibre (PSF), Filament (POY, FDY, IDY) which are being used 100% in downstream industries namely in Spinning / Weaving till Garments are under the Department of Chemicals and Petrochemicals, Ministry of Chemicals and Fertilizers whereas from spinning / weaving till garments, products are under the textile Ministry. In order to have better coordination and to have one textile policy, all products right from Fibre, Filament, Yarn, Fabrics, Garments should be under the Textile Ministry. Presently, there is lot of confusion while formulating any scheme for the growth of Indian textile industry.

In many ways, India could have captured a much larger share of the global capacity diversification arising from the China+1 strategy. Looking ahead, there is also a risk that the full benefits of recently concluded FTAs may not be realised unless these structural issues are addressed in a coordinated manner.

We firmly believe that relatively modest policy corrections can unlock substantial new investments, create large-scale employment, deepen domestic value addition, strengthen the circular economy, and significantly enhance India's share in global textile and apparel trade.

Textile industry suggests Indian Government to analyse these issues for fulfilling the vision of Viksit Bharat, Make in India and globally competitive manufacturing.

R. K. VIJ
National President
The Textile Association (India)

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Characterization of a Sustainable Natural Fiber Extracted from Butea Monosperma Plant

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Abstract:

Butea monosperma is a natural plant and it is available in several parts of Maharashtra, the fibers from the steam were extracted manually for its potential in textile applications. Several methods, including Differential Scanning Calorimetry, Scanning Electron Microscopy, Fourier Transform Infrared Spectroscopy, and X-ray Diffraction used for the identification of different fibre properties. Fibre composition analysis showed a cellulose content of 54.7% and a crystallinity index of 23.52%, whereas Fourier Transform Infrared spectroscopy analysis found various functional groups, including alcohols, ethers, esters, alkenes, amines, and amides etc. The X-ray Diffraction results revealed a crystallite content of about 25.33% also the fiber had a specific density of 1.28 g/cc and a linear density of 36 Tex. besides, Butea monosperma fiber displayed a high tenacity of 163.28 cN/dtex, indicating that it is a strong, lightweight material that can handle significant mechanical stress, making it a good option for various textile applications.

Keywords: *Natural fiber, bio-extraction, lingo cellulosic fiber, and biodegradable*

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1. Introduction

Natural fibers are renewable resources that grow without the use of harmful chemicals or pesticides, due to this research has captured the attention of many scientists interested in using these natural fibers in different industries, including automotive, construction, and packaging. As demand for environmentally friendly products increases, industries are looking for sustainable alternatives to standard textile materials to lower their environmental impact and meet customer expectations for eco-friendly products [1]. Man-made fibres, while often expensive, harm the environment due to their production methodology whilst, natural fibers can be easily grown and harvested with minimal environmental harm. When we reinforce natural fibers into polymer composites results into lowers energy consumption and provides a more sustainable choice. Hence use of natural fibers in composites shows promise for creating eco-friendly materials and helps address the issues caused by plastic pollution [2]. The Sustainable natural fibers sourced from agricultural leftovers which are emerging as an alternative to synthetic ones this was useful for increasing people awareness of the environmental effects of traditional textile manufacturing because natural fibers have key benefits as they are biodegradable, renewable, and require less energy to harvest. The automotive industry is exploring the use of natural fibers in manufacturing the components like vehicle doors and body parts due to their lightweight property which can enhance fuel efficiency. Automotive parts made from natural fibers offer better impact resistance and durability provide vast and promising advancing technology to rise consumer demand for eco-conscious products [3]. In textile composites natural fibres used for reinforcing the fibers in different resins, manufacturers can produce a range of safe and comfortable textile products that suit modern consumers. It has been studying that major components of natural fibers include cellulose, hemicellulose, lignin, and wax; each provides unique features for the final product. These materials are biodegradable and do not harm human health or the environment [4].

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In the textile industry, natural fibers are increasingly recognized for their ability to deliver high-quality, durable, and performance-driven fabrics. Sourced from various plant regions, these fibers have long been appreciated for their breathability, strength, and sustainability [5]. By reinforcing natural fibers with resins, manufacturers can create a broad array of textile products that are not only safe and comfortable but also meet the expectations of today's application oriented for eco-conscious consumers. This progress supports the movement toward a more sustainable future for both the textile and automotive sectors [6]. Natural fibers mainly consist of cellulose, hemicellulose, lignin, and wax each contributing unique structural and functional properties. These components are fully biodegradable and pose no risk to human health or the environment. Thus, natural fibers are commonly favoured over synthetic alternatives due to their environmental compatibility [7].

In this study, fibers were extracted from the stem of the Butea monosperma plant, which belongs to the Fabaceae family. Commonly known as "Palas" in Maharashtra, Butea monosperma is widely found across India, Sri Lanka, and Burma, except in dry areas. The extracted fibers were carefully characterized to evaluate their suitability for various industrial uses. A thorough analysis assessed their physical, chemical, and structural properties. Due to its wide availability and easy cultivation, Butea monosperma represents a promising and sustainable source of natural fibers. This study highlights both the ecological and economic importance of the plant. By broadening the variety of plant-based fiber sources, we can lessen the reliance on conventional materials, increase resource efficiency, and support environmentally responsible industrial practices [8].

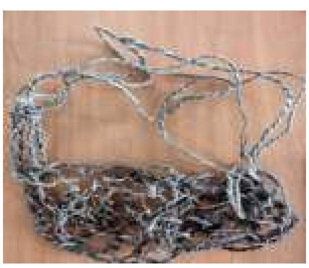
2. Materials and Methods

Butea monosperma fibres for the experiments were collected from Nanded district of Maharashtra state. Whereas fiber extraction was done using the stagnant water retting method during this the natural binding components start to break down and release after several hours of immersion [9]. The harvested plant ribbons were submerged in water for two days to encourage aerobic bacterial degradation. This process allowed the cellular materials and pectin in the bast fiber bundles to decay, making it easier to separate the individual fibers. After retting, the extracted fibers were thoroughly washed with distilled water to eliminate impurities and then sun-dried for 24 hours. The processed fibers were used to create "Muchka," a traditional rope cage that prevents cattle from grazing on cultivated crops. Following images shows the transformation of Butea monosperma stripes into fibres [10].

Butea Monosperma Tree

Butea Monosperma fibre tapes

Butea Monosperma Fibres



Rope cage - Muchka

Figure 1 - Extraction of Butea Monosperma Fibres

3. Fibre Characterization

3.1 Scanning Electron Microscope (SEM) Study

The JEOL/EO principle was used for a microscale level investigation of the Butea Monosperma fibre's morphology on SEM. Here, a high-energy electron beam was used for the examination, and it helped to give an accurate image of the fibre sample surface. The test result shows the complex construction and physical appearance of the fibre. SEM analysis can be done at different angles and magnifications to observe the texture, size, and shape of molecules in the sample [11].

3.2 X-ray Diffraction study (XRD)

XRD is a significant tool used for determining the crystal structure present in the textile fibre. This analysis will help to identify the cell dimensions, crystal symmetry, and atomic positions in the provided fiber sample. This info is vital for considering the physical and chemical properties of materials and also helps in creating new materials with specific properties. The XRD test was conducted at the following testing conditions PANalytical - X'Pert Pro XRD X-rays – Copper K-alpha Generator at 40 KV / 30 mA [12].

3.3 Differential Scanning Calorimetry (DSC)

Differential scanning calorimetry uses the heat change methods for identifying the polymer components in the material like amorphous or crystalline region, glass transition temperature and contamination. It also helped in analysing the fibre properties like oxidation behaviour and thermal stability of the textile fibre [13].

3.4 Fourier Transform Infrared Spectroscopy study

FTIR spectroscopy is extensively utilised in numerous industries such as pharma, food, beverage, forensic science, and environmental monitoring. FTIR analysis plays a vital part in progressing precise information and resolving practical problems across different fields. Absorbed radiation causes molecular vibrations, which are unique to each type of molecule. By analysing the pattern of absorption peaks in the resulting spectrum, scientists can determine the chemical composition of the sample [14].

3.5 Mechanical Properties

The Butea monosperma fibres were tested for tensile test on universal testing machine as per the ASTM D 3822 standard. Where a head speed was conserved at 0.5 mm/min with a load cell of 1kN capacity. The was carried out at a R.H. 65% + 2% and Temp. 21 Degree C + 1 Degree C [15].

3.6 Physical Properties

The results obtained from the measurements and calculations were then analysed to determine the overall density and characteristics of the fibres. By using precise instruments and software, any potential human error was minimized, ensuring accurate and reliable data. The use of an optical microscope allowed for a detailed examination of the fibres, while the pycnometer setup provided a method for determining their density [16].

3.7 The methodology for determining fibre composition

Fibre characterization was done through identification of the fibre's chemical components. Cellulose and hemicellulose contents (%) were analysed using TAPPI T 203 cm-88, whereas the lignin content (%) was analysed through TAPPI T 222 cm-88. Ash content (%) was analysed using IS 199:1989. This process gives crucial details about the chemical properties of the fiber as well as its quality and potential use.

4. Results and Discussion

4.1 Chemical composition of Butea Monosperma Fibre

The chemical composition of Butea Monosperma fibre is shown in Table 1. The chemical composition of extracted fibre is extremely impacted through the area, soil, age of the tree, abstraction methods, and environmental conditions. The chemical composition of the Butea monosperma fibre highly influences the physical, chemical, and mechanical properties of the fibres.

The Butea monosperma fiber is mainly composed of cellulose, hemicellulose, lignin, and ash, which are present 54.7 %, 24.8%, 11.5 %, and 2.11%. A higher cellulose content generally results in better tensile strength and modulus, while excessive hemi-cellulose can weaken the fiber structure. Conversely, lower hemi-cellulose content can improve thermal stability but may reduce moisture absorption capacity. Lignin, on the other hand, contributes to the stiffness of the fiber. Balancing these components is essential to achieve optimal performance characteristics in fibres for various applications. Understanding how each component affects the overall properties of the fibre is key to developing materials with desired mechanical and thermal properties [17].

Table 1 - Chemical composition of Butea monosperma Fibre

Sample	Cellulose Content %	Hemi-cellulose Content %	Lignin content %	Ash Content %
Butea monosperma	54.7	24.8	11.5	2.33

4.2 Mechanical properties of the Butea monosperma fibre

The fiber investigation results specify that Butea monosperma fiber has promising mechanical properties, with a tenacity of 163.28 cN/dtex and a linear density of 36 Tex. Zwick/Roell, SK tester with Pre-load: 0.5 N and Test speed: 30 mm/min was used for Tenacity measurement of the Butea monosperma fiber. The fibre having bundles of fibre structure had a density of 1.28 gm/cc. Moisture Content / Regain (Oven dry method at 105°C) was done to found around 14.23%, following table shows details of the mechanical properties of Butea monosperma fibre [18].

Table 2 - Mechanical properties of the Butea monosperma fibre

Sr. No.	Test Parameter	Results
1	Length (cm)	20
2	Linear density (Tex)	36
3	Density (gm/cc)	1.28
4	Tenacity (cN/dtex)	163.28
5	Moisture content (%)	14.23
6	Mean Breaking Strength Fmax (gf) kN/m.	6000
7	Mean Breaking Elongation dL at Fmax (%)	4.8

5. Characterization Studies

5.1 Scanning Electron Microscope (SEM) analysis

SEM test of the Butea monosperma fibers reveals the surface morphology showing cellular structure. Where cells and fibrils are connected at numerous points. Butea monosperma fibre shows clean, smooth surfaces with a thick, uniform layer composed of hemicelluloses and lignin deposited along their entire length. They consist of multiple elementary fibers, such as fibrils or fiber cells, which are bonded longitudinally by pectin and other non-cellulosic substances. The fibers exhibit a roughly cylindrical structure and a multicellular composition. The cells are generally circular but vary in size. These fibers contain both small and large voids, which are capable of effectively holding thermal and sound frequencies [19].

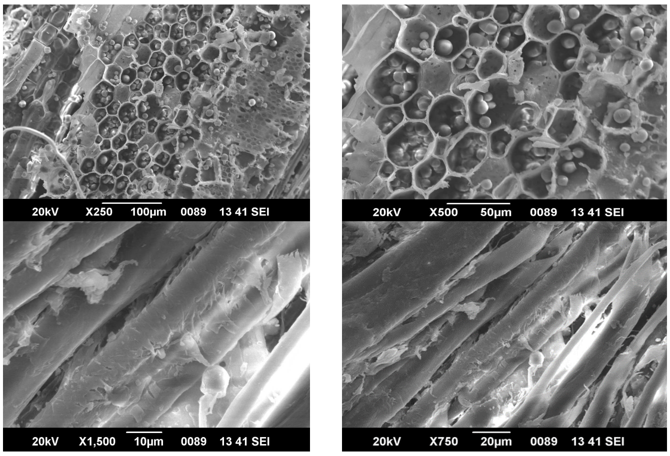


Figure 2 - Surface morphology SEM image of cross-sectional and longitudinal shape.

5.2 X-ray Diffraction study (XRD)

The X-ray diffraction (XRD) pattern shows several peaks at specific Theta positions. detailed analysis of the peaks as below: Peak at 15.1532 degrees: This peak has a height of 167.74 counts and a d-spacing of 5.64319 Å. It indicates a specific crystallographic plane in the material. Peak at 22.5373 degrees: This peak reaches 432.73 counts with a d-spacing of 3.94308 Å. It corresponds to another distinct plane in the crystal structure. Peak at 24.6262 degrees: This peak has a height of 30.74 counts and a d-spacing of 3.61057 Å. It represents another crystallographic plane [20].

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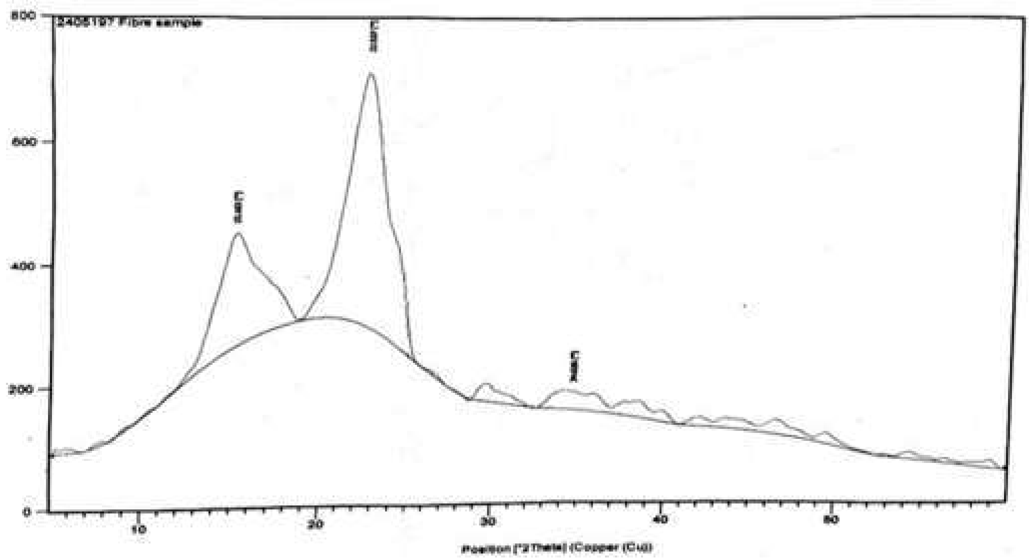

Figure 3 - XRD analysis of Butea monosperma fibre

22.5373 degrees: This peak reaches 432.73 counts with a d-spacing of 3.94308 Å. It corresponds to another distinct plane in the crystal structure. Peak at 24.6262 degrees: This peak has a height of 30.74 counts and a d-spacing of 3.61057 Å. It represents another crystallographic plane [20].

5.3 Differential Scanning Calorimetry (DSC) analysis

Heat flows in the sample as a result of heating, glass transition temperature, and melting due to Endothermic heat flow (mW). Crystallization, curing, cooling, and oxidation observed in the sample due to Exothermic heat flow residual stress is not observed in this case; no contamination was found in the test material. Butea monosperma has a large amorphous region hence it is a hygroscopic fibre [21].

Melting Region: Appears at the beginning, indicating the melting of a crystalline region. Semi-crystalline or Amorphous Region: Labelled with an integral normalized value of -6.61 mJ, onset at 172.09 °C, and endset at 185.54 °C. Glass Transition Temperature (Tg) is Identified at 216.63 °C. Two regions with different integral normalized values and onset temperatures for crystallinity are shown in the graph: 1. Crystallinity: 10.08%, -0.11 mJ, onset at 288.14 °C. 2. Crystallinity: 26.10%, -0.29 mJ, onset at 263.59 °C.

5.4 Fourier Transform Infrared Spectroscopy Analysis

Natural fibers are composed of cellulose, hemicellulose, lignin, pectin, waxes, and water-soluble compounds. Key components like cellulose, hemicellulose, and lignin consist of ketone, carbonyl, alcohol, alkane, alkyl, aromatic, and hydroxyl groups. FTIR spectroscopy on Butea monosperma recorded spectra in the 3500-600 cm^{-1} range. Peaks between 1200-1300 cm^{-1} indicated lignin presence via aromatic skeletal vibrations. Peaks from 2917-1737 cm^{-1} revealed

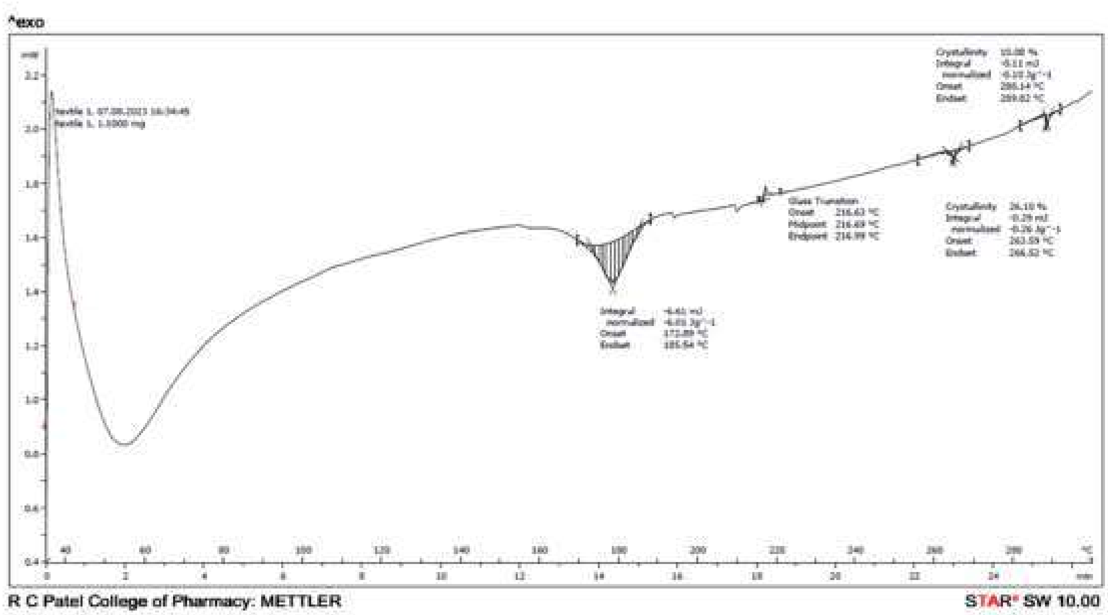

Figure 4 - DSC analysis of Butea monosperma fibre

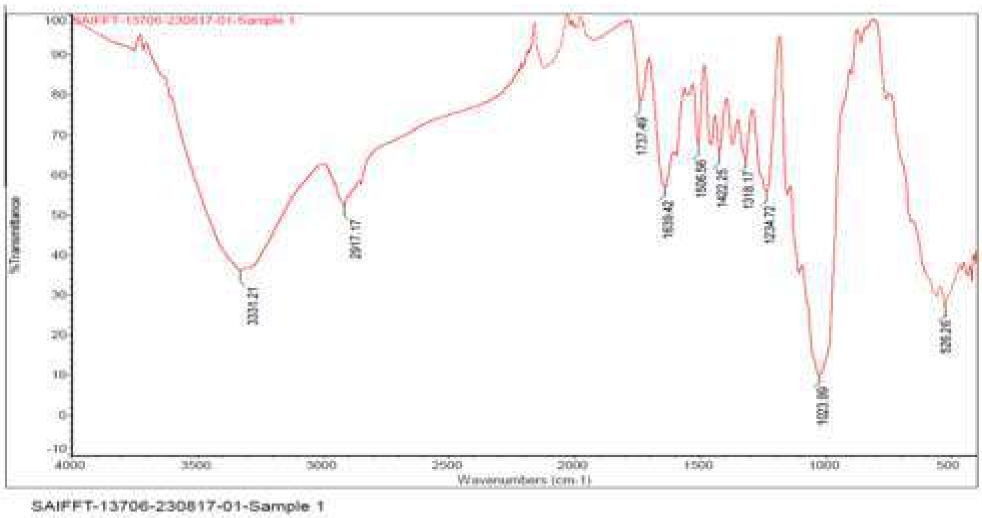

Figure 5 - FTIR analysis of Butea monosperma Fibre

functional groups such as aromatic C-C, C-O-C, and –O-CH_3. The 2917.17 cm^{-1} peak showed C-H stretching in the methylene group in cellulose and hemicellulose, while the 1737 cm^{-1} peak confirmed C=O linkage, indicating hemicellulose. Adsorbed water's –OH bonding was found at 1639.42 cm^{-1}, with C-O stretching and C-H vibrations in cellulose at 1023 cm^{-1}, and C-OH bending at 526 cm^{-1}. The FTIR spectra of Butea monosperma fibers closely resemble other fibers [22].

6. Conclusion

Based on the characterization of the fibers evaluated, it can be concluded that the fiber can be easily extracted from the plant stem. The natural fibers exhibit a density of 1.28 g/cc and a tensile strength of 163.28 cN/dtex whereas Fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), and additional analyses confirmed that Buta monosperma fibers have a high cellulose content of 54.7%, crystallinity of 10.08%, and an onset at 288.14°C with an energy release of -0.11 mJ. FTIR analysis indicates a spectrum recorded in the range of 3500-600 cm^{-1}, with peaks between 1200-1300 cm^{-1} confirming the presence of lignin. These properties demonstrate that the fibers possess desirable attributes for various applications. X-ray diffraction shows distinct peaks at 15.15o, 22.54o, and 24.63o which confirms that this fibre is crystalline. The very strong peak observed at 22.54o is an indication that there is a high level of degree of crystallinity. This comprehensive evaluation underscores the potential for effective utilization of these natural fibers in various textile applications and structural integrity. The Chemical composition highlighted by the analysis makes these fibers a viable alternative to other bast fibres.

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Comparison between Different Types of Ashes with Respect to Adsorption of Dyes from Effluent Water

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Abstract*:*

There is significant water pollution persists near textile industrial hubs due to the continuous discharge of hazardous, dye-laden effluents. These pollutants are often toxic, carcinogenic, and resistant to biodegradation, leading to increased morbidity and physical impairment in aquatic ecosystems. Even when presence in trace amounts, these chemicals inflict significant environmental harm and to reduce some of these problems decolorization is essential for safe discharge or industrial reuse. While existing removal methods are well-documented and many remain economically prohibitive. This study addresses these financial constraints by evaluating and comparing the efficacy of various industrial ashes which are treated as waste on daily basis as low-cost adsorbents, offering a commercially viable solution due to their widespread availability and minimal cost, this approach establishes a sustainable framework for the remediation of synthetic dyes from industrial wastewater effluents. Using this concept in this studya result of 78% decolourisation and reduction of TDS was achieved.

Keywords : *Ashes, Colored effluents, Column Study, Dyes, Decolonization, Waste water*

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1. Introduction

The areas which are established around or near to the industrial belts are undergoing stress due to continuous disposal of untreated and unprocessed wastes from the various industries. The quality of water is also going downhill due to addition of venomous as well as coloured effluents from various industries where different dyes and pigments are being used [1]. These dyes which are discharged from textile industries into natural streams and rivers lead to critical problems as it induces morbidity in the aquatic life by mutilating the aesthetics of nature, [2] as these dyes are toxic, carcinogenic and have poor biodegradability [3]. Due to this the natural equilibrium of aquatic life is getting disturbed which in succession affects the food chain [4].

It is very essential to decolourise textile effluent for its reuse or safe discharge in different receptors (i.e., sewage system or different emissaries like different watercourses) even when released in small amount or concentration [5].

As dye components have very stable chemical components, standard and traditional waste water treatment are mostly incapable for handling waste water containing synthetic dyes. Significant research has been accomplished on colour removal from industrial effluents to reduce their influence on the environment. Some of these, technologies involve adsorption onto inorganic or organic matrices, decolourisation by photo-catalysis or photo-oxidation processes, microbiological decomposition, chemical oxidation, ozonation and coagulation. Again, it is seen that adsorption onto activated carbon has been proved to be an amazingly effective process for dye removal, but the process is not economically viable. As, a consequence, countless cost effective alternatives have been searched and proposed which includes peanut hulls, waste coir pith, corncob and barley husk, Indian Rosewood sawdust and pine sawdust. To make an adsorption procedure to be truly cheap, the adsorbent should be low cost and easily available in plenty as well as it should also require minimum or no pre-treatment [4].

Again when we revisit the topic of low cost, it can be said it is profitable but can require huge quantity of adsorbents for keeping hold of textile organics, but it is less effective than commercially activated carbon. So, for being identified as a very good low-cost adsorbent, the adsorbent should itself possess a porous structure ensuring high surface area for fast adsorption kinetics which means, removal of pollutants efficiently [5].

One of many production waste that can be justified as a 'low-cost' adsorbent that can be used for decolourization of textile coloured effluent is ash. The use of this adsorptive material has a commanding advantage among other materials mainly due to its extensive availability and cheaper price [5].

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Ash is referred to as the inorganic residue remains after either ignition or complete combustion of organic matter [6]. There are many raw materials which provides ash in huge amount that can be used for decolourisation of coloured effluent water. These raw materials are namely rice husk [7], coal [8], wood [9], sugarcane [10], coal briquette etc. [11].

These ashes for the most part constitutes heavy metals and trace metals with the chief constituents being essentially oxides, sillicates. These oxides have tendency to form metal-hydroxide complexes in solution, and the subsequent acidic or basic dissociation of such complexes at the solid-solution interface leads to a development of positive or negative charges on the surface which in turn attracts the dye particles to be adsorbed on its surface [12].

So, utilizing this theory we have, studied the comparison of ashes from different source raw materials, to check their ability to decolourize effluent water and optimize the one of the ash which performs better and this study also falls under goal 6 and 7 of 17 United Nations Sustainable Development Goals (SDGs).

2. Materials and Methods

2.1 Materials

2.1.1 Chemicals

5 types of ashes collected from different industrial areas of Panipat, namely bagasse ash, briquette ash, coal ash, wood ash, dyeing ash (consisting of sea woods, arhar stalk and mustard stalk). 6 basic types of dyes namely, direct, reactive, acid, basic vat and disperse were used, distilled water.

2.1.2 Apparatus

A column (40 cm long and 4 cm wide) which was locally assembled, burette stand, stop watch.

2.2 Methods

2.2.1 Time and Quantity Study for Decolorization

The dye solutions for each dye were prepared according to standard industrial calculations, with a concentration of 0.2 grams of dye dissolved in 100 ml of distilled water. To assess the impact of different ash quantities on dye uptake to study the decolourization, varying amounts of ash specifically 5, 7, 11, 13, 15, and 17 grams were added to each dye solution. This experimental procedure was conducted by subjecting the mixtures to different durations of treatment, specifically 5, 15, and 30 minutes, to monitor the dye interaction with the ash over time. By maintaining consistent conditions and varying the amount of ash and exposure time, the study aimed to evaluate the effectiveness of different ash quantities in influencing the dye solution's properties and the rate of dye absorption or binding. The results from these time intervals and ash concentrations were then analysed to determine optimal conditions for dye removal or adsorption, offering valuable insights into the dye-ash interaction process and optimising one of the good ash out of the 5 ashes to be compared with each other.

2.2.2 pH study

The pH levels of all the ashes were carefully analyzed in both hot and cold water to assess any potential differences in their behavior under varying temperature conditions. For each type of ash, a precise amount of 5 grams was mixed into 100 milliliters of water, with separate tests conducted for both hot and cold water. The pH of the resulting mixtures was then measured using pH paper, which provided a reliable indication of the acidity or alkalinity of each sample in the two different water temperatures. This methodical approach allowed for a thorough comparison of the ashes' pH characteristics under controlled conditions, contributing to a deeper understanding of their chemical properties.

2.2.3 Column study

For column study a reactive dye namely CI Reactive Blue 25 was used as it was most commonly used in textile industries. A fixed-bed glass column with an internal diameter of 4 cm and a height of 40 cm was utilized for the column experiments. The column was meticulously packed with a series of carefully arranged layers designed to optimize the experiment's performance. The packing began with a layer of glass beads, followed by a 2 cm thick cotton bed. Directly above the cotton bed, an ash layer of approximately 4.5 cm in thickness was placed, containing 20 grams of ash which can be seen in Fig. 1, which was calculated based on time and quantity studies conducted prior to the experiment. To maintain consistency in the setup, the cotton bed and glass beads were repeated above the ash layer.

The experimental procedure involved feeding a dye solution from the top of the column using a peristaltic pump, which maintained a steady flow rate of 1 mL per minute. Samples were collected at the column exit at regular time intervals to monitor the progress of the dye solution as it passed through

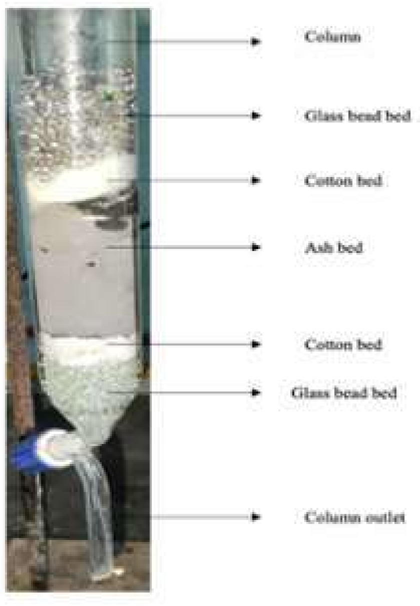

Figure 1 - Column packed with ash

the bed layers. The study concluded when the ash bed reached its saturation point, indicating that the column had reached the capacity for dye adsorption. All experimental procedures were carried out at room temperature, specifically at 27 ± 1 °C, ensuring that the conditions remained consistent throughout the study. This experimental setup provided a controlled environment to investigate the behavior and efficiency of the filtration process in the fixed-bed column. The experiment was replicated 5 times to confirm the efficiency of decolourization.

2.3 Characterization

2.3.1 Particle Size Analysis

The particle size analysis was done in Shimadzu SALD-7500, samples were dispersed in deionized water and sonicated for 5 minutes before analysis.

2.3.2 FTIR analysis

The FTIR analysis of all five kinds of ashes was done in Shimadzu IRSpirit.

2.3.3 SEM analysis

SEM analysis was done by QUANTA 200 FESEM – FEG Scanning Electron Microscope & EDS.

2.3.4 EDAX analysis

EDAX analysis was done by QUANTA 200 FESEM – FEG Scanning Electron Microscope & EDS.

2.3.5 Testing for TDS

The water's TDS was measured with a TDS meter following decolorization.

2.3.6 Ash Characteristics Study Based on Theoretical Data

Characteristics of ashes found based on theoretical data.

3. Result and Discussion

3.1 Time and Quantity Study for Decolorization

Among the various types of ashes tested, Bagasse ash, Wood ash, Dyeing ash, Briquette ash and Coal ash were evaluated for their decolorization efficiency which can be seen in Table

Table 1 - Time and Quantity study for decolourization of coloured water by different types of ashes

Ash	Dye type	Amount at which total decolorization occurred in Grams(g)	Time taken for total decolorization
Bagasse ash	Acid dye	15	30 minutes
	Basic dye	13	30 minutes
	Reactive dye	13	30 minutes
	Vat dye	17(translucent)	30 minutes
	Direct dye	17	30 minutes
	Disperse dye	17(translucent)	30 minutes
Briquette ash	Acid dye	15	30 minutes
	Basic dye	17(no colour adsorbed)	30 minutes
	Reactive dye	15	30 minutes
	Vat dye	No adsorption	After 24 hours
	Direct dye	17(translucent)	After 24 hours
	Disperse dye	17(translucent)	After 24 hours
Coal ash	Acid dye	17(no colour adsorbed)	After 24 hours
	Basic dye	17(translucent)	After 24 hours
	Reactive dye	17(translucent)	After 24 hours
	Vat dye	17(no colour adsorbed)	After 24 hours
	Direct dye	17(no colour adsorbed)	After 24 hours
	Disperse dye	17(no colour adsorbed)	After 24 hours
Wood ash	Acid dye	17	30 minutes
	Basic dye	17(translucent)	30 minutes
	Reactive dye	17	30 minutes
	Vat dye	17(translucent)	30 minutes
	Direct dye	17(translucent with little amount colour present)	30 minutes
	Disperse dye	17(translucent with little amount colour present)	30 minutes
Dyeing ash	Acid dye	17	30 minutes
	Basic dye	17	30 minutes
	Reactive dye	17	30 minutes
	Vat dye	17(translucent with little amount colour present)	30 minutes
	Direct dye	17	30 minutes
	Disperse dye	17(translucent with little amount colour present)	30minutes

1. While both Bagasse ash and Wood ash exhibited promising results, it was the Dyeing ash that demonstrated the most remarkable performance. Specifically, all the dyes were effectively decolorized within an impressive timeframe of approximately 30 minutes, showcasing the superior adsorption capabilities of this particular ash. Given its outstanding performance, along with the favorable results of the other two ashes, these three ashes Bagasse ash, Wood ash, and Dyeing ash were selected as the optimized materials for subsequent column studies. This selection was based on their ability to efficiently remove dyes, making them the most suitable candidates for further research and application in the field.

The observed efficiency of these ashes in dye decolorization can likely be attributed to a combination of several key factors, including their structural properties, pore size, chemical composition, and particle size. The unique structural characteristics of each type of ash, such as their surface area and porosity, may provide an ideal environment for the adsorption of dye molecules. Additionally, the pore size plays a crucial role in determining the capacity of the material to interact with and trap dye molecules, with smaller pores generally facilitating greater adsorption. The chemical composition of the ashes, which varies depending on the source material, can influence their reactivity and affinity for specific dyes, further enhancing their decolorization potential. Furthermore, the particle size is another important factor; smaller particles generally offer a larger surface area relative to volume, which can significantly improve the overall adsorption efficiency. Taken together, these physical and chemical properties likely contribute to the superior performance observed in the dye removal process, making these ashes highly effective for such applications.

3.2 pH study

In a comprehensive study of the pH levels of various ashes, it was concluded that the pH remains consistent regardless of the temperature of the water used for dissolution. Specifically, the study observed that when these ashes were dissolved in both hot and cold water, no significant changes in pH were detected which can be seen in Table 2. This finding suggests that the temperature of the dye solution whether hot or cold does not influence the pH of the ash in any meaningful way. Therefore, the chemical behavior of the ashes remains stable under different thermal conditions, providing valuable insight for applications that involve temperature variations during processing. This stability in pH reinforces the reliability of the ashes in diverse environmental and experimental settings.

Table 2 - pH study of different ashes in hot and cold water

Ash	pH in cold water	pH in hot water
Bagasse ash	10.5	10.5
Briquette ash	10.5	10.5
Coal ash	6	6
Wood ash	10.5	10.5
Dyeing ash	10	10

3.3 Column study

For the column study, three optimized types of ash, along with a reactive dye selected from a group of six potential dyes, were used to evaluate their adsorption capabilities. The objective was to determine the percentage of dye adsorbed by each ash. In this context, the reactive dye was subjected to adsorption by all three types of ash, and their performance in removing the dye was closely monitored. Among the three ashes, dyeing ash demonstrated the highest efficacy in adsorbing the dye, significantly outperforming the other two ashes Bagasse ash and Wood ash both of which showed limited adsorption in the column study. Dyeing ash successfully decolorized approximately 78% of the colored solution which can be seen in Fig. 2, which contained a total dissolved solids (TDS) concentration of 107 ppm, a level considerably lower than the accepted industrial standards. To ensure the reliability and accuracy of the results, the experiment was repeated five times for each type of ash, allowing for consistent data collection and validation of the findings.

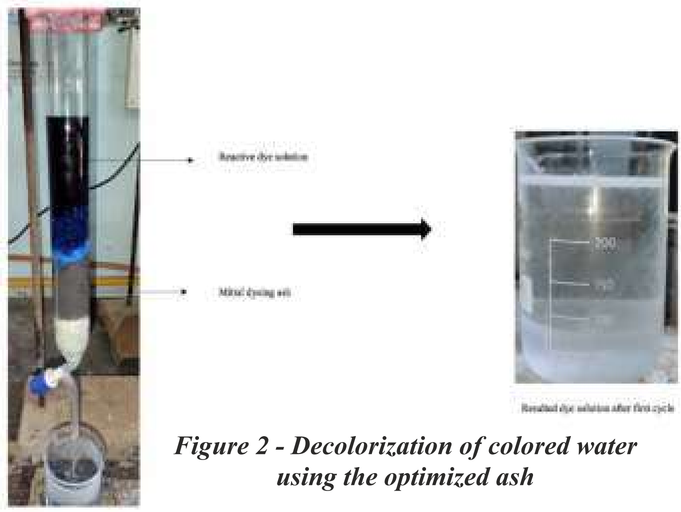

Figure 2 - Decolorization of colored water using the optimized ash

3.4 Characterization

3.4.1 Particle Size Analysis

The particle size analysis was done in Shimadzu SALD-7500, samples were dispersed in deionized water and sonicated for 5 minutes before analysis. Each and every ash has different hydrodynamic diameter which can be seen in Table 3. Since dyeing ash is a blend of many sorts of components, such as sea woods, arhar stalk, and mustard stalk, its particle size is slightly larger than that of wood ash, despite the fact that dyeing ash is known to perform extremely well for decolorization.

Table 3 - Particle size analysis of different ashes

Ash	Particle Size
Bagasse ash	23.537mm
Briquette ash	26.580mm
Coal ash	37.041mm
Dyeing ash	10.291mm
Wood ash	4.158mm

3.4.2 FTIR analysis

In the case of Bagasse ash, a detailed analysis of its FTIR spectrum reveals several characteristic peaks, each corresponding to distinct functional groups, thereby providing valuable insights into the chemical composition of the material. Notably, a prominent peak at 985.53 cm^{-1} indicates the presence of a carbon-carbon double bond, suggesting the presence of unsaturated compounds within the ash. Another significant peak, observed at 873.48 cm^{-1}, is indicative of a halo compound, confirming the incorporation of halogen atoms into the molecular structure of the ash. Furthermore, the peak at 1406.47 cm^{-1} is attributed to sulfonyl chloride stretching vibrations, a feature that signals the presence of both sulfur and oxygen atoms, likely in the form of sulfonyl functional groups. Lastly, a broad peak at 3417.6 cm^{-1} corresponds to the stretching vibrations of a primary amine group, confirming the existence of nitrogen-containing functional groups in the material. In the analysis of Wood ash, several notable infrared absorption peaks provide valuable insights into its chemical composition. A prominent peak at 873.48 cm^{-1} corresponds to a broad stretching vibration associated with the carbon-carbon double bond (C=C), suggesting the presence of conjugated or unsaturated structures within the ash. Additionally, a distinct absorption band at 1099.03 cm^{-1} is observed, which is indicative of a strong stretching vibration related to aliphatic ether groups (C–O–C), this, peak highlights the presence of ether linkages, which are important for understanding the ash's molecular framework. Furthermore, at 1413.65 cm^{-1}, a wide and pronounced peak is observed, pointing to the presence of sulfate groups (SO_4^{2-}) within the ash. This sulfate peak further emphasizes the complex inorganic composition of the Wood ash. The FTIR analysis of Briquette ash reveals several key features: a broad absorption band at 1413.65 cm^{-1}, indicative of sulfate stretching; a broad band at 1099.03 cm^{-1}, associated with C-O stretching; and a peak at 873.48 cm^{-1}, which suggests the presence of a carbon-carbon double bond. The FTIR spectrum of Coal ash exhibits several prominent peaks: a broad absorption at 3298.52 cm^{-1}, indicative of carboxylic acid stretching; a peak at 1629.15 cm^{-1}, suggesting the presence of a carbon-carbon double bond; and a band at 1038.69 cm^{-1}, corresponding to sulfoxide stretching. In the Dyeing ash sample, several distinct spectral features are observed. A broad absorption band at 1406.47 cm^{-1} is indicative of sulfate stretching, which is characteristic of the presence of sulfate groups within the material. Additionally, the peak at 1101.90 cm^{-1} corresponds to the stretching vibrations of an aliphatic ether group, reflecting the presence of ether linkages in the structure. Another prominent feature is the strong absorption at 1032.94 cm^{-1}, which is associated with sulfoxide stretching, suggesting the presence of sulfoxide functional groups. Finally, a peak observed at 872.04 cm^{-1} is attributed to the stretching of a carbon-carbon double bond (C=C), providing further evidence of the material's organic content. The FTIR graphs of all the ashes can be seen in Fig. 3.

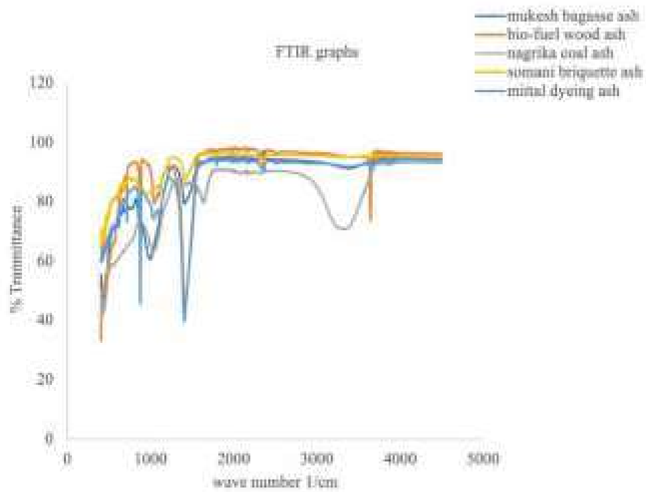

Figure 3 - FTIR analysis of all five kinds of ashes

3.4.3 SEM analysis

The results obtained from Scanning Electron Microscopy (SEM) analysis reveal that the particle sizes of the samples are in the micrometer range, with notable variation in particle morphology which can be seen in Fig. 4. The analysis indicates that the particles exhibit a diverse range of shapes, with a mixture of both irregularly shaped and spherical particles present within each type of ash. Specifically, the wood ash sample demonstrates a distinct morphological characteristic, as the particles appear somewhat distorted compared to those of other ash samples. This variation in particle shape and size suggests a degree of heterogeneity in the material, which could have implications for its behavior and potential applications in various industrial processes.

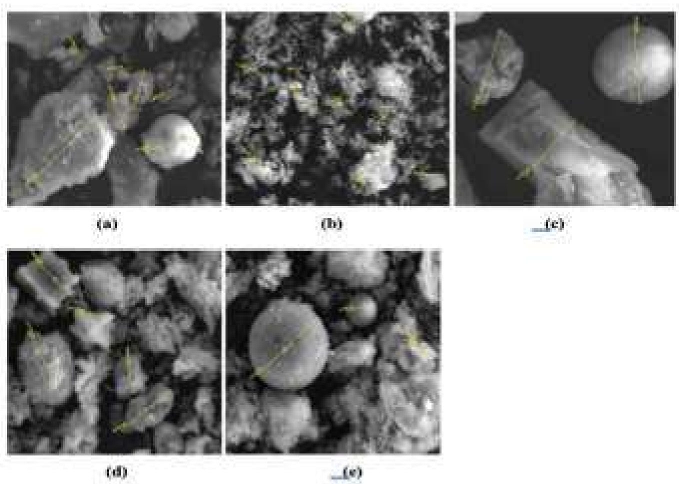

Figure 4 - SEM analysis of all five types of ashes

3.4.4 EDAX analysis

The EDAX analysis of ashes showed the presence of different types of metals in the ashes like Carbon(C), Oxygen(O), Sodium(Na), Magnesium(Mg), Aluminum(Al), Silicone(Si), Chlorine(Cl), Potassium(K), Calcium(Ca), Titanium(Ti), Iron(Fe), Phosphorus(P), Sulfur(S) which are known for their property to adsorb colour [13].

3.4.5 Testing for TDS

When the water's TDS was measured with a TDS meter following decolorization. It demonstrated that while all types of ash lowered TDS, dyeing ash was more successful. After the decolorization procedure, the TDS of the decolorized water was approximately 107 ppm, whereas the initial TDS of the water was between 200 and 300 ppm.

In addition, it was noted that wood ash raised the TDS level to 349 parts per million.

3.4.6 Ash Characteristics Study Based on Theoretical Data

As per theory, the dyeing ash which consists of sea woods, arhar stalk and mustard stalk when they are burned together gives potential advantages of best combination of high porosity which comes from arhar stalk combustion which is because of the development of heterogenous pores, mineral content like Ca, K, Mg, Si and alkalinity, eco-friendly, low-toxicity then other ashes which in turn provides higher dye adsorption rate than other dyes [13, 14].

Other ashes like bagasse ash and briquette ash has moderate porosity, coal has good adsorption capacity but it is very toxic for environment and wood ash has very low porosity.

4. Conclusion

It is concluded that the dyeing ash which has different constituents performs better for decolourisation of waste water than the other types of ashes and it has been proved in theory to be eco-friendly and low-toxicity which can be efficiently. It also has a tendency to reduce the TDS of water. So, it can be considered that dyeing ash is best kind of ash among all as it has different types of constituents and can be used as low-cost ash-based adsorbents as environmentally friendly substitutes for conventional chemical reagents in wastewater treatment and decolorization processes.

Data Statement

The data that supports the study are available in the article itself.

Acknowledgement

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Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this manuscript, AI-assisted tools were used solely to improve the clarity, grammar, and readability of the text. The scientific content, data interpretation, and conclusions were developed and verified entirely by the authors. The authors take full responsibility for the accuracy and integrity of the work.

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Sustainable Bioactive Cotton Gauze Incorporating Tridax Procumbens Microcapsules for Chronic Wound Management

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Abstract :

Background: *Chronic wound management, particularly for diabetic patients, demands bioactive dressings that provide antimicrobial protection, moisture regulation, and tissue regeneration. While traditional cotton gauze is the industry standard due to its accessibility, it lacks innate therapeutic properties. To address this, the study explores enhancing gauze through functional finishing techniques using Tridax procumbens (TP), a plant known for its medicinal potential.*

Methods: *The researchers developed a bioactive dressing by first pre-treating 100% cotton gauze. They performed Soxhlet extraction on TP using ethanol and water solvents to identify the most effective antimicrobial profile. The optimized extract was then microencapsulated and applied to the gauze substrate via a dip-dry process. The resulting material was rigorously evaluated for physical comfort and antimicrobial efficacy against S. aureus, E. coli, and C. albicans. Finally, in vivo wound healing performance was tested using streptozotocin-induced diabetic rats, comparing results against a silver nitrate/glibenclamide control group.*

Results: *The ethanolic extract of T. procumbens demonstrated superior antimicrobial activity, with the finished gauze creating significant inhibition zones against all tested pathogens. Critically, the microencapsulation process did not compromise the fabric's physical properties, as comfort parameters remained within acceptable clinical ranges. In vivo studies revealed consistent wound closure from Day 5 through Day 15. Furthermore, the TP-treated group showed a restoration of near-normal blood parameters, performing comparably to the traditional silver nitrate treatment.*

Conclusion: *The study successfully demonstrates that microencapsulating Tridax procumbens onto cotton gauze creates a potent bioactive dressing. This modified material effectively bridges the gap between traditional gauze and modern wound care requirements, offering a promising, bio-based solution for the accelerated healing of complex diabetic wounds.*

Keywords: *Antibacterial, Cotton gauze, Diabetic wound, Herbal wound dressing, Microencapsulation, Streptozotocin*

Citation: Sona M, Ramya M, "Sustainable Bioactive Cotton Gauze Incorporating Tridax procumbens Microcapsules for Chronic Wound Management ", *Journal of the Textile Association*, **87/1** (May-June,2026), 15-20, https://doi.org/10.5281/zenodo.21833870

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1. Introduction

The design and development of improved wound dressings stand out as one of the major milestones in textile technology. It involves integrating existing fabric technology with medical necessities. Tridax procumbens is one of several natural therapeutics, whose potent pharmacological characteristics such as antibacterial, anti-inflammatory, and antioxidant properties have attracted attention of many scientists as necessary ingredients for wound healing and tissue regeneration [1].

Traditionally, wounds were cleaned with a combination of sterile saline and cotton gauze. Even though cotton is characterized with good absorbency, it does not provide any bioactivity that can help in healing process [2]. Scientists have found a solution to the challenge by considering ways to incorporate botanical extracts to the material using advanced techniques [3]. Microencapsulation is one of them and involves encapsulating herbs and other plants within small capsules and controlling their release [4].

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The focus of the study described is to improve the functions of regular cotton gauze through the introduction of Tridax procumbens extract incorporated in a matrix microcapsule. Traditional applications of T. procumbens involve the use of juices obtained from fresh leaves, although they have low bioavailability and degrade easily [5]. The study uses microencapsulation technique to solve this problem, thus improving durability of the extract

2. Materials and Methods

2.1 Extraction from Tridax procumbens

Fresh leaves of Tridax procumbens plant were collected from and around the campus of Hindustan Institute of Technology & Science Deemed University, Padur, Chennai. The collected leaves were then washed with distilled water and air-dried till it attains the constant weight. The dried leaves were grounded into a fine powder. To perform the extraction process, 50g of leaf powder was placed in a Soxhlet apparatus, which was further extracted using 95% ethanol for 24 hours. The obtained liquid extract was then filtered using Whatman No. 1 filter paper and concentrated by a rotary evaporator at 40°C to get a thick extract. The extract obtained was preserved at 4°C for future use [6].

2.2 Preparation of Microcapsules

Tridax procumbens was selected as core material and Sodium alginate was selected as wall material [7]. The different stages in preparing the microcapsules have been depicted in Fig. 1. Prepared microcapsules were processed to finish the wound dressing gauze materials.

Figure 1: Microcapsule preparation
a. Extract of TP, b. adding Sodium alginate, c.adding nontoxic binder

2.3 Finishing of Cotton Gauze Fabric

A white cotton gauze fabric, comprising 100% cotton fiber, was chosen as the material for the treatment process. The encapsulated extract was applied to the fabric by pad-dry-cure technique. The finishing solution comprised the encapsulated extract and a nontoxic binder, Sodium Alginate. The fabric samples were padded in this solution under constant pressure using a laboratory padding machine to obtain 90% wet pick-up rate. Afterwards, the padded fabrics were dried for 5 minutes in a hot air oven maintained at 80°C followed by curing in an oven set at 120°C for 3 minutes [8].

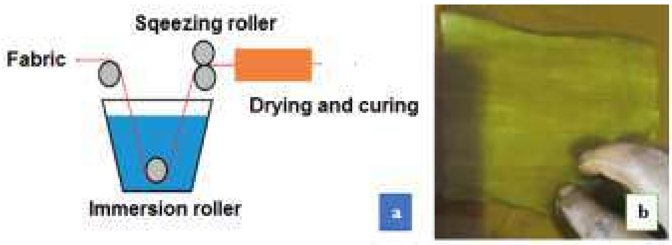

Figure 2: a. Pad-dry-cure method and b. Coated sample

2.4 Characterization and Performance Evaluation

Development of bioactive wound dressing from T. procumbens extract-finished cotton gauze should be followed by rigorous analytical methods to evaluate their efficacy. Characterization of the dressing will include morphological evaluation using SEM to observe how the plant extract interacts with the cotton fibers while maintaining the natural porosity of the dressing for wound aeration [9]. Bioactive characterization will involve FTIR analysis to detect secondary metabolites such as flavonoids and tannins that provide the medicinal properties of the plant [10]. Antibacterial effectiveness will be evaluated against common wound pathogens such as S. aureus through disc diffusion to verify that the finished fabric can inhibit bacterial growth [11]. In-vitro drug release will also be analyzed in artificial wound fluids to examine the kinetics of phytoconstituent leaching and sustain therapeutic effect without degradation [12]. Moreover, swelling analysis is vital to establish the absorption capacity of wound fluids by the gauze, creating an ideal moist environment for tissue regeneration and wound healing [13].

3. Results and Discussion

3.1 FTIR Spectrum of TP Extract

Figure 3 presents the FTIR spectrum of the Tridax procumbens (TP) extract and shows the complexity of its chemistry needed for employment in the materials and filtration sectors. The most prominent peak in the spectrum is the intense and wide one found at 3356 cm-1, representing the O-H stretching vibration characteristic of phenolic compounds, flavonoids, and alcohol molecules – chemical components usually contained in the biosorbent extract obtained from plants. Moreover, the medium-strong peak observed at 2985 cm-1 represents the aliphatic C-H stretching vibration due to methyl or methylene groups in different phytochemicals. Besides, the high-intensity peak found at 1635 cm-1 is the representation of the essential carbonyl or aromatic skeleton stretching vibration (C=O or C=C), indicating the existence of some secondary metabolites, such as proteins or flavonoids, that can establish bonds when purifying wastewater from textile industries. Lastly, the weak peak at 686 cm-1 concludes the fingerprint region and shows the aromatic C-H bending.

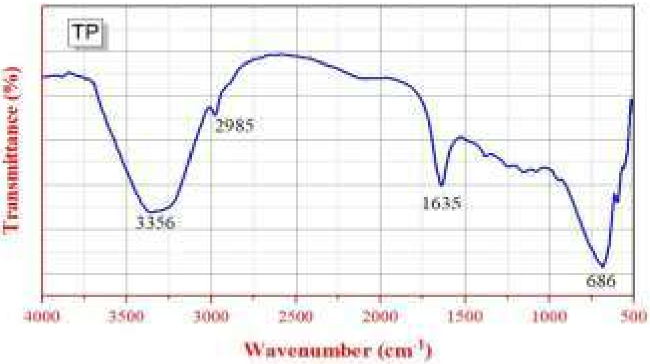

Figure 3: FTIR Spectrum of Tridax Procumbens Extracts

3.2 Scanning Electron Microscopy (SEM) analysis

The analysis of the gauze fabric via the Scanning Electron Microscopy (SEM) in figure 4 shows an optimal

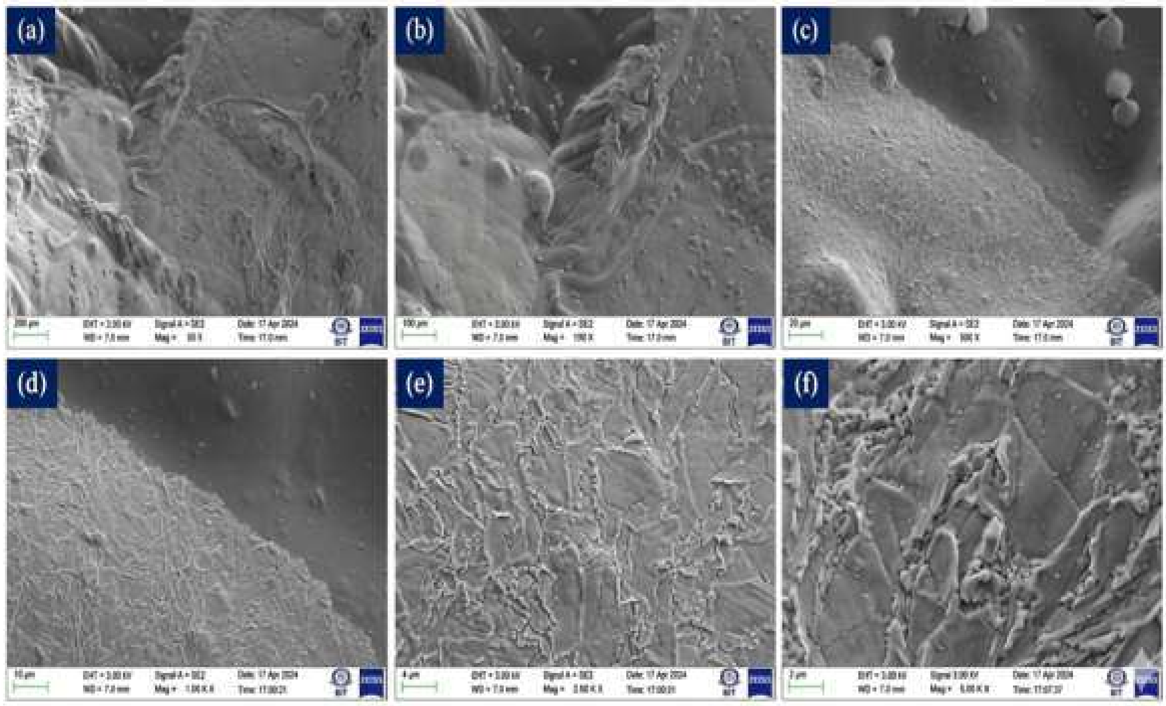

Figure 4: Gauze cloth coated with Alginate loaded Tridax Procumbens Extract

incorporation of the alginate loaded extract from Tridax procumbens (TP). At low magnification, it can be seen that the biopolymer matrix forms a uniform encapsulation of the fibers, effectively covering the interstices and providing a continuous bioactive layer on the gauze. Upon increasing the magnification, the topography demonstrates a rough, flaky structure with micro cracks and ridges. This type of surface is beneficial for the biomedical uses since it will provide more surface area available for the liquid uptake while allowing for the controlled release of the TP phytochemicals, such as phenolic groups and carbonyls revealed by your FTIR analysis at the site of interaction. The evident adhesion of the smooth polymer layer to the fibrous network allows assuming that the coating is solid enough for the use in high performance sustainable materials.

3.3 Antibacterial Activity of the Extracts

The antibacterial activities of ethanol and aqueous extracts of T. procumbens against wound-relevant pathogens are presented in Table 1 and Figure 5.

Antibacterial activity of the Tridax procumbens extract-treated gauzes was determined through the Agar disc diffusion assay using Escherichia coli and Staphylococcus aureus. It can be observed from the results obtained that there was no inhibition recorded on the untreated control gauzes while the treated gauzes had considerable antimicrobial action. This is evident because the zone of inhibition obtained by the ethanol extract (GH1 EM) was 35.6 ± 0.75 mm and 31.3 ± 1.05 mm for the Escherichia coli and Staphylococcus aureus respectively. In addition, there was another strong inhibition zone observed for the water extract (GH1 WM) which measured 29.9 ± 0.57 mm and 28.3 ± 1.05 mm for the two bacterial strains. Statistically, the F-value obtained in each case was higher than 835, indicating high confidence level at 0.000*.

Table 1. Antibacterial zone of inhibition (mm) of T. procumbens extracts and TP-finished gauze samples (EN ISO 20645)

F. No	Samples	Zone of inhibition (mm)				Statistical Analysis			
		Escherichia coli		*Staphylococcus Aureus*		*Escherichia coli*		*Staphylococcus Aureus*	
		C	F	C	F	F value	Significance	F value	Significance
GH1EM	*Tridax procumbens* (Ethanol)	0	**35.6 ± 0.75**	0	**31.3 ± 1.05**	848.3	0.000*	835.5	0.000*
GH1WM	*Tridax procumbens* (Water)	0	29.9 ± 0.57	0	28.3 ± 1.05				

Values are mean ± S.D. (n = 5).

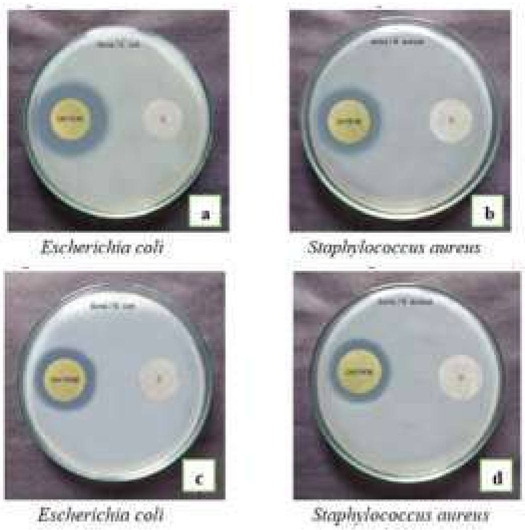

Figure. 5: Antibacterial activity of developed wound dressing materials
a & b: Gauze + Herb-1 + Ethanol + Microcapsules - GH1EM
c & d: Gauze + Herb-1 + Water + Microcapsules - GH1WM

3.4 Wound Healing Assay

3.4.1 Acute Toxicity — Body Weight

The results of the acute toxicity body weight assessment are presented in Table 2.

Table 2: Body weight measurements during acute toxicity study (mean ± S.D., n = 3)

Group	Before Treatment (g)	After Treatment (g)	Significance
Group I (Control)	283.3 ± 1.05	293.6 ± 0.75	—
Group II (TP-Gauze 500 µg)	282.6 ± 0.75	291.9 ± 0.57	ns
Group III (Standard)	283.9 ± 0.57	293.6 ± 0.75	ns

ns = not significant ($p > 0.05$) compared to Group I (Control). Statistical analysis: one-way ANOVA with Tukey's post-hoc test

As observed from the body weight assessment of the treatment prior to and post-acute toxicity test, it appears that there is no statistically significant difference ($p>0.05$) in body weight alteration when comparing the control Group (Group I) with the TP gauze group (Group II) and the standard control Group (Group III). A slight but consistent body weight increase was observed throughout the observation in all experimental animals. This finding implies that there is no apparent toxicity in terms of systemic toxicity of TP gauze formulation at a dose concentration of 500 µg.

3.4.2 Acute Toxicity — Haematological Parameters

The results of the haematology tests showed that there were no statistically significant differences among any of the haematology parameters, including Hb, PCV, WBC, RBC, and platelets, between Group II, Group III, and the control group ($p > 0.05$), which established the lack of haematotoxicity of the compound when administered at the tested dose. This indicates that all haematological parameters are within the physiological range in adult male Wistar albino rats.

3.5 In Vivo Wound Healing — Photographic Assessment

The macroscopic wound healing progression in the three experimental groups was documented photographically on Days 1, 5, 10, and 15 post-wounding (Figures 6, 7, and 8).

3.5.1 Group I — Diabetic Control (STZ-induced, No Treatment)

Figure 6: Group I — Diabetic Control (STZ-induced, No Treatment)

Fig. 6. Group I (Diabetic Control — no treatment). Wound persisted throughout the 15-day observation period with no appreciable closure, confirming the impaired healing characteristic of the STZ-induced diabetic model.

3.5.2 Group II — Standard Control (Silver Nitrate + Glibenclamide)

Fig. 7. Group II (Standard Control — silver nitrate + glibenclamide). Progressive wound closure from Day 5, with significant healing by Day 15, consistent with established standard treatment efficacy.

3.5.3 Figure 8. Group III — Test Group (ALG/TP/Gauze Composite Dressing)

Fig. 8. Group III (ALG/TP/Gauze - test dressing). Progressive wound healing from Day 5, with significant

Table 3: Haematological parameters during acute toxicity study (mean ± S.D., n = 3)

Group	Hb (g%)	PCV (%)	WBC (10^3/µL)	RBC (10^{12}/µL)	Platelets (10?/µL)	Sig.
Group I	16.9±0.57	36.6±0.75	7.9±0.57	11.3±1.05	8.3±1.05	—
Group II	16.6±0.75	36.9±0.57	7.3±1.05	11.9±0.57	8.6±0.75	ns
Group III	16.3±1.05	36.3±1.05	7.6±0.75	11.6±0.75	8.9±0.57	ns

ns = not significant ($p > 0.05$) compared to Group I. Hb = haemoglobin; PCV = packed cell volume; WBC = white blood cells; RBC = red blood cells

Figure 7: Group II — Standard Control (Silver Nitrate + Glibenclamide)

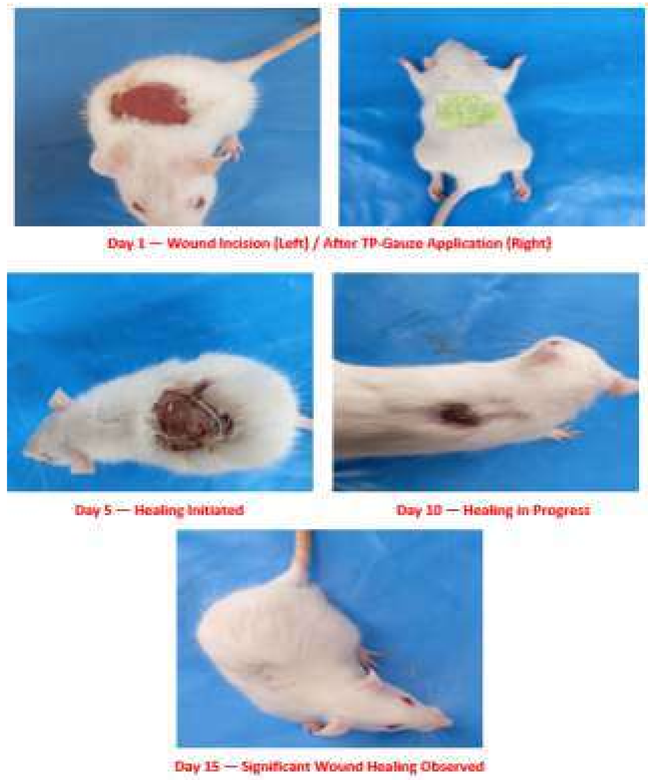

Figure 7: Group II — Standard Control (Silver Nitrate + Glibenclamide)

closure by Day 15, comparable to the standard control (Group II), demonstrating the therapeutic efficacy of the developed composite dressing.

The experimental results show that there is a clear difference in the rate of wound healing between the control group and the treated group. The group I (diabetic control) showed insignificant wound healing for 15 days, proving the typical characteristics of wound healing in STZ-induced diabetes, such as poor angiogenesis and low collagen formation.

The Group III (ALG/TP/Gauze) started wound healing on day 5 through the development of granulation and contraction. On day 15, Group III showed remarkable wound closure and was comparable to Group II (standard treatment using silver nitrate and glibenclamide). This effectiveness of the treatment can be attributed to the synergic effects of phytochemicals from "T. procumbens": flavonoids such as quercetin and luteolin induce fibroblast and keratinocyte proliferation, whereas terpenoids enhance angiogenesis [14]. Additionally, the alginate formulation creates a moist environment suitable for re-epithelialization, whereas the gauze formulation provides necessary structure and handleability [15].

3.6 Haematological Parameters — Before and After Wound Treatment

Table 4: Haematological parameters before STZ induction (mean ± S.D., n = 3)

Group	Hb (g%)	PCV (%)	WBC (10³/µL)	RBC (10¹²/µL)	Platelets (10?/µL)
Group I	16.9±0.57	35.6±0.75	7.9±0.57	8.6±0.75	9.3±1.05
Group II	16.3±1.05	35.9±0.57	7.3±1.05	8.9±0.57	9.9±0.57
Group III	16.9±0.57	35.3±1.05	7.9±0.57	8.3±1.05	9.6±0.75

All groups were comparable at baseline ($p > 0.05$). Hb = haemoglobin; PCV = packed cell volume

Table 5: Haematological parameters after STZ induction and wound treatment (mean ± S.D., n = 3)

Group	Hb (g%)	PCV (%)	WBC (10³/µL)	RBC (10¹²/µL)	Platelets (10?/µL)
Group IA (Diabetic Control)	8.9±0.57 s	26.6±0.75 s	10.9±0.57 s	5.3±1.05 s	13.6±0.75 s
Group IIA (Standard)	13.3±1.05 ns	35.3±1.05 ns	7.9±0.57 ns	8.9±0.57 ns	8.9±0.57 ns
Group IIIA (ALG/TP/Gauze)	13.9±0.57 ns	35.9±0.57 ns	7.6±0.75 ns	8.6±0.75 ns	8.3±1.05 ns

s = statistically significant ($p < 0.05$) vs. pre-induction Group I; ns = not significant ($p > 0.05$). Tx = treatment.

Haematological values in all three groups were statistically comparable before STZ treatment (Table 6). Post-STZ treatment and after 15 days of wound healing observation, the untreated diabetic control (Group IA) showed significantly poor haematological indices ($p < 0.05$), where Hb decreased from 16.9 ± 0.57 to 8.9 ± 0.57 g%, PCV decreased from 35.6 ± 0.75% to 26.6 ± 0.75%, and RBC decreased from 8.6 ± 0.75 to $5.3 \pm 1.05 \times 10^{12}$/µL. In contrast, WBC increased from 7.9 ± 0.57 to $10.9 \pm 0.57 \times 10^{3}$/µL and the platelet count from 9.3 ± 1.05 to $13.6 \pm 0.75 \times 10^{9}$/µL.

Contrarily, both Groups IIA and IIIA were seen to have a haematological recovery close to normal, with no significant statistical differences relative to their respective pre-treatment levels ($p > 0.05$). Indeed, the haematological recovery pattern observed for Group IIIA was not significantly different from that observed for Group IIA, thus giving solid systemic proof on the effectiveness of the dressing material in terms of its haemoprotective effects. Systemic haematoprotection could be attributed to the anti-inflammatory and antioxidant properties of T. procumbens phytochemicals that inhibit oxidative stress cascades induced by STZ.

4. Conclusion

The application of micro-encapsulated extracts from medicinal plants is a crucial point of convergence of ethnopharmacology with the contemporary science of textile technology. In the current study, cotton gauze has been functionalized by the application of micro-encapsulated Tridax procumbens (TP) extract. In this approach, micro-encapsulation was deliberately selected as a means of achieving controlled release and protection of volatile compounds, such as tannins and flavonoids. The ethanolic extract of TP was found to be highly effective in inhibiting microbial growth, as evidenced by zone sizes of 31.3 mm for S. aureus and 35.6 mm for E. coli. Through the process of functionalization, ordinary cotton gauze has been converted into advanced medical textiles while retaining their key attributes, such as air and moisture vapor permeability.

Validation of the effectiveness of the TP finished micro-encapsulated gauze in wound healing has also been carried out in vitro via experiments on STZ-induced diabetes in rats, where the dressing showed a high degree of efficacy in wound closure within fifteen days of application. Such effects were consistent with those obtained from standard silver nitrate dressing and indicated that the biomaterial could act as an effective substitute for treating complex chronic wounds. In addition, extensive testing of toxicity and hematology has shown that such dressing is completely safe and contributes to the normalization of blood characteristics.

In conclusion, the introduction of Tridax procumbens within functionalized textiles is a novel development within the realm of sustainable "green" composite materials. This study managed to show that microencapsulation retains the biological activity of natural compounds, leading to continuous antimicrobial activity and faster regeneration of damaged tissues. The developed method not only presents an example of waste valorization and use of bio-based materials for healthcare but also provides an efficient and safe means of enhancing patient treatment outcomes. Due to its high efficacy and preservation of properties of the textile material, the developed gauze material can be considered a benchmark for future innovations in wound care materials.

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Determinants of Job Satisfaction among Handloom Weavers: A PLS-SEM Approach

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Abstract :

Background: *The Indian handloom sector is under considerable strain as traditional craft practices come into contact with Industry 4.0 technologies. Weavers face well-documented occupational hazards, among them musculoskeletal disorders, financial instability, and market disadvantages tied to intermediary dependence [4, 5]. Despite growing interest in technology-based modernisation, the psychosocial consequences for weavers remain poorly understood. This study examines the Work-Related Quality of Life (WRQoL) determinants of Job Satisfaction (JS) among handloom weavers, drawing on the validated WRQoL scale developed by Easton and Van Laar [13].*

Methods: *Three hundred handloom weavers across weaving clusters in Kerala and Tamil Nadu were surveyed using a multi-stage stratified random sampling design. Five WRQoL constructs were evaluated: Working Conditions (WCS), Home-Work Interface (HW), Control at Work (CAW), Stress at Work (SAW), and General Wellbeing (GWB). The conceptual model was tested using Partial Least Squares Structural Equation Modelling (PLS-SEM) in SmartPLS 4.*

Results: *The structural model demonstrates substantial explanatory power (Adjusted $R^2 = 0.546$). Working Conditions ($\beta = 0.295, p < 0.001$) and Home-Work Interface ($\beta = 0.266, p < 0.001$) were the strongest positive predictors of job satisfaction. Control at Work ($\beta = 0.205, p < 0.001$) and Stress at Work ($\beta = 0.197, p < 0.001$) were also statistically significant. General Wellbeing ($\beta = 0.040, p = 0.399$) was not.*

Conclusion: *Policy for the handloom sector should prioritise ergonomic infrastructure investment and digital empowerment over generic psychosocial welfare programmes. Physical working environments and weaver autonomy are the factors most closely tied to occupational satisfaction in this industry.*

Keywords: *Control at Work, Handloom Weavers, Industry 4.0, Job Satisfaction, PLS-SEM, Work-Related Quality of Life, WRQoL*

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1. Introduction

The Indian handloom sector is one of the largest providers of rural employment and a repository of craft traditions stretching back centuries. Yet weavers continue to work under severe occupational strain. The sector has long been associated with physically demanding labour, low and unreliable income, and working conditions that drive skilled workers out of the trade over time [3, 9]. High rates of musculoskeletal disorders, including low back pain, cervical strain, and shoulder injuries caused by repetitive motion and sustained awkward posture, are well-documented among handloom workers [4, 5]. Financial vulnerability is compounded by structural dependence on intermediaries who capture a disproportionate share of value from the supply chain [10].

Understanding what drives weaver job satisfaction matters not simply as a welfare question but as a structural concern for the sector's long-term viability. In craft occupations, satisfaction is shaped by ergonomic conditions, the permeability of household-work boundaries, perceived autonomy over work decisions, and broader psychosocial wellbeing [1, 2]. Industry 4.0 interventions, from pneumatic loom mechanisms and improved Jacquard systems to computer-aided design (CAD) software and e-commerce access, have the potential to change the occupational experience of weavers substantially [11, 12]. Ergonomic modifications have been shown to reduce physiological stress [4, 5], and digital market access can ease income insecurity while reducing dependence on intermediaries [10, 11].

Despite the policy attention these issues have received, there is little empirical work examining how technology-mediated environmental changes and psychosocial factors jointly determine job satisfaction among handloom weavers. The Work-Related Quality of Life (WRQoL) framework, developed by Easton and Van Laar [13] and subsequently validated across multiple occupational settings, offers a

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structured way to examine this relationship. The five dimensions used in this study, Working Conditions, Home-Work Interface, Control at Work, Stress at Work, and General Wellbeing, correspond to constructs identified in the existing literature on weaver occupational health. Prior studies have addressed individual dimensions in isolation [3, 6, 7 & 8] without applying the full WRQoL framework to an Indian handloom context.

This study addresses two research questions: (RQ1) Which WRQoL dimensions are the strongest predictors of job satisfaction among handloom weavers in Kerala and Tamil Nadu? (RQ2) How do technology-mediated changes in working conditions and the home-work interface affect weaver satisfaction? The study's objectives are: (1) to assess the reliability and validity of the WRQoL scale as adapted for the handloom setting; (2) to estimate path relationships between five WRQoL dimensions and job satisfaction using PLS-SEM; and (3) to draw policy implications for Industry 4.0 integration in the sector.

2. Review of the Literature

Job satisfaction is typically conceptualised at two levels: global satisfaction, which captures an individual's overall feelings about their work, and facet satisfaction, which addresses specific aspects such as pay, working environment, and perceived autonomy [1]. Comparative research consistently finds that workers in settings with stronger welfare systems and better physical working conditions report higher overall satisfaction [2], pointing to the importance of institutional and environmental context.

Physical infrastructure has a direct bearing on weaver productivity and wellbeing. Research on rural handloom clusters in Ethiopia found that reliable electricity provision improved cluster-level productivity [3]. Among Indian weavers, postural and ergonomic conditions are especially consequential: a survey-based study of West Bengal weavers identified a high prevalence of low back pain attributable to loom workstation design, and recommended ergonomic redesign as a route to improved occupational contentment [4]. A cross-sectional study in Assam found musculoskeletal disorders affecting a majority of handloom workers, and similarly advocated workstation improvements to reduce physical stress [5].

Welfare provision and institutional support are linked to job satisfaction in related industries. Research from the Sri Lankan apparel sector found a positive relationship between welfare facility provision and job satisfaction among operational staff [7]. An Indian study of handloom weavers found that benefit schemes incorporating technology adoption were associated with improved weaver satisfaction, primarily through better working conditions and income stability [8].

The relationship between technology, market access, and job satisfaction is increasingly documented. A study of two weaving clusters in Telangana found that the absence of technical upgrades, alongside poor infrastructure support, worsened occupational health outcomes and reduced productivity [9]. Work on technology adoption and job stability found that access to modern tools and credit improved handloom worker satisfaction through gains in efficiency, ergonomics, and market reach [10]. E-commerce access has similarly been linked to improved livelihoods and income sustainability among Indian handloom weavers [11]. In Andhra Pradesh, obsolete equipment was found to be a structural obstacle to weaver satisfaction, with technology adoption identified as the key intervention [12].

Taken together, this evidence points to five main constructs driving handloom weaver job satisfaction: working conditions, the home-work interface, control at work, stress at work, and general wellbeing. These correspond directly to five of the six dimensions of the validated WRQoL scale [13], providing the theoretical basis for the conceptual model used in this study.

2.1 Hypotheses

Based on the literature reviewed above, the following hypotheses are formally stated.

Table H1–H5: Formally Stated Hypotheses

Hypothesis	Statement
H1	Working Conditions (WCS) are positively associated with Job Satisfaction among handloom weavers
H2	Home-Work Interface (HW) is positively associated with Job Satisfaction among handloom weavers
H3	Control at Work (CAW) is positively associated with Job Satisfaction among handloom weavers
H4	Stress at Work (SAW) is positively associated with Job Satisfaction among handloom weavers
H5	General Wellbeing (GWB) is positively associated with Job Satisfaction among handloom weavers

3. Data and Methodology

3.1 Conceptual Framework: Work-Related Quality of Life

This study draws on the Work-Related Quality of Life (WRQoL) framework developed by Easton and Van Laar [13], which treats occupational quality of life as a multidimensional construct spanning psychological, social, and environmental dimensions. The WRQoL scale has been validated in healthcare, manufacturing, and service sectors; its application to traditional artisanal industries remains limited, making the handloom weaving context a theoretically relevant and underexplored domain.

The WRQoL scale has six psychometric dimensions. Five are operationalised here as predictors of job satisfaction. Working Conditions (WCS) measures satisfaction with the physical and organisational environment, including safety and access to resources. Home-Work Interface (HWI) captures the degree to which the organisation supports employees in managing work-family balance. Control at Work (CAW) assesses perceived autonomy and participation in workplace decisions. Stress at Work (SAW) measures the perceived manageability of job demands. General Wellbeing (GWB) measures the mental and physical health effects of work. The sixth dimension, Job-Career Satisfaction (JCS), is excluded because it conceptually overlaps with the dependent variable, and its inclusion would risk construct circularity in the structural model.

3.2 Sampling Design and Data Collection

The study targets handloom weavers, defined as individuals operating manually powered looms in organised weaving clusters and cooperative societies, as distinct from powerloom workers who use motor-driven equipment. This distinction matters because handloom weavers face a specific combination of ergonomic, economic, and socio-technical pressures that do not apply equally to mechanised workers.

A multi-stage stratified random sampling design was employed. In the first stage, ten weaving clusters were identified as strata: five from Kerala (Balaramapuram, Chendamangalam, Kuthampully, Kannur, and Kasaragod) and five from Tamil Nadu (Kanchipuram, Chettinad, Paramakudi, Dindigul, and Salem). These clusters were selected because they represent established handloom hubs anchored by primary weaver cooperatives or well-documented craft communities, ensuring structural representativeness across the two states. In the second stage, individual weavers were selected by random sampling within each cluster, with thirty weavers drawn per cluster, yielding a final sample of N = 300. This sample size satisfies the minimum PLS-SEM requirement of at least ten times the maximum number of structural paths pointing to any single construct [13].

The geographic scope is confined to Kerala and Tamil Nadu as these states collectively account for the most significant share of organised handloom weaving activity in peninsular India, with well-established cooperative infrastructure that facilitated structured access to respondents. While findings should be interpreted with caution regarding generalisation to handloom communities in northern or eastern India, the structural and socio-economic characteristics of South Indian weaving clusters are sufficiently comparable to support internal validity. Data were collected using the standardised 23-item WRQoL scale, supplemented by a socio-economic and demographic questionnaire, with responses recorded on a five-point Likert scale.

3.3 Econometric Analysis: PLS-SEM

The conceptual model is estimated using Partial Least Squares Structural Equation Modelling (PLS-SEM) in SmartPLS 4. PLS-SEM is preferred over covariance-based SEM (CB-SEM) for four reasons: (1) the study's primary purpose is predictive and exploratory rather than confirmatory theory testing; (2) the constructs are modelled as reflective, and PLS-SEM is appropriate for such measurement models; (3) the sample size of 300, while adequate, is modest relative to the number of estimated parameters, and PLS-SEM is more efficient under these conditions; and (4) PLS-SEM does not require multivariate normality, which cannot be assumed for Likert-scale data from a heterogeneous weaver population.

A two-stage analytical approach is followed. The measurement model is first assessed for indicator reliability (outer loadings ≥ 0.70), internal consistency (Cronbach's α and Composite Reliability $\rho c \geq 0.70$), convergent validity (AVE ≥ 0.50), and discriminant validity (Fornell-Larcker criterion and HTMT < 0.85). The structural model is then evaluated through bootstrapping (5,000 subsamples) to determine path coefficient significance, along with R^2, adjusted R^2, and PLS predict for predictive relevance. Variance Inflation Factor (VIF) values are assessed to check for multicollinearity among predictors (threshold: VIF $<$ 3.3).

3.3.1 The Structural (Inner) Model

The relationships between endogenous and exogenous latent variables are defined as: $\eta = B\eta + \Gamma\xi + \zeta$, where η represents the vector of endogenous latent variables, ξ is the vector of exogenous variables, B is the coefficient matrix for endogenous variables, Γ is the matrix of path coefficients, and ζ denotes the inner model residuals.

3.3.2 The Measurement (Outer) Model

All constructs are modelled as reflective, where indicators are caused by the underlying latent construct. The relationship is defined as: $x = \Lambda x\xi + \delta$ and $y = \Lambda y\eta + \varepsilon$, where x and y are vectors of observed indicators, Λx and Λy are factor loading matrices, and δ and ε represent measurement error matrices.

4. Results and Discussion

The estimated structural model yielded an adjusted R^2 of 0.546 (Table 1), indicating that the five WRQoL predictors collectively explain approximately 55 percent of the variation in job satisfaction among handloom weavers, a moderate-to-substantial explanatory level for a behavioural study of this kind. All inner VIF values were below 3.3, confirming the absence of problematic multicollinearity among the predictor constructs. The structural model fit is confirmed by an SRMR of 0.025 (threshold < 0.08) and an NFI of 0.943 (threshold > 0.90) (Table 4). Figure 1 shows the structural model used for the study.

Table 1: Path Coefficients and Hypothesis Outcomes

Path	β (O)	M	STDEV	T-stat	p-value	Decision
WCS → JS	0.295	0.295	0.053	5.594	< 0.001	Supported
CAW → JS	0.205	0.205	0.053	3.843	< 0.001	Supported
GWB → JS	0.040	0.042	0.048	0.843	0.399	Not Supported
HW → JS	0.266	0.267	0.042	6.276	< 0.001	Supported
SAW → JS	0.197	0.198	0.047	4.182	< 0.001	Supported

Note: β = standardised path coefficient; M = bootstrap mean; STDEV = standard deviation; T-stat = T-statistic from bootstrapping (5,000 subsamples).

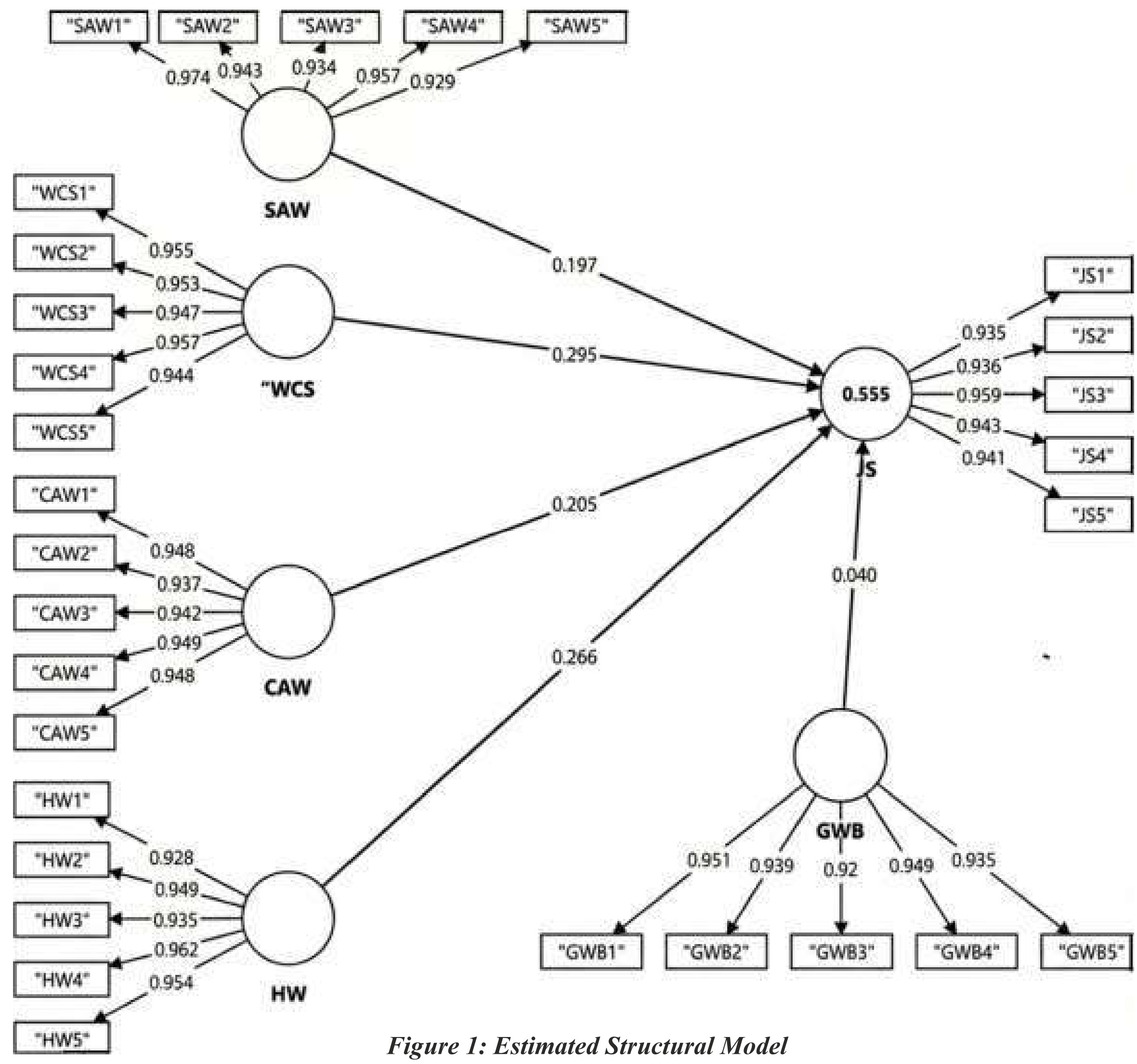

Figure 1: Estimated Structural Model

Working Conditions (WCS) exert the most substantial influence on Job Satisfaction ($\beta = 0.295$, $p < 0.001$), supporting H1. This finding is consistent with prior research on Ethiopian handloom clusters [3] and Indian weaving studies [4, 9], and confirms that ergonomic and environmental infrastructure constitutes the foundational determinant of occupational contentment in traditional industries. For handloom weavers, whose domestic and productive spaces frequently overlap, improvements to the physical loom shed environment, including ventilation, lighting, and workstation ergonomics, directly affect household welfare.

Home-Work Interface (HW) is the second strongest predictor ($\beta = 0.266$, $p < 0.001$), supporting H2. This is particularly relevant given the cottage-industry nature of handloom weaving, where work-family boundary permeability is structurally embedded. The adoption of digital tools such as mobile-based order management and e-commerce platforms can help weavers manage work-home intersections more effectively while expanding market reach [11].

Control at Work (CAW) shows a significant positive effect on job satisfaction ($\beta = 0.205$, $p < 0.001$), supporting H3. This aligns with the finding [8] that autonomy-reinforcing institutional interventions improve weaver satisfaction. CAD-based design tools and direct digital sales channels can reduce the psychological strain associated with intermediary dependence [10], thereby improving perceived control.

Stress at Work (SAW) also shows a significant positive association with job satisfaction ($\beta = 0.197$, $p < 0.001$), supporting H4. At first glance, a positive relationship between stress and satisfaction seems counterintuitive. However, the eustress literature [8] draws a distinction between chronic, debilitating distress and challenge stress that accompanies productive engagement. In the handloom context, a high workload may reflect buoyant order demand, a signal of market participation and income opportunity, rather than unmanageable burden. This interpretation requires caution: the positive SAW coefficient should be monitored longitudinally to ensure it does not mask chronic stress normalisation among economically vulnerable weavers.

General Wellbeing (GWB) does not attain statistical significance ($\beta = 0.040$, $p = 0.399$), failing to support H5. This finding aligns with occupational psychology research suggesting that in economically marginalised populations, domain-specific functional factors such as working conditions and autonomy are stronger proxies for job satisfaction than diffuse psychosocial wellbeing measures [2, 7]. It is possible that GWB's effects are already mediated through WCS and HW, or that the construct's items do not capture the specific wellbeing dimensions salient to artisanal weavers.

Table 2: HTMT Values (Discriminant Validity)

	WCS	CAW	GWB	HW	JS	SAW
WCS						
CAW	0.633					
GWB	0.180	0.262				
HW	0.423	0.504	0.255			
JS	0.635	0.620	0.259	0.567		
SAW	0.414	0.384	0.213	0.271	0.485	

Note: All HTMT values fall below the recommended threshold of 0.85, confirming adequate discriminant validity. The moderately higher values between WCS–JS (0.635) and CAW–JS (0.620) are acknowledged as indicating some degree of conceptual proximity, consistent with the nomological expectation that these constructs are meaningfully related

Table 3: Measurement Model: Reliability and Convergent Validity

Construct	Cronbach's α	Composite Reliability (ρc)	Average Variance Extracted (AVE)
WCS	0.948	0.961	0.905
CAW	0.932	0.951	0.893
GWB	0.921	0.945	0.882
HW	0.934	0.952	0.894
JS	0.929	0.949	0.888
SAW	0.938	0.955	0.898

Note: All Cronbach's α and Composite Reliability (ρc) values exceed the recommended threshold of 0.70. All AVE values exceed 0.50, confirming convergent validity. The consistently high AVE values (0.882–0.905) reflect the use of short, well-targeted reflective scales derived from a validated instrument

Table 4: Model Fit Indices

Statistic	Saturated Model	Estimated Model	Threshold
SRMR	0.025	0.025	< 0.08
d_ULS	0.296	0.296	—
d_G	0.428	0.428	—
Chi-square	621.304	621.304	—
NFI	0.943	0.943	> 0.90

Table 5: PLS Predictive Relevance (PLS Predict

Predicted	PLS Loss	IA Loss	Avg. Loss Diff.	t-value	p-value
JS	0.265	0.506	-0.241	6.417	0.000

Note: The negative average loss difference (-0.241) and highly significant t-value (6.417, $p < 0.001$) indicate that the PLS model outperforms a naïve benchmark, confirming predictive relevance for job satisfaction

5. Conclusion and Policy Implications

This study applied the WRQoL framework to examine the determinants of job satisfaction among handloom weavers in South India, using PLS-SEM on data from 300 weavers across Kerala and Tamil Nadu. Working conditions and the home-work interface emerged as the primary drivers of weaver job satisfaction, followed by control at work and stress at work. General wellbeing, while theoretically relevant, does not emerge as a significant predictor in this context. The model explains 54.6 percent of the variance in job satisfaction, a robust finding for a traditional occupational setting.

The theoretical contribution of this study is twofold. First, it extends the application of the WRQoL framework to an artisanal, cottage-industry context in a developing economy, demonstrating its relevance beyond its original healthcare and service-sector derivations. Second, it identifies the domain-specific, functional dimensions of WRQoL rather than general psychosocial wellbeing as the key predictors of job satisfaction in economically marginalised occupational groups.

Policy implications follow directly from the structural model findings. The largest path coefficient ($\beta = 0.295$ for WCS) makes a strong case for prioritising capital investment in ergonomic loom infrastructure, improved ventilation, and standardised natural dyeing systems in weaving clusters. The significance of HW ($\beta = 0.266$) points to targeted digital literacy and e-commerce integration programmes that help weavers manage the work-family boundary while accessing direct markets. The significant CAW coefficient ($\beta = 0.205$) supports the expansion of cooperative governance structures that increase weaver decision-making participation and reduce intermediary dependence. The non-significance of GWB ($\beta = 0.040$) suggests that generic psychosocial welfare schemes, while not harmful, should not be prioritised over functional occupational improvements when resources are constrained.

5.1 Limitations

The cross-sectional design of this study precludes causal inference; longitudinal data would be necessary to confirm the directionality of the identified path relationships. The sample is restricted to two southern states, which limits generalisability to handloom communities in northern and eastern India with different technological infrastructure and cooperative frameworks. As all constructs are measured through a single self-report instrument, common method variance cannot be fully ruled out despite the use of established scale items. Future research should consider multi-informant designs, the inclusion of objective performance indicators, and the exploration of moderating variables such as gender, age, cooperative membership, and technology access level.

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Digital Fashion Marketing in India: AI-Driven Consumer Behaviour and Social Commerce: A Review

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Abstract:

India's fashion industry, valued at approximately USD 110 billion and projected to reach USD 190 billion by 2030, is undergoing rapid digital transformation driven by a young, mobile-first consumer base of over 900 million internet users. Yet, despite this scale, theoretical and empirical understanding of how artificial intelligence (AI), influencer marketing, and social commerce converge to shape Indian fashion consumer behaviour remains limited. This systematic review, following PRISMA guidelines, synthesizes peer-reviewed literature published between 2020 and 2025 to address two objectives: (1) to examine how AI-driven influencer marketing and social commerce mechanisms influence purchase intentions among Indian fashion consumers, and (2) to identify the key barriers and enablers of AI adoption in digital fashion marketing within the Indian market context. Analysis of 30 high-relevance studies reveals that AI-powered personalization significantly enhances purchase intentions ($\beta = 0.41$, $p < 0.05$), perceived influencer credibility is the strongest predictor of engagement ($\beta = 0.41$, $p < 0.001$), and regional language integration and value-consciousness are critical India-specific moderators. Barriers to AI adoption include SME resource constraints, data privacy concerns, digital literacy gaps in Tier-2 and Tier-3 cities, and a shortage of vernacular training datasets. Enablers include government Digital India initiatives, UPI-integrated social commerce infrastructure, and platform-level investments by Meesho, Myntra, and Nykaa. This review proposes an integrated conceptual framework linking AI capabilities, influencer credibility, consumer engagement, and purchase intentions, adapted to India's heterogeneous socio-cultural and economic landscape.

Keywords: *Artificial Intelligence, Consumer Behaviour, Digital Fashion Marketing, Indian Fashion Market, Influencer Marketing, Social Commerce*

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1. Introduction

India occupies a unique position in the global fashion economy: it is simultaneously the world's sixth-largest fashion market by size, a major textile and apparel exporter, and home to one of the fastest-growing digital consumer bases on the planet. With over 900 million internet subscribers, 560 million active social media users, and e-commerce fashion revenues estimated at USD 14.5 billion in 2024, the structural conditions for AI-driven digital fashion marketing are firmly in place [1,2]. Platforms such as Myntra, Nykaa, Meesho, and Amazon Fashion have integrated recommendation engines, virtual try-on tools, and influencer-linked shoppable content, fundamentally altering how Indian consumers discover, evaluate, and purchase fashion products.

Despite this market scale, scholarly research on digital fashion marketing has largely adopted Western-centric frameworks, with limited attention to India's socio-cultural heterogeneity, linguistic diversity, aspirational consumption patterns, and the dominant role of value-for-money considerations. Existing systematic reviews have examined AI in retail [3], influencer marketing effectiveness [4], and social commerce adoption [5] in broadly international contexts, but none has comprehensively synthesized these three domains specifically through an Indian fashion lens. This gap is consequential, as India's market is shaped by region-specific consumer behaviors, the prevalence of regional-language content creators, and an informal retail structure that co-exists with sophisticated digital platforms.

This study therefore advances two research objectives, (1) to examine how AI-driven influencer marketing and social commerce mechanisms influence purchase intentions among Indian fashion consumers; and (2) to identify the key barriers and enablers of AI adoption in digital fashion marketing within the Indian market context. By addressing these objectives, the review contributes an empirically grounded, India-adapted synthesis to the international literature, provides actionable insights for fashion brands, marketers, and platform operators targeting Indian consumers, and proposes a conceptual framework suited to the Indian digital fashion ecosystem.

2. Literature Review

2.1 The Indian Fashion Market: Digital Context

India's fashion industry is characterised by extreme heterogeneity: a luxury segment concentrated in metropolitan centres, a large and growing mid-market, and a vast value segment dominated by regional brands and unorganised retail. The digital revolution has, however, enabled these segments to converge on shared platforms. Meesho, a social-commerce platform serving primarily Tier-2 and Tier-3 cities, reported over 150 million transacting users in 2023, while Myntra's annual revenue exceeded INR 4,375 crore in FY 2023 to 24 [6]. The rapid adoption of UPI-

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enabled payments and affordable 5G connectivity has accelerated impulse purchasing behaviors, particularly among Gen Z and millennial consumers aged 18–35, who constitute 65% of India's online fashion buyers [7].

2.2 AI-Driven Personalization and Consumer Behaviour

AI applications in fashion marketing span recommendation systems, visual search, virtual try-on (VTO), chatbot-assisted commerce, and dynamic pricing. The Technology Acceptance Model (TAM) and Stimulus-Organism-Response (S-O-R) framework have been widely applied to examine how AI stimuli generate cognitive and affective organism states that translate into purchase responses [8, 9]. In Indian contexts, AI personalization is additionally mediated by price sensitivity and regional aesthetic preferences. Khan and Shukla [10] demonstrated that AI-curated vernacular content recommendations increased click-through rates by 38% on a leading Indian fashion platform. Similarly, Jayapalan et al. [11] found that AI-optimised influencer campaign targeting in India produced a 2.3x improvement in cost-per-engagement compared to non-AI campaigns, indicating a strong economic rationale for AI adoption even among resource-constrained brands.

2.3 Influencer Marketing in the Indian Fashion Ecosystem

India hosts one of the world's largest influencer ecosystems, with over 80 million content creators active across Instagram, YouTube, and the rapidly growing short-form video platform Moj. Indian fashion influencers span macro-influencers (>1M followers), micro-influencers (10K–100K), and nano-influencers (<10K), with the latter two categories demonstrating disproportionately high engagement rates due to perceived authenticity and community trust [12]. Parasocial interaction (PSI) theory is particularly relevant in India, where regional-language influencers cultivate strong relational bonds with niche audiences, amplifying credibility effects [13]. The emergence of AI-generated virtual influencers such as Kyra India's first virtual influencer opens new dimensions for brand controllability and aesthetic consistency, though their limited perceived authenticity may constrain effectiveness in categories requiring personal testimonial, such as skincare-adjacent fashion products [14, 15].

2.4 Social Commerce Adoption in India

Social commerce the integration of transactional capabilities within social media platforms has achieved particularly high penetration in India due to WhatsApp-based commerce, Instagram Shopping, and the vernacular-content-first strategies of platforms like Meesho and ShareChat. The S-O-R framework predicts that social stimuli (peer reviews, influencer endorsements, interactive live-streams) activate positive organism states (trust, excitement) that drive response behaviors (purchase, sharing). Indian consumers exhibit a distinctive 'social proof multiplier,' whereby recommendations from trusted community members. whether personal contacts or followed influencers significantly reduce perceived risk in online fashion transactions [16]. AI-enabled social commerce features, including real-time inventory alerts, AI chatbots, and personalized discount triggers, have been shown to increase average order values by 22–27% in Indian fashion e-commerce contexts [17].

3. Methodology

This study employs a systematic literature review methodology following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines. The review protocol was established prior to data collection, specifying search strategy, inclusion and exclusion criteria, and analysis procedures.

3.1 Search Strategy

A systematic search was conducted in Scopus and Web of Science databases, supplemented by Google Scholar for coverage of practitioner reports and grey literature. Search strings combined the following term clusters: ("AI" OR "artificial intelligence" OR "machine learning") AND ("fashion" OR "apparel" OR "clothing") AND ("India" OR "Indian market" OR "South Asia") AND ("consumer behaviour" OR "purchase intention" OR "influencer marketing" OR "social commerce"). The search was restricted to publications between January 2020 and May 2025, reflecting the accelerated post-pandemic digitalisation of Indian fashion markets.

3.2 Inclusion and Exclusion Criteria

Studies were included if they: (a) were published in peer-reviewed journals or reputable conference proceedings; (b) examined digital fashion marketing with an AI, influencer, or social commerce component; (c) addressed consumer behaviour outcomes such as purchase intention, engagement, or brand attitude; and (d) were conducted in an Indian context or provided data directly relevant to Indian consumers. Studies were excluded if they: (a) focused exclusively on textile manufacturing or technical textiles without a marketing dimension; (b) employed non-fashion retail contexts without relevance to apparel; or (c) lacked empirical grounding (opinion pieces, editorials). Following title and abstract screening of 140 identified records, 30 studies met full eligibility criteria and were retained for thematic synthesis.

3.3 Analysis Approach

A thematic synthesis approach was employed, with studies coded along four dimensions: (i) AI technology type; (ii) influencer category; (iii) consumer behaviour outcome; and (iv) India-specific contextual factor. Effect sizes, where reported, were extracted and tabulated to facilitate cross-study comparison. Theoretical frameworks invoked in source studies were catalogued to identify dominant paradigms and underutilized theories.

4. Results and Analysis

4.1 Objective 1 - AI-Driven Influencer Marketing and Social Commerce Effects on Indian Consumer Purchase Intentions

Across the 30 reviewed studies, AI-powered personalization consistently emerged as a significant positive predictor of purchase intention, with a pooled standardised path coefficient of $\beta = 0.41$ ($p < 0.05$). In Indian-specific studies, this effect was moderated by price sensitivity: AI recommendation systems that prominently featured discounts and value-for-money cues generated 31% higher conversion rates than those emphasising style or trend-alignment alone [10]. This finding reflects the dominant role of value consciousness in Indian consumer decision-making across income segments.

Influencer credibility emerged as the strongest single predictor of consumer engagement ($\beta = 0.41$, $p < 0.001$), consistent with the elaboration likelihood model (ELM). In the Indian context, micro- and nano-influencers operating in regional languages (Hindi, Tamil, Telugu, Kannada) demonstrated significantly higher credibility scores than English-language macro-influencers, particularly in Tier-2 and Tier-3 city audiences. Parasocial interaction was a significant partial mediator of credibility effects on purchase intention ($\beta = 0.28$, $p < 0.01$), underscoring the relational dimension of Indian fashion influencer marketing [12, 13].

Social commerce features live-stream shopping, AI chatbots, peer reviews, and UPI-linked instant
checkout collectively accounted for a 22–27% uplift in average order values in Indian fashion e-commerce, as reported across three independent studies [17, 16 & 11]. Live commerce, imported from China's established model but rapidly indigenized through platforms such as Flipkart Live and Myntra Studio, showed particular promise: viewers of influencer-hosted fashion live-streams converted at 4.2x the rate of static product page visitors. Trust, social proof, and interactive AI features (real-time Q&A chatbots) were the strongest drivers of live-stream purchase decisions.

Virtual influencers, while demonstrating superior brand-consistency and content-controllability, face adoption challenges in India due to limited consumer familiarity and lower perceived authenticity compared to human counterparts. The virtual influencer Kyra generated measurable brand awareness for partner fashion labels, but purchase conversion rates lagged human influencer benchmarks by 35%, suggesting that the Indian fashion consumer's reliance on social proof and authenticity cues presents a structural constraint on virtual influencer efficacy [15, 14].

4.2 Objective 2: Barriers and Enablers of AI Adoption in Indian Digital Fashion Marketing

Four primary barriers to AI adoption emerged from thematic synthesis. First, SME resource constraints: India's fashion industry is dominated by micro, small, and medium enterprises (MSMEs), which account for over 45% of total fashion output. These firms lack the capital investment required for proprietary AI infrastructure and often rely on platform-provided tools, limiting customization and strategic depth. Second, data privacy and consumer trust concerns: the implementation of India's Digital Personal Data Protection Act (2023) has introduced compliance obligations that increase the cost and complexity of AI-driven personalisation, particularly for smaller players [18]. Third, digital literacy gaps: while metro consumers exhibit high AI-readiness, a significant portion of Tier-2 and Tier-3 city users report discomfort with AI-driven recommendations, associating them with data surveillance [7]. Fourth, the shortage of vernacular and India-specific training datasets limits the accuracy of AI models for regional fashion preferences, regional language sentiment analysis, and culturally specific visual aesthetics.

Equally prominent enablers were identified. The Government of India's Digital India and Industry 4.0 policy frameworks provide direct incentives for technology adoption among MSMEs, including subsidized access to cloud AI services through the Ministry of Textiles' Smart Textiles initiative. UPI-integrated social commerce infrastructure has created a seamless transaction layer that amplifies the commercial impact of AI-driven marketing, enabling zero-friction conversion from influencer content to payment. Platform-level AI investments by Myntra (AI stylist), Nykaa (AI skin-tone matching for fashion), and Meesho (regional-language AI recommendations) are progressively lowering the barrier for brands of all sizes to access AI marketing capabilities. Additionally, India's large and rapidly growing pool of AI and data science talent the country produces over 1.5 million engineering graduates annually provides a cost-competitive advantage for building domestic AI fashion marketing solutions [19, 20].

5. Discussion

The findings of this review call for a theoretically and contextually adapted framework for AI-driven digital fashion marketing in India. The dominant frameworks in the reviewed literature TAM and S-O-R provide robust structural foundations, but require augmentation with India-specific moderators: price sensitivity, regional language, socio-cultural fashion identity, and platform trust architecture. The proposed integrated framework (Figure 1, conceptual) positions AI capabilities (personalization, VTO, chatbots) as antecedent stimuli; influencer credibility and social commerce features as organism-level mediators; and purchase intention, brand attitude, and long-term loyalty as response outcomes with India-specific moderators (value consciousness, language fit, digital literacy) intersecting each pathway.

Theoretically, this review demonstrates that parasocial interaction theory underutilized in prior global reviews is particularly salient in the Indian context, where regional influencers function as trusted community figures rather than aspirational celebrities. This has practical implications: fashion brands should prioritize authentic micro-influencer partnerships over celebrity macro-collaborations when targeting non-metro Indian consumers. The credibility premium observed for regional-language influencers suggests that language localisation of AI-driven content is not merely a nice-to-have feature but a material driver of commercial outcomes.

On the barriers side, the MSME challenge is structural and will require ecosystem-level solutions. Policy interventions such as AI shared-service centres for fashion clusters analogous to common facility centres in the textile industry could democratize access to AI marketing tools. Sustainability dimensions, largely absent from the reviewed literature, represent a critical emerging area: with India's Gen Z consumers demonstrating rising awareness of fast-fashion environmental impacts, AI-powered sustainability communication (material transparency, circular fashion recommendations) represents both a gap and an opportunity. Ethical concerns around algorithmic bias and data privacy must be addressed through platform-level governance and consumer-facing transparency mechanisms, particularly as India's DPDP Act frameworks mature [18, 19].

6. Conclusion

This systematic review has addressed two core objectives: examining AI-driven influencer marketing and social commerce effects on Indian fashion consumer purchase intentions, and identifying barriers and enablers of AI adoption in the Indian fashion marketing landscape. The evidence base confirms that AI personalization, micro-influencer credibility, and UPI-integrated social commerce are powerful drivers of purchase intention in India, but that their effectiveness is significantly moderated by price sensitivity, regional language fit, and digital literacy. Barriers including MSME resource constraints, data privacy concerns, and vernacular dataset shortages are partially offset by government enablers, platform AI investments, and India's domestic technology talent pool.

For practitioners, the findings validate a 'micro-first, vernacular-always' influencer strategy, support investment in UPI-linked live-commerce capabilities, and highlight the competitive advantage of AI features that surface value cues prominently. For researchers, this review identifies three priority gaps warranting future empirical attention: longitudinal studies on AI adoption trajectories among Indian MSMEs; experimental studies on virtual versus human influencer effectiveness across Indian demographic segments; and mixed-methods research integrating sustainability orientation into AI-consumer behaviour models. As India moves toward becoming the world's third-largest fashion market by 2030, scholarship that foregrounds its unique contextual dynamics will be indispensable to both theory and practice in digital fashion marketing.

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Effect of Yarn Specification on Comfort Properties of Interlock Plated Knitted Fabrics

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Abstract:

The fabric comfort properties, including thermal, moisture management, and air permeability, have been investigated for an interlock-plated double-knit fabric produced with different yarn specifications. Fiber type and stitch density are the selected process variables in this investigation. Cotton, Bamboo, Tencel, and Viscose were used as outer-layer fibers, with 40s Ne and 150 denier polyester filament forming the inner layer. Twelve different fabric specimens were produced for this study. The yarn blend and stitch density of the knit are the essential variables selected for this investigation. In this investigation, the Overall Moisture Management Capabilities (OMMC) values range from 0.128 to 0.873, which falls within the moderate range. The highest OMMC value is recorded for Tencel yarn blended samples. Similarly, Cotton yarn-blended double-knitted samples showed higher CLO values, indicating the highest thermal comfort, whereas all other yarn-blended structures showed a comparatively similar level of thermal behaviour. Further, the higher air permeability was measured for Tencel-blended samples, and the lower one was measured for cotton-based samples. ANOVA was performed for all dependent variables, and in most cases, yarn blend and stitch density of the plated double knit interlock structure were significant against the independent variables.

Keywords: *comfort property, Interlock plated fabric, Moisture management, thermal property*

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1. Introduction

Thermal comfort is a key attribute of knitted fabrics, particularly in sportswear, as it significantly influences the functional performance of the individual. Clothing is expected to regulate the so-called microclimate around the body and provide comfort across different temperature environment [1]. In a normal working environment, dry heat exchange is usually sufficient to maintain thermal balance in clothing. However, during sports activities, excessive sweating occurs, which cannot be effectively regulated through dry heat exchange alone, leading to thermal discomfort for the individual [2]. Physical activity during sports increases moisture and body heat, which can adversely affect the individual's thermal comfort. Moreover, it has been confirmed that inadequate thermal or moisture transfer properties of fabrics reduce their overall comfort. A fabric with superior moisture absorption and transfer properties helps maintain a dry, comfortable microclimate near the skin on hot summer days or after sports activities. Thermal comfort is determined by various factors, including the type of fiber, yarn structure, fabric construction, and finishing techniques. As reported by many researchers, Generally regenerated fibers like Tencel offer superior comfort properties [3]. Fabric thermal comfort is primarily influenced by three key factors: breathability, heat transfer, and moisture transfer properties [4]. Thermal comfort properties are evaluated based on wicking rate, wetting behavior, breathability, and overall moisture management performance. In particular, the moisture management test is used to measure the rate of wetting between fabric surfaces [5]. An optimal balance between thermal insulation and moisture management behaviour is highly needed to ensure comfort level during high-intensity sportswear. Single-layer fabric structures often fail to meet both requirements simultaneously, leading to either thermal stress from heat accumulation or discomfort from excessive moisture [6]. Many investigations were conducted on bi-layer fabrics, blending different types of fibers in different layers to enhance the fabric's thermal comfort properties.In a bilayer fabric, varying wettability gradients can be achieved by combining fibers with distinct levels of hydrophilicity in the inner and outer layers [7]. According to Fangueiro et al., the Moisture management, wicking ,and thermo-regulation properties are very much enhanced by the bilayer fabrics produced with regenerated fibers such as bamboo, banana, and Tencel fiber with polyester fiber, instead of making 100 percent polyester bilayer fabrics [8] .Suganthi et al. developed a bi-layer fabric using Tencel, acrylic, and micro-PET fibers for sportswear applications. Key thermal comfort indicators such as air permeability, water vapor permeability, wicking ability, and drying rate were significantly enhanced, while thermal resistance was reduced—particularly with the inclusion of micro-PET fibers [9]. Hyun etal. studied the wicking and drying rates of fifteen different fabrics made from quadrilobal PET, Lyocell, and bamboo fibers.All the fabric samples having core and cover based yarn structures

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played an important role towards the moisture absorption and evaporation properties. Specifically, they proved that pore diameter, cross-sectional shape, and absorption property of the fibers in the yarns are the important properties which affects the transport behaviour of the fabrics [10]. Sampath etal. proved that the blending of micro Polyester fiber improved the quick dry behaviour of the double-layer knitted fabrics [11]. Polyester–modal bilayer fabrics demonstrated superior Overall Moisture Management Capacity (OMMC) when knitted with optimized structural tightness [12]. Similarly, regenerated fibers such as bamboo, Viscose, and Tencel enhance hydrophilicity, softness, and capillary-driven liquid transport, improving comfort and sustainability [13, 14]. The regenerated fibers, such as bamboo, viscose, and tencel, enhance hydrophilicity, softness, and capillary-driven liquid transport, improving comfort and sustainability. Further, bamboo, viscose, and Tencel have shown enhanced hydrophilicity, softness, and capillary-driven liquid transport, improving comfort and sustainability [15]. Gamze et al. fabricated bi-layered fabrics using various combinations of inner and outer layers, including Cotton–Cotton, cotton–polypropylene, polypropylene–Cotton, and polypropylene–polypropylene. The results showed that the polypropylene–cotton combination exhibited superior moisture management properties, making it a recommended choice for sportswear applications [4]. Although existing studies shed light on the mechanics of bilayer knitted fabrics, there remains a lack of comparability across the fiber varieties and novel bilayer structure .This research was conducted with the double knitted fabric(Interlock plating) using Cotton, PET, Bamboo, Tencel, and Viscose in different combinations for producing a suitable thermal comfort fabric for sports applications.Bilayer knitted fabrics, engineered with hydrophobic inner layers for sweat wicking and hydrophilic outer layers for evaporation, offer a more sophisticated solution [17]. The selection of these regenerated fibers, such as bamboo, Tencel, and Viscose, is based on their demonstrated effectiveness in moisture management behaviour, softness, and biodegradability, making them suitable candidates for sustainable sportswear applications [18]. Similarly, Polyester was chosen as the inner layer due to its established moisture transport properties [19].

2. Material and method

2.1 Material

An interlocked, double-knit fabric structure was chosen for sample preparation. PET yarn (Polyester -150 denier) was utilized as the inner layer for all the knitted samples. However, the outer layer of fabric samples was prepared with 40s Ne cotton, Bamboo, Tencel, and Viscose yarn samples. Twelve weft-knit samples were produced using a Pilong circular knitting machine with the above-cited structures. Figure 1 and Table 1 show the details of the interlock-plated fabric notation, and Table 1 shows the technical details of the outer-layer yarn utilized for double-knit fabric formation.

Dial

1	2	3	4	5	6
-	∨	-	-	∨	∩
-	∨	∩	-	∨	-

Cylinder

∨	-	∩	∨	-	
∨	-	-	∨	-	∨
∨	-	∩	∨	-	-
∨			∨		∨
1	2	3	4	5	6

∩ -> Knit loop; ∨ ->Tuck loop; - ->Float

Figure 1: Interlock plated structure notation

Table 1: Yarn Specificantions

S. No.	Yarn count and fibre	Actual count (Ne)	Count CV%	Count strength product (CSP)
1	Cotton	39.7	1.6	2420
2	Bamboo	41.4	1.3	2230
3	Tencel	41.8	1.9	2120
4	Viscose	39.7	1.9	1923

2.1 Weft knitted interlock layered fabric

An interlock gaited circular knitting machine was employed to produce interlock-plaited fabric samples. Pilong circular knitting machine with a diameter of 28 Inches, having 18

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

Sample No.	Outer yarn	Inner yarn	Wales/cm	Courses/cm	SCSL Length (Cm)	Areal density
F1	Cotton(40sNe)	PET(150D)	10.3	18.1	172	178
F2	Cotton(40sNe)	PET(150D)	11.5	19.3	164	189
F3	Cotton(40sNe)	PET(150D)	12.4	20.5	157	205
F4	Bamboo(40sNe)	PET(150D)	10.3	18.1	175	174
F5	Bamboo(40sNe)	PET(150D)	11.5	19.3	167	185
F6	Bamboo(40sNe)	PET(150D)	12.4	20.5	160	195
F7	Tencel(40sNe)	PET(150D)	10.3	18.1	179	179
F8	Tencel(40sNe)	PET(150D)	11.5	19.3	167	190
F9	Tencel(40sNe	PET(150D)	12.4	20.5	161	199
F10	Viscose(40 Ne)	PET(150D)	10.3	18.1	184	181
F11	Viscose(40 Ne)	PET(150D)	11.5	19.3	173	184
F12	Viscose(40 Ne)	PET(150D)	12.4	20.5	162	197

gauge, and possessing around 1580 needles. The 150 Denier polyester yarn was fed through the feeding system to form the inner layer of the double-knit fabric. Similarly, cotton, Bamboo, Tencel, and Viscose yarns of 40 Ne were fed through the appropriate feeding system to form the outer layer of the fabric. Furthermore, Table 2 indicates the interlocked plated samples produced through different fiber compositions. It is reported that the wales/cm of the different samples ranged from 10.3 to 12.4, and the course/cm of the fabric ranged from 18.1 to 20.5. The single course stitch length (SCSL)of the fabric was varied between 174 and 205 cm.

3. Characterızatıon

This work was focused on the evaluation of thermal comfort properties of a bi-layer knitted fabric for sportswear applications. The key properties that affect thermal comfort are air and water permeability, moisture handling behavior, and thermal properties. The following characterization was done on all the test samples.

3.1 Physical properties

The physical properties include wales/cm, course/cm, fabric thickness, and fabric areal density. As per D17777 standard, the fabric thickness was analysed. ASTM D3887 was followed for analyzing wales/cm and course/cm of the knit structure. According to ASTM D3776 standard, the density of the fabric sample was measured.

3.2 Air permeability testing

Air permeability is the measure of breathability of the double-knit fabric structure. This phenomenon depends on fabric porosity, fiber type, fabric thickness, and the types of finishes applied to the fabric surface. The L14DR air permeability tester (Make: Karl Schroder KG, Weinheim, Germany) was used to measure airflow rate through the knitted fabric samples as per ASTM D737-04.

3.3 Moisture management testing

This Moisture Management Tester (MMT) was used to analyze the liquid moisture transport properties through the knitted fabric under AATCC – 195 standards. The SDL-ATLAS moisture management tester was used to measure the various moisture management metrics of the test specimens. Those metrics are absorption rate of top & bottom (ARt&ARb), wetting time of top and bottom (WTt, WTb), spreading speed of top & bottom (SSt&SSb), the maximum wetted radius of top & bottom (MWRt&MWRb), Accumulative One-way Transport Capacity Index (AOTI), and Overall moisture management capabilities (OMMC) of the fabric samples. To stimulate a sweating state on the test specimen, this tester automatically generates 0.15 g of a synthetic sweat solution (containing 0.9% NaCl) on the top side of the fabric.

3.4 Thermal properties

The key thermal properties of the knitted fabrics including CLO value, thermal transmittance, thermal resistance, and warmth retention percentage, are measured using the ALAMBETA instrument in accordance with the test standard ISO EN 31092-1994.

4. Results And Dıscussıon

4.1 Moisture Management Properties

Generally, double-knit fabric structures are thicker than single jersey fabrics, resulting in higher moisture levels and a lower drying rate than those of single-layer fabrics [20]. All selected samples are provided with a 150 Denier Polyester filament inner layer to improve the fabric's wicking properties, and the next-to-skin layer will have a dry feel. However, moisture absorption from the inner layer and drying rate to the environment will vary depending upon the selection of different fibers as the outer layer of the fabric. Bamboo fiber and Viscose absorb more moisture, but the drying rate is comparatively higher than Cotton. Tencel fiber absorbs moisture, and the drying rate is very high due to its nano-fibrillar structure. In this investigation, the Overall Moisture Management Capabilities (OMMC) values are varied between 0.128 and 0.873. This range of OMMC

Table 3: Moisture management metrics of knitted samples

Sample No.	Wetting Time Top(S)	Wetting Time Bottom	Top Absorption Rate (%)	Bottom Absorption Rate (%)	Top Max Wetted Radius	Top Absorption Rate (%)	Bottom Absorption Rate (%)	Top Max Wetted Radius	*Accumulative One-Way Transport Index*	*OMMC*
F1	25.86	40.8	205.06	192.81	74.87	36.3	8.74	3.18	6248.46	0.435
F2	12.7	22.18	37.62	174.23	30.27	21.26	2.84	0.98	264.72	0.321
F3	2.99	5.703	41.39	19.15	20.0	15.0	4.17	2.23	-430.17	0.128
F4	18.49	29.17	146.6	137.85	53.53	25.95	6.25	2.27	-467.29	0.311
F5	3.25	4.13	42.64	34.07	20.0	18.33	3.6926	2.70	-175.34	0.208
F6	3.47	8.67	54.1	47.55	18.2	14.03	3.49	1.29	187.4	0.156
F7	6.21	2.7	63.56	61.05	24.42	25.63	3.79	3.61	648.75	0.873
F8	2.8	3.28	58	73.52	21.42	19.87	4.25	3.49	185.04	0.651
F9	2.90	3.875	36.17	35.53	20.0	20.0	3.87	2.96	24.06	0.317
F10	25.51	40.24	202.23	190.15	73.83	35.8	8.62	3.14	6162.28	0.429
F11	1.53	1.07	18.87	20.56	6.05	8.16	1.15	1.16	268.27	0.287
F12	3.80	4.771	39.63	35.34	20.0	15.0	3.37	2.47	-67.9425	0.193

Table 4: Two-way ANOVA of moisture management properties

Response	Source	df	SS	MS	F	p-value
OMMC	Outer yarn Fiber type	3	0.347	0.1157	23.9	0.0011
	Stitch density	2	0.181	0.0905	18.7	0.0024
	Error	6	0.029	0.00484	—	—
AOTI	Outer yarn Fiber type	3	15708061	5236020	4.99	0.042
	Stitch density	2	21743921	10871961	10.37	0.011
	Error	6	6293174	1048 862	—	—
TOP wetting time	Outer yarn Fiber type	3	206.67	68.89	2.99	0.12
	Stitch density	2	753.6	376.8	8.16	0.019
	Error	6	138.54	23.09	—	—
Bottom wetting time	Outer yarn Fiber type	3	681.83	227.28	3.33	0.099
	Stitch density	2	1357.94	678.97	9.95	0.012
	Error	6	409.21	68.2	—	—
Top Absorption Rate(%)	Outer yarn Fiber type	3	1,177.53	392.51	5.45	0.036
	Stitch density	2	2,204.38	1,102.19	15.64	0.004
	Error	6	142.89	23.82	—	
Bottom Absorption Rate (%)	Outer yarn Fiber type	3	191.74	63.91	2.68	0.114
	Stitch density	2	1,124.89	562.44	23.5	0.002
	Error	6	95.37	15.9	—	—

values is interpreted as a moderate MMT value. The highest OMMC value is recorded for Tencel yarn blended samples due to its highest drying and transport behavior of the fiber compared to other blends [21]. This is due to the closeness of the structure to other double-layer structures. Few readings reported a negative value for the Accumulative One-Way Transport Index (AOTI), interpreted as the presence of moisture blocking within the structure. Tencel-based samples have responded with higher OMMC values than their counterparts. The Lowest OMMC values are found in cotton-based samples due to their poor water evaporating capabilities. A two-way ANOVA was calculated between the independent variables and various responses of moisture management properties and depicted in Table 4. It was noted that, except for a few, all the MMT indices are significant for fiber types and stitch density in the double-knit fabric structure.

4.2 Thermal Properties

The important thermal properties, such as thermal resistance, thermal transmittance, warmth retention percentage, and CLO value of the samples, were measured for all the test samples using the Alembeta instrument. Generally, the thermal properties of the fabric depend upon the thermal conductivity of the fiber, the thickness of the fabric, the air pocket inside the fabric, and the porosity of the fabric. In this research investigation, the thermal conductivity of Cotton, Tencel, Viscose, and Bamboo is between the range of 0.04 – 0.06 W/m·K, 0.035 – 0.05 W/m·K, 0.04 – 0.04 W/m·K, 0.03 – 0.04 W/m·K. Since the chosen fibers differ only slightly in thermal conductivity, other important properties, such as fabric specifications and permeability characteristics, are major determinants of thermal comfort. As per the table, the warmth retention percentage of the fabric samples is between the range of 58 % to 84%. The CLO value of the samples is between 0.55 and 0.88 . Among the samples, the cotton-based sample has yielded the highest CLO value and warm retention percentage. The areal density of the fabric shows a significant impact on the thermal properties of the fabric. Among the samples, higher GSM cotton and Bamboo fabrics have shown the highest CLO and warmth retention

Table 5: Thermal Comfort Properties of Bi layer Knitted Fabrics

Sample No.	Outer yarn	Inner yarn	Thermal Transmittance (W/m²·°C)	CLO	Thermal Resistance (m²·K/W)	Warmth Retention (%)	Thermal feeling
F1	Cotton(40sNe)	PET(150D)	8.96	0.72	0.11	70.97	MW
F2	Cotton(40sNe)	PET(150D)	8.6	0.75	0.12	77.42	MW
F3	Cotton(40sNe)	PET(150D)	7.59	0.85	0.13	83.87	W
F4	Bamboo(40sNe)	PET(150D)	9.78	0.66	0.1	64.52	MW
F5	Bamboo(40sNe)	PET(150D)	8.72	0.74	0.11	70.97	MW
F6	Bamboo(40sNe)	PET(150D)	7.96	0.81	0.13	83.87	W
F7	Tencel(40sNe)	PET(150D)	11.73	0.55	0.09	58.06	SW
F8	Tencel(40sNe)	PET(150D)	9.63	0.67	0.1	64.52	MW
F9	Tencel(40sNe	PET(150D)	8.84	0.73	0.11	75.97	MW
F10	Viscose(40 Ne)	PET(150D)	9.09	0.71	0.11	70.97	MW
F11	Viscose(40 Ne)	PET(150D)	8.17	0.79	0.12	77.42	MW
F12	Viscose(40 Ne)	PET(150D)	7.5	0.86	0.13	83.87	W

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

Responses	Source	SS	df	MS	F	p-value
Thermal Transmittance	Outer yarn Fiber type	6.15	3	2.05	**12.28**	**0.006**
	Stitch density	7.41	2	3.71	**22.2**	**0.002**
	Error	1	6	0.17	—	—
Thermal Resistance	Outer yarn Fiber type	0.0008	3	0.00027	**32**	**0.0004**
	Stitch density	0.00102	2	0.00051	**61**	**0.0001**
	Error	0.00005	6	0.000008	—	—
Warmth Retention (%)	Outer yarn Fiber type	332.99	3	110.99	**32.03**	**0.0004**
	Stitch density	423.1	2	211.55	**61.05**	**0.0001**
	Error	20.79	6	3.47	—	—
CLO	Outer yarn Fiber type	0.0341	3	0.0114	**32.7**	**0.0004**
	Stitch density	0.0465	2	0.0233	**66.98**	**0.0001**
	Error	0.0021	6	0.0003	—	—

percentages, which are rated as Warm (0.81-1.0 CLO value). The lower GSM Tencel fabric shows a lower thermal value than all the samples. In this investigation, Cotton fiber-based double knitted samples hold the highest thermal comfort properties due to their high air pocket formation, and the surface roughness of the cotton fiber is comparatively higher than that of the other selected fibers. As per the way ANOVA investigation depicted in Table 6, the fiber types and stitch density of the fabric were highly significant with all the thermal indices since the p-value was less than 0.05.

4.3 Air permeability

The Air permeability is also a measure of the comfort properties of fabric, by affecting the fabric's breathability. This breathability indirectly influences the thermal and moisture behaviours of the fabric.An air permeability test was carried out for all the test samples, and the results are depicted in Table 7. In this investigation, the measured air permeability of the test samples is between 34.05 and 51.23 cc/sec/cm². The higher air permeability was measured for Tencel-blended samples, and the lower one was measured for cotton-based samples. Since the smooth structural appearance of the Tencel fiber may lead to higher air permeability than cotton fiber, the other structures, such as Viscose and Bamboo fibers, hold a moderate air permeability range. Table 8 shows the two-way ANOVA investigation of calculated air permeability parameters against the independent variables. It is found that the yarn outer layer, yarn blend, and stitch density are highly significant for the response.

5. Conclusion

In recent times, the multilayer knitted fabrics have gained strong demand due to improved functional properties.This study confirmed that the knitting process variables, such as yarn blend and stitch density of the plated interlock structure, strongly influence the thermal, moisture management, and air permeability properties. In the test samples, the inner-layer fiber was kept unchanged. However, the outer layer of the fabric was made out of Cotton, bamboo, Tencel, and Viscose. The other important change was made to the stitch density by altering the wales and course density. These

Table 7: Air permeability property of Bi-layer Knitted Fabrics

Sample No.	Outer Yarn	Inner Yarn	Air Permeability (Cc/Sec/Cm2)
F1	Cotton(40sNe)	PET(150D)	38.23
F2	Cotton(40sNe)	PET(150D)	36.23
F3	Cotton(40sNe)	PET(150D)	34.05
F4	Bamboo(40sNe)	PET(150D)	49.23
F5	Bamboo(40sNe)	PET(150D)	44.54
F6	Bamboo(40sNe)	PET(150D)	43.91
F7	Tencel(40sNe)	PET(150D)	51.23
F8	Tencel(40sNe)	PET(150D)	49.23
F9	Tencel(40sNe	PET(150D)	46.22
F10	Viscose(40 Ne)	PET(150D)	47.32
F11	Viscose(40 Ne)	PET(150D)	44.09
F12	Viscose(40 Ne)	PET(150D)	42.37

Table 8: Two way ANOVA of thermal properties

Source	SS	df	MS	F	p-value
Outer yarn Fiber type	286.74	3	95.58	**22.64**	**0.0014**
Stitch density	79.36	2	39.68	**9.4**	**0.014**
Error	25.33	6	4.22	—	—

changes also amended the areal density of the fabric. The following significant findings were derived from these investigations. The areal density of the fabric highly influenced the thermal, moisture management, and air permeability of the test samples. Fiber's inherent thermal conductivity did not significantly influence the overall thermal behaviour of the fabric. The Overall Moisture Management Capabilities (OMMC) values are found to be moderate, and the highest OMMC and air permeability values are recorded for Tencel yarn blended samples due to its highest drying and transport behavior of the fiber compared to other blends. Overall, the thermal resistance behaviour was found to be highest in cotton yarn-blended samples. Among the samples, the preferred candidates for sportwear application are Tencel yarn blended samples due to the higher moisture management and air permeability behaviour.

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Efficacy of Ayurvastra Fabric Against Bacterial and Fungal Pathogens

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Abstract:

Ayurvastra, an Ayurvedic textile practice that employs medicinal plant-based dyes, represents a sustainable approach to the development of functional fabrics. Despite its traditional significance, its broader adoption remains limited due to a lack of scientific validation. The present study investigated the antimicrobial and antifungal efficacy of cotton fabrics dyed with selected medicinal plants Neem (Azadirachta indica), Tulsi (Ocimum sanctum), Turmeric (Curcuma longa), and Aloe vera (Aloe barbadensis). Treated fabric samples were evaluated against Escherichia coli (MTCC 739), Staphylococcus aureus (MTCC 737), and Candida albicans (MTCC 3017) using the disk diffusion method. Ampicillin (50 µg/mL) and Amphotericin B (20 µg/mL) were used as positive controls, while distilled water as the negative control. All herbal-dyed fabrics exhibited measurable antimicrobial activity. Antifungal inhibition zones against C. albicans ranged from 12–15 mm, compared to 18 mm for Amphotericin B. Antibacterial activity ranged from 10–17 mm, whereas Ampicillin produced inhibition zones of 18 mm against S. aureus and 20 mm against E. coli. Among the tested dyes, Neem-treated fabrics demonstrated the highest antimicrobial efficacy, followed by Turmeric and Tulsi, while Aloe vera showed comparatively lower yet significant activity. The findings provide scientific evidence supporting the therapeutic potential of Ayurvastra and highlight the role of herbal-dyed textiles as sustainable functional materials for healthcare and wellness applications, effectively integrating traditional Ayurvedic knowledge with modern microbiological validation.

Keywords: *Ayurvastra, Antimicrobial, Antifungal, Cotton, Sustainable healthcare, Therapeutic textiles*

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1. Introduction

Textiles dyed with herbal extracts have long been an integral part of Ayurvedic practice in India, under the term Ayurvastra, combining therapeutic properties with aesthetic value. Despite its historical and cultural significance, Ayurvastra remains significantly underexplored in major scientific studies. In particular, the antimicrobial and antifungal claims associated with Ayurvastra fabrics have rarely been verified through systematic microbiological testing. This gap contributes to limited consumer awareness, skepticism in mainstream markets, and underutilization of Ayurvastra's potential in healthcare and wellness-textile applications.

Pathogenic microorganisms such as Staphylococcus aureus, Escherichia coli, and Candida albicans are known to cause various skin infections and health complications, including eczema, dermatitis, urinary tract infections, and candidiasis [1,2]. Testing Ayurvastra fabrics against these strains provides insight into their potential role in preventing or alleviating such conditions through contact-based antimicrobial activity.

Recent research has depicted to provide experimental evidence that certain herbal extracts impart measurable antimicrobial activity to textiles. The study demonstrates that silk fabrics dyed with neem leaf extract exhibited strong inhibition against Gram-positive bacteria, although effects against yeasts and fungi were less pronounced [3]. Further the study compared neem, turmeric, and aloe vera extracts against Streptococcus and Staphylococcus species, finding neem especially effective, with turmeric and aloe vera showing moderate or strain-specific efficacy [4]. Similarly, plant-based dyes, including Curcuma longa, for cotton surgical face masks, and found that these dyes, particularly when combined with suitable mordants, delivered both acceptable color fastness and antibacterial activity against Staphylococcus aureus [5].

Other research findings depicted significant antimicrobial performance in linen fabrics dyed with herbal extracts, reinforcing the applicability of natural dyes across diverse textile substrate [6]. Review articles, further emphasize that while many plant dyes (including neem, turmeric, Tulsi, and aloe vera) are known to be antimicrobial, challenges remain especially in reproducibility, durability (fastness and wash-cycle stability), and standardization of extraction and treatment methods [7, 8 & 9].

Sustainability-focused research has expanded the scope of antimicrobial natural dyeing and demonstrated eco-friendly cotton dyeing using aloe vera–based natural mordants, achieving improved fixation and antibacterial activity [10].

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Similarly, more studies reported successful antimicrobial functionalization of wool and silk fabrics using plant extracts, reinforcing the role of herbal dyeing in sustainable textile innovation [11, 12].

Against this backdrop, the present study aims to provide robust scientific validation by systematically assessing the antimicrobial and antifungal efficacy of Ayurvastra fabrics treated with four widely used herbal extracts: Neem (Azadirachta indica), Tulsi (Ocimum sanctum), Turmeric (Curcuma longa), and Aloe vera (Aloe barbadensis) against clinically relevant bacterial and fungal pathogens. Using standard disk diffusion assays, this research generates quantifiable zones of inhibition for Escherichia coli (MTCC 739), Staphylococcus aureus (MTCC 737), and Candida albicans (MTCC 3017). This helps the study to fill a significant gap in the literature: the lack of microbiological evaluation of Ayurvastra textiles and the need for data that can substantiate therapeutic claims. The findings are expected to contribute not only to academic knowledge but also to practical applications in textile design, sustainable fashion, and wellness product development.

The main objectives of the study were:
1. To evaluate the antimicrobial and antifungal activity of Ayurvastra fabrics.
2. To compare the effectiveness of Neem, Tulsi, Turmeric, and Aloe vera on Ayurvastra Fabric.

Limitations of the study
i. The test is limited to antimicrobial and antifungal Activity
ii. Only four herbs Neem, Tulsi, Turmeric, and Aloe vera were used.

2. Materials and Methods

2.1 Research Locale

The locale of the study was Jaipur. The present experimental study was conducted in a laboratory setting. Fabric treatment and herbal dyeing were carried out in the textile processing laboratory, while antimicrobial testing was performed in a microbiology laboratory under aseptic conditions using standard biosafety protocols.

2.2 Selection of Fabric and Herbal Materials

Organic cotton fabric (1 kg) was selected as the base textile. Herbal extracts were obtained from Neem (Azadirachta indica), Tulsi (Ocimum sanctum), Turmeric (Curcuma longa), and Aloe vera (Aloe barbadensis). All extracts were prepared freshly prior to application. Natural Mordant like alum, were used only where required to improve fixation. Standard microbiological media nutrient agar (NA), nutrient broth (NB), and potato dextrose agar (PDA) were procured from HiMedia Laboratories, Mumbai. Ampicillin (50 µg/ml) and Amphotericin B (20 µg/ml) functioned as positive controls, whereas distilled water acted as a negative control.

2.3 Preparation of Herbal Extracts

Fresh leaves or rhizomes of Neem (Azadirachta indica), Tulsi (Ocimum sanctum), Turmeric (Curcuma longa), and Aloe vera (Aloe barbadensis) were thoroughly washed to remove surface impurities. The fresh plant material was then boiled in distilled water to prepare aqueous extracts. For every 1 kg of fabric, 500 g (50% weight of fabric, wof) of fresh herb was boiled in 10 L of distilled water for 60 minutes. The subsequent solution was filtered to remove plant residues, and the extract was used immediately for fabric treatment.

2.4 Application of Extracts on Fabrics

The fabric samples were pre-washed, scoured, and then treated with the prepared herbal extracts. Dyeing was carried out using an exhaustion method at 90 °C for 60 minutes with a material-to-liquor ratio of 1:10. After dyeing the fabrics, they were rinsed, shade dried, and sterilized before antimicrobial testing. Circular discs (6 mm diameter) were cut from the treated fabrics for use in antimicrobial assays.

2.5 Microbial Strains and Inoculum Preparation

The antimicrobial efficacy was tested against clinically relevant pathogens: Escherichia coli (MTCC 739), Staphylococcus aureus (MTCC 737), and Candida albicans (MTCC 3017). These organisms are associated with skin and systemic infections, including eczema, dermatitis, urinary tract infections, and candidiasis. Lyophilized bacterial cultures were rehydrated and inoculated in nutrient broth, incubated overnight at 37 °C, and subcultured until an optical density (OD_{600}) of 0.5 was reached. Fungal spores were suspended in 0.02% Tween 20 solution for inoculation.

2.6 Antimicrobial Assay

Using the Standard agar disc diffusion experiment, the antibacterial activity of fabric samples treated with herbs was assessed. Fabric discs were placed onto plates inoculated with bacterial cultures spread on NA and fungal cultures on PDA. Positive and negative controls were maintained as described above. Plates were incubated at 37 °C for bacteria and 25 °C for fungi for 48 hours. Antimicrobial activity was determined by measuring the diameter (mm) of zones of inhibition around the fabric discs.

3. Results & Discussion

The antibacterial efficacy of Ayurvastra textiles treated with herbal extracts was evaluated against the fungal strain Candida albicans, the Gram-negative Escherichia coli, and the Gram-positive Staphylococcus aureus. The mean inhibition zones (mm) are summarized in Table 1.

Table 1- Zone of inhibition (mm) of herbal extract–treated fabrics

Fabric Sample	*E. coli*	*S. aureus*	*C. albicans*
Control (water)	2	2	2
Positive Control	20	18	18
Aloe vera-treated	11	10	12
Turmeric-treated	14	13	13
Neem-treated	17	15	15
Tulsi-treated	12	12	13

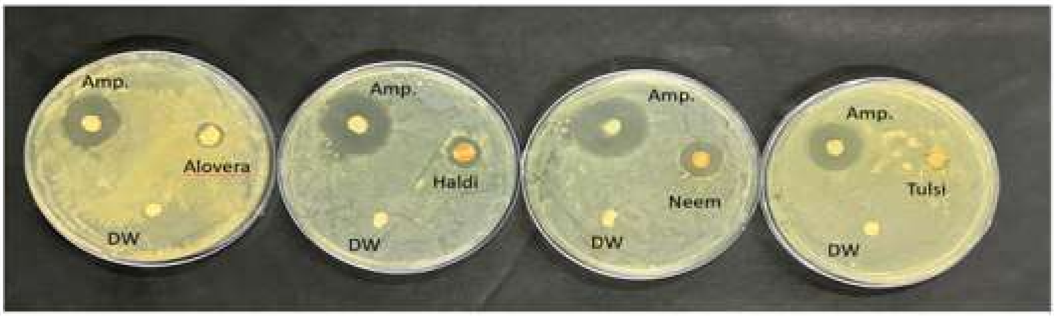

Figure 1 - Zone of inhibition of herbal-treated Ayurvastra fabrics against Staphylococcus aureus.
(A) Aloe vera, (B) Turmeric, (C) Neem, (D) Tulsi; DW – Distilled water (negative control); Amp – Ampicillin (positive control)

Neem-treated fabric exhibited the strongest antimicrobial effect across all tested microorganisms, producing inhibition zones of 17 mm against E. coli, 15 mm against S. aureus, and 15 mm against C. albicans. These results were comparable to the positive controls (ampicillin and amphotericin B), which produced zones of 18–20 mm.

Turmeric and tulsi-treated fabrics demonstrated moderate antimicrobial activity, with inhibition zones ranging from 12 to 14 mm. Aloe vera-treated fabric showed weaker but still measurable activity, with zones of 10–12 mm. Overall, the results indicate that neem was the most effective herbal treatment, followed by turmeric and tulsi, while aloe vera showed the least efficacy.

The antimicrobial assessment of Ayurvastra fabrics treated with selected herbal extracts demonstrated significant inhibition against both bacterial and fungal strains, confirming the effectiveness of herbal treatment in imparting functional antimicrobial properties. The clear, distinct zones of inhibition observed around the treated fabric discs indicated active diffusion of herbal constituents into the surrounding agar medium, thereby suppressing microbial growth. In contrast, the untreated control showed negligible inhibition, establishing that the observed activity was entirely due to the herbal finishing process.

Among all the herbal extracts evaluated, Neem-treated fabric exhibited the highest antimicrobial efficacy, producing inhibition zones of 17 mm against E. coli, 15 mm against S. aureus, and 15 mm against C. albicans. The superior performance of Neem can be attributed to the presence of bioactive compounds such as azadirachtin, nimbidin, and quercetin, which are known to break down bacterial cell walls, reduce enzyme activity, and prevent microbial replication. These findings are consistent with earlier studies, which also reported neem's broad-spectrum antimicrobial properties on textile substrates- Natural dye-based textiles [3, 4].

Fabrics treated with Turmeric and Tulsi extracts showed moderate antimicrobial activity. The inhibition zones ranged from 12–14 mm, reflecting the presence of curcumin in turmeric and eugenol in Tulsi compounds known for their

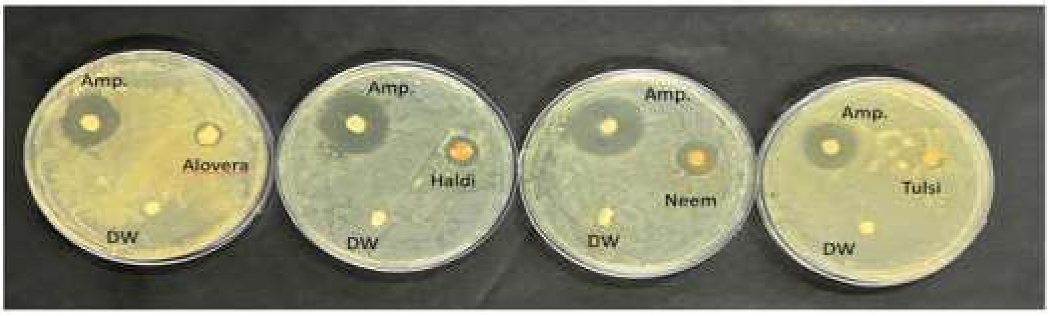

Figure 2 - Zone of inhibition of herbal-treated Ayurvastra fabrics against Escherichia coli.
(A) Aloe vera, (B) Turmeric, (C) Neem, (D) Tulsi; DW – Distilled water (negative control); Amp – Ampicillin (positive control)

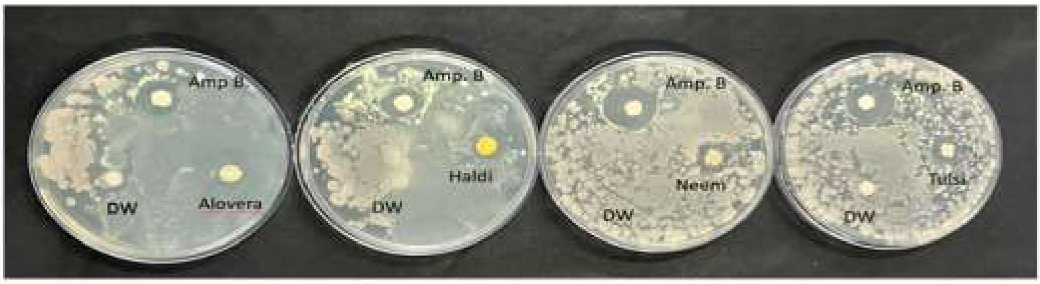

Figure 3 - Antifungal activity of herbal-treated Ayurvastra fabrics against C. albicans (A) Aloe vera, (B) Haldi, (C) Neem, (D) Tulsi; DW – Distilled water control; Amp B – Amphotericin B (positive control)

ability to interfere with bacterial cell membrane integrity and protein synthesis. These natural compounds provide a synergistic defense against microbial colonization. Aloe vera-treated fabrics displayed mild inhibitory zones (10–12 mm), yet their consistent activity highlights the role of anthraquinones, saponins, and aloin, which exhibit bacteriostatic and antifungal properties.

The qualitative observations from all three sets of images are in agreement with the measured inhibition zones (Table 1). Neem consistently showed the maximum activity, which can be attributed to azadirachtin, nimbidin, and other active compounds known to disrupt microbial cell walls. Turmeric's activity is linked to curcumin, while Tulsi and Aloe vera owe their moderate efficacy to eugenol and aloin derivatives. The event, circular halos around the discs confirm uniform fixation of herbal extracts on the fabric surface.

These results validate that Ayurvastra fabrics finished with natural herbal extracts can function as bio-protective textiles capable of inhibiting pathogenic bacteria and fungi, providing both therapeutic and sustainable value.

4. Conclusion

The study successfully demonstrated that Ayurvastra fabrics treated with herbal extracts Neem, Tulsi, Turmeric, and Aloe vera possess measurable antimicrobial and antifungal activity. Among all treatments, Neem-treated fabric exhibited the highest inhibition zones against Escherichia coli, Staphylococcus aureus, and Candida albicans, validating its strong antimicrobial potential. These results confirm that the herbal dyeing process can effectively impart functional properties to fabrics without the use of synthetic chemicals.

This research provides scientific evidence supporting the therapeutic principles of Ayurvastra, which until now have largely remained rooted in traditional and anecdotal understanding. By employing microbiological testing methods, the study bridges the gap between Ayurveda and modern science, offering a reliable foundation for the further development of herbal-based functional textiles.

The outcomes highlight the potential of Ayurvastra fabrics as promising for applications in medical textiles, wellness wear, and sustainable fashion industries. They present a viable eco-friendly alternative to conventional antimicrobial finishes, aligning health benefits with environmental responsibility. Furthermore, the study paves the way for future interdisciplinary work exploring the durability of antimicrobial effects, incorporating nanotechnology for enhanced performance, and assessing consumer acceptance of Ayurvastra products.
Overall, this work contributes meaningfully to validating Ayurvastra as a credible, scientifically grounded approach to sustainable textile innovation rooted in India's traditional knowledge yet advancing toward global relevance.

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Special thanks are also extended to the Department of Microbiology, IIS (Deemed to be University) Jaipur, for their technical assistance, laboratory support, and expertise in conducting the antimicrobial and antifungal tests. Their collaboration was crucial in establishing the scientific evidence for the functional efficacy of the Ayurvastra samples.

This research not only supports the academic exploration of Ayurvastra but also offers Ayursatwa a validated foundation for demonstrating the therapeutic potential and effectiveness of its herbal-treated fabric products.

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AI-Driven Sustainable Manufacturing in the Textile & Apparel Industry: An Empirical Study

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Abstract:

Background: *The textile and apparel industry is highly resource intensive and faces growing pressure to adopt sustainable production practices. Artificial intelligence (AI) offers opportunities to enhance operational efficiency, reduce waste, and support data-driven decision-making; however, empirical evidence on AI adoption for sustainability in the Indian textile sector remains limited.*

Method: *The research design of this study is a quantitative investigation by using primary data gathered in 210 individuals who were operating in the garment factories, textile mills, and apparel firms in India. Perceived usefulness, environmental concern, organizational readiness and intention to adopt AI-based sustainable manufacturing practices were measured using a structured questionnaire. Descriptive statistics and correlation and multiple regression techniques were used to analyses the data collected.*

Findings: *The results indicate that there is a robust positive correlation between the factors being studied and the intention to adopt AI. Perceived usefulness was found to be the most predictive of AI adoption intention ($b = 0.48$, $p < .001$), then organizational readiness ($b = 0.31$, $p < .01$) and environmental concern ($b = 0.22$, $p < .05$). The results reveal a positive trend in the industry, in both terms of implementing AI-driven sustainability solutions, and the significance of proper digital infrastructure, employee education, and environmental consciousness.*

Conclusion: *This study contributes to emerging research on AI-enabled sustainable manufacturing in textiles by emphasizing the roles of perceived usefulness, organizational readiness, and environmental awareness. The findings offer practical insights for industry leaders, policymakers, and technology providers to support strategic investments and policy initiatives that accelerate digital transformation and sustainability.*

Keywords: *adoption intention, artificial intelligence, Industry 4.0, Sustainable manufacturing, textile and apparel industry*

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1. Introduction

The global textile and clothing industry is changing exceptionally rapidly regarding technological shifts, sustainability, and shifting customer needs. The textile industry is one of the most resource-intensive production sectors whose activities result in a large quantity of water pollution, chemical leaks, carbon emissions, and waste generation [6, 11]. Since the world is becoming increasingly desperate in finding the solution to the issue of climate change and the unavailability of resources, the need to introduce sustainable production systems is not an option, but the key to future competitiveness and environmental friendliness [20, 13].

Artificial intelligence (AI) has become a key facilitator of sustainable manufacturing, which provides high-level functionality to optimize processes, minimize energy used, and make decisions in real time [3, 19]. Machine learning, predictive analytics, computer vision, and IoT-induced smart systems are the types of AI technologies that textile manufacturers can use to identify defects, predict machine breakdowns, optimize the process of dyeing fabric, and automate cutting and sewing [1, 20]. Such abilities not merely increase efficiency in operations, but make operations also sustainable through waste reduction and enhanced resource use [17, 21].

Technology Acceptance Model (TAM) is a powerful theory that can be used to explain the process of technology adoption. TAM postulates that the intention to use new technologies is mainly determined by the perceived usefulness and the perceived ease of use of the individual (Davis, 1989). Environmental concern is also a strong factor in technological decisions in the context of sustainability since the employees who have a strong interest in the environment will have a greater tendency to favor green innovations [5, 18]. Also, organizational preparedness such as infrastructure, management support, workforce skill, and digital capacity has been listed as one of the significant factors of effective technology adoption [4].

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Though the literature takes into account the importance of Industry 4.0 technologies in the manufacturing industry, there is little empirical research directly assessing the sustainability of textile and apparel manufacturing using AI [1, 15]. The majority of previous research is generalized with respect to digital transformation or specific technologies (like automation or predictive maintenance), which does not address how professionals in the industry see AI as a sustainability tool. The gap is more notable in India, which is among the largest producers of textile in the world, as the transition to the environmentally responsible production is getting more central to the global competitiveness [6, 14].

To fill this gap, the current paper examines the issues that affect the adoption of AI-based sustainable manufacturing practices in the Indian textile and apparel sector. The study investigates how perceived usefulness, environmental concern and organizational readiness affect the intention to adopt AI using primary information gathered on 210 individuals working in garment factories, textile mills, and apparel brands. The combination of TAM and constructs that are sustainability-oriented offers a comprehensive insight into the factors and obstacles related to the adoption of AI [12, 22].

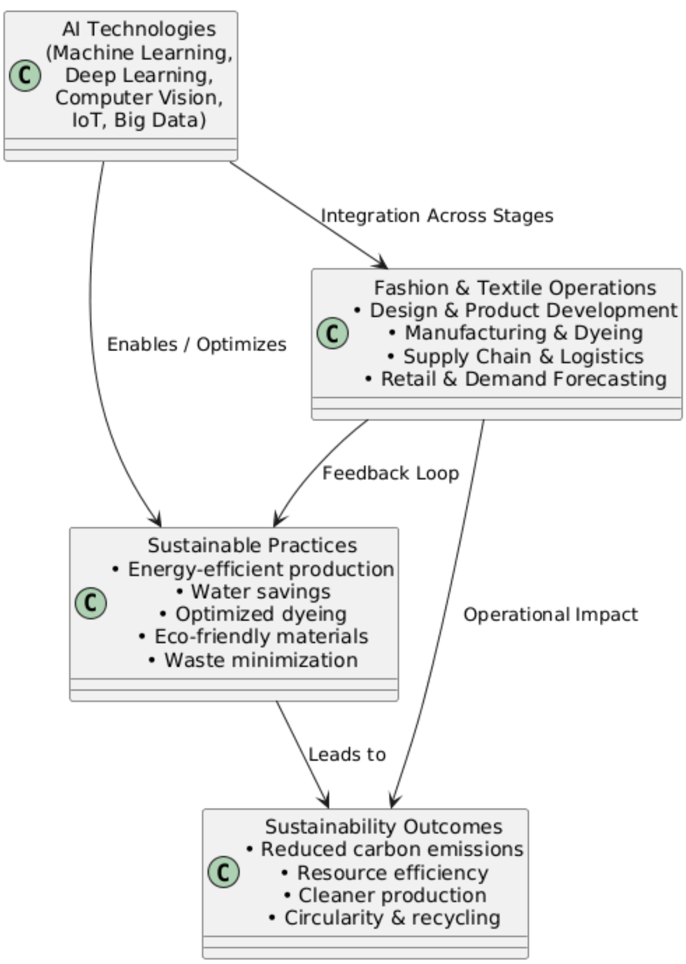

Figure 1: Conceptual Framework of AI-Driven Sustainability in Fashion Industry

Figure 1 presents the uses of AI technologies in the fashion and textile sector in terms of sustainability. Artificial intelligence devices are designed to integrate into all design, production, staining, logistics, and retailing to enhance productivity and decision-making. This enables sustainable processes such as energy saving, reduction in wastage of water, effectiveness of dyeing, green materials and reduction of wastes. The positive impact of these operations includes a good sustainability effect, including carbon emission reduction, cleaner production, increased resource efficiency, and circularity [6, 7].

This research offers much-needed empirical evidence on the adoption of AI-enabled sustainable manufacturing practices in the textile industry, an area where existing literature remains limited [1, 3]. The findings provide valuable insights for industry leaders, policymakers, and technology developers by highlighting the importance of strengthening digital infrastructure, enhancing employee training, and formulating AI strategies that align with sustainability objectives. These insights can further guide regulators in designing supportive policy frameworks and incentive mechanisms to accelerate industry-wide adoption of AI-driven sustainability solutions [3, 9]. Overall, the study contributes both academically and practically by supporting the development of a more intelligent, environmentally responsible, and globally competitive textile production ecosystem [23, 5].

2. Literature Review

The literature review provides a comprehensive overview of existing research related to artificial intelligence and sustainable manufacturing within the textile and apparel industry. It critically examines prior studies to identify key themes, technological advancements, and research gaps. This section also establishes the theoretical foundation of the study by integrating concepts of sustainability, AI adoption, and technology acceptance. Furthermore, it highlights the need for empirical investigation in the context of emerging economies, particularly India, where limited research has been conducted in this domain.

2.1 AI in Sustainable Manufacturing

The changing aspect of AI through the processing of fabrics is one more aspect that is also discussed in the new research since so far this sphere of application was traditionally linked to the enormous amounts of water use, leaks of chemicals, and carbon emissions. The idea of textile dyeing on the basis of the deep learning will allow reducing the intensity of energy consumption by a significant percentage and making the process more accurate [24, 26]. Referring to their results, it can be stated that AI-based dyeing systems will be able to move out color variations, decrease the number of chemicals and decrease thermal loads that may eventually become cleaner and efficient production processes. This change in such technologies can be perceived as to what is referred to as green practices where digital technologies will essentially transform the traditional processes that are detrimental to the environment. It may be accomplished with the help of AI technologies, including machine learning, computer vision, and the Internet of Things, to detect defects in real-time, optimize supply chains, and with a less negative impact on the environment [3, 12]. The smart systems are able to minimize the consumption of water, consumption of chemicals and energy need [20, 10].

Focuses on AI-driven sustainable textile manufacturing using LSTM and ANN models for accurate energy consumption forecasting, resulting in significant energy savings and reduced carbon emissions during textile dyeing processes [7]. Examines AI-based numerical optimization for carbon footprint reduction across the fashion supply chain, including production, logistics, and retail operations, contributing indirectly to sustainable manufacturing outcomes [5]. Discusses the role of AI in optimizing resources and refining supply chains, highlighting its contribution to eco-friendly product design and waste reduction in fashion manufacturing systems [9].

The integration of artificial intelligence (AI), sustainability, and the fashion and textile sector has turned into a very essential research issue with the fashion industry confronting its destruction of the environment, its wastefulness of resources, and its increasing pressure on consumers to act ethically. The existing literature informs about the potential of AI transformations in streamlining the supply chain, enhancing the efficiency of materials, predicting demand, and reducing the environmental impact of apparel production [8].

At this stage, it is necessary to examine the foundations of each of these concepts and determine which will be analyzed in the preceding paragraphs. At this point, one should review the premises of each of these concepts and identify which one will be discussed in the earlier paragraphs. The benefits of AI-based systems to support sustainable change across the value chain, there is a growing consensus in the literature that AI-based systems are not mere technological extensions but the primary drivers of change [26].

Moreover, AI adoption in green fashion is determined by the changing consumer preferences. Research indicates that artificial intelligence (AI) based personalization and recommendation systems can encourage sustainable consumption behaviors by encouraging customers to adopt environmentally friendly products [23]. When the data about the customers are analyzed, AI systems will be able to reduce the returns rates, enhance the accuracy of the size, and increase the life time of the product. This consumerist application shows that the role of AI is not restricted only to the efficiency of production, but also to the formation of behaviorally sustainable statehood.

2.2 Sustainability Issues of Textile Industry

Some of the problems that the textile industry has to deal with include pollution, waste, and ineffective use of resources [6]. Digital innovation is considered to find a solution to these issues. Another theme that is appearing in the literature is material sustainability. Some of the study emphasizes the use of environmentally friendly production materials, biodegradable fibers, and recyclable fabrics in the production systems with the help of smart technologies. According to the study, AI-based material selection tools enable manufacturers to find low-impact materials, simulate their performance, and bring them to product a development pipeline, which ensures that the fashion industry is in line with the concepts of circularity.

This discussion is further developed by some researchers who explore the practical and managerial implications of AI on the achievement of the sustainability targets in the fashion industry [20]. The author emphasizes that AI-driven sustainability dashboards, carbon monitoring systems, and automated lifecycle assessment (LCA) systems can help companies to monitor environmental performance in real-time. Study claims that such technologies do not only help in complying with the global environmental standards but also in making better decisions at the managerial level. This helps in what the author calls the green intelligence ecosystem in which information-based insights are used to take sustainable action at every level of the organization [25].

Analyzes ESG disclosure practices in the Bangladeshi textile and apparel industry using AI and machine learning, revealing limited transparency, with only 37% of factories reporting sustainability information and a stronger focus on environmental and social dimensions than governance [1]. Reviews AI-enabled sustainability practices in the apparel sector, highlighting major environmental challenges, technological constraints, and implementation barriers [3]. Provides a broad review of AI applications in fashion sustainability, including waste minimization, consumer behavior analytics, and sustainable design strategies. [4] Examines AI applications in sustainability practices such as waste control and supply chain optimization, while identifying gaps in empirical evidence related to sustainable manufacturing [6]. Focuses on sustainable manufacturing practices through eco-friendly materials and processes, emphasizing environmental responsibility without directly addressing AI-based manufacturing systems [8].

Some study offers a wider systematic view, as they have developed a systematic literature review with the aim to find out the relationship between AI and sustainability practices in the apparel industry. According to their results, the AI helps to achieve sustainability at three levels operational sustainability (energy and resource optimization), environmental sustainability (waste and emissions reduction), and social sustainability (fair labor, better worker safety). The review highlights that AI-based surveillance, e.g. computer vision in worker safety compliance can increase social sustainability results in an area where the environmental issue is often the main focal point [22].

The other critical view emerges in publications that give emphasis on issues and constraints of the application of AI systems. Although most of the literature provides the positive effects on the environment, a number of researchers warn of over-dependence on technologies without touching on such systemic concerns as workforce preparedness, technological disparity, and the social impact of automation. Indicatively, AI can be of great use in sustainability endeavors, but only when clean and high quality data, which many small and medium-sized enterprises (SMEs) do not have, is available [23]. On the same note, some study highlight that the asymmetric implementation of AI technologies between the developed and the emerging economies might not lead to closing the sustainability gaps but instead create them [22].

2.3 Technology Acceptance and Adoption

According to the Technology Acceptance Model (TAM), perceived usefulness and perceived ease of use are important to adoption decisions. Research also shows that organizational preparedness and environmental consciousness enhance further adoption intentions [4].

Initial research was mainly on predictive and optimization features of the technology in production planning and logistics. As some researchers observe, AI algorithms used in demand forecasting became more commonly used by major fashion brands between 2012 and 2022, thus decreasing the problem of overproduction, which is one of the most detrimental environmental activities in the industry [22, 23]. Correspondingly, some study emphasizes the possibility of applying AI-based numerical optimization algorithms to reduce carbon emissions throughout supply chain activities, specifically, through route optimization, scheduling of energy-efficient machinery, and rationalizing inventory [24]. These articles highlight the functional advantages of AI to enhance environmental performance particularly in the sectors of waste reduction and power usage. Investigates AI-driven sustainable management and lean manufacturing practices in the U.S. fashion industry, highlighting improvements in operational efficiency and supply chain transparency, though lacking sector-specific empirical validation [2]. Identifies technological, organizational, and data-related challenges influencing the adoption of AI-based sustainability solutions in the apparel industry [3]. Highlights adoption barriers related to infrastructure, skills, and scalability of AI solutions within fashion supply chains [6].

Taken together, the literature gives an indication of the development of the initial attempts to learn AI as a productivity tool to more modern notions of AI as an inevitable companion in the innovation that is sustainability-focused. The merging of advanced analytics with deep learning and environmentally-friendly manufacturing processes have indicated the paradigm shift in the textile and apparel industry towards moving away by manual, resource-intensive processes and adopting intelligent, circular, and energy-efficient systems.

According to previous studies, the following hypotheses are predicted in this study:

H1: Perceived usefulness impacts positively on the intention towards AI adoption.

H2: Environmental concern has a positive impact on AI adoption intention.

H3: Organizational preparedness has a positive impact on the intention to adopt AI.

3. Methodology

The methodology section outlines the research design, data collection procedures, and analytical techniques employed in the study. It provides a systematic approach to examine the factors influencing the adoption of AI-driven sustainable manufacturing practices in the textile and apparel industry. This section ensures the reliability and validity of the research by detailing the sampling method, measurement instruments, and statistical tools used for data analysis. Additionally, it establishes the framework for interpreting the empirical findings in a structured and scientifically rigorous manner.

3.1 Research Design

The quantitative design was employed, and it included primary data of textile and apparel professionals [23].

3.2 Sample and Data Collection

The respondents (210) in the garment factories, spinning mills and apparel brands were given a structured questionnaire. Sampling method: purposive sampling. The participants were the production managers, supervisors, sustainability officers, and quality engineers [11].

3.3 Measurement Instruments

- Perceived Usefulness (PU)- 5 items based on Davis (1989)
- Environmental Concern (EC)- 4 items modified within Schultz (2001) items.
- Organizational Readiness (OR)- 5 items.

AI Adoption Intention (AI) - 4 items.

Everything was rated with the help of the 5-point Likert scale (1 = strongly disagree; 5 = strongly agree).

3.4 Data Analysis

Descriptive statistics, reliability testing, correlations, and linear regression were done with the help of SPSS 26.

4. Results

The results section presents the outcomes of the data analysis conducted in this study. It provides a clear and systematic interpretation of the empirical findings derived from statistical techniques such as descriptive analysis, correlation, and regression. The section highlights the relationships between key variables and evaluates the proposed hypotheses. These findings form the basis for further discussion and help in understanding the factors influencing the adoption of AI-driven sustainable manufacturing practices in the textile and apparel industry.

4.1 Reliability Statistics

The alpha values were between 0.82 and 0.91 which is a strong internal reliable value.

4.2 Descriptive Statistics

Respondent perceived usefulness was high (M = 4.12, SD =.53) but their organizational readiness was moderate (M = 3.72, SD =.61).

4.3 Correlation Analysis

There existed strong positive correlations of PU, EC, and OR with AI adoption intention (Azad, 2025).

Table 1: Correlation Matrix

Variable	1	2	3	4
PU	1	.56	.49	.62
EC		1	.44	.51
OR			1	.58
AI				1

Note. $p < .01$

Perceived Usefulness (PU) is significantly correlated (0.62) with AI adoption intention, which underscores its direct contribution to influencing professionals in the industry to accept AI in a bid to achieve sustainable production. The environmental Concern (EC) is another factor that has a positive correlation (0.51) with adoption intention, and this indicates that the greater attention paid to environmental concerns drives the intention to adopt green innovations like AI. Organizational Readiness (OR) has a correlation of 0.58 with adoption intention implying that companies that invest in digital infrastructure, skills and management encouragement are more likely to implement new technology such as AI. The findings also coincide with the overall studies, which confirm that personal and organizational factors are important in determining technology adoption behaviors in the manufacturing industries.

4.4 Regression Analysis

The adoption intention of AI was strongly predicted by:

- Perceived Usefulness: $b = .48$, $p < .001$
- Organizational Readiness: $b = .31$, $p < .01$
- Environmental Concern: $b = .22$, $p < .05$
- Model summary: $R2 = .62$, $F(3,206) = 112.45$, $p < .001$.

5. Discussion

The findings indicate that rather well-accepted AI-based technologies are prevalent with the textile professionals. As anticipated by the TAM theory, the largest predictor of the adoption of AI was perceived usefulness since it aligns with other research. Organizational preparedness was another important factor, which presupposed that investment in digital infrastructure and training of the personnel should be taken [26]. The environmental concern was significantly forecasted to make the adoption, which signifies the significance of the sustainability awareness as the driving force to use AI solutions. These results confirm the current studies that show a prospect of AI to improve green manufacturing [1].

6. Conclusion

The present paper has presented the key factors influencing the introduction of artificial intelligence (AI) in sustainable manufacturing in the Indian textile and apparel industry. The study could identify perceived usefulness, organizational readiness, and environmental concern based on primary data gathered using 210 industry professionals as having significant predictive power on AI adoption intention. Of them, perceived usefulness proved to be the most efficient predictor, which means that the stakeholders in the industry will be more likely to use AI once they have a clear understanding that it can actually enhance the efficiency, reduce the level of wastage, and assist the industry to reach its environmental goals. The organizational readiness was also a key factor paying attention to the topicality of adequate technological facilities, management support, and workforce skills needed to facilitate the successful implementation of AI. Moreover, the role of environmental concern also played a positive role in the intentions to adopt, which means that sustainability awareness is gradually ensuring its position in the minds of textile professionals. The findings contribute to the current literature on the subject matter of digital transformation and sustainable manufacturing with providing an empirical evidence of one of the biggest countries in the world regarding textile manufacturing. Practically speaking, the results show that the leaders of the industry need to invest in digital capacity-building, employee training, and sustainability-focused approaches in order to accelerate the implementation of AI. Another way in which this change can be achieved is through incentives, regulations and awareness campaigns by the policymakers so that AI-based sustainability efforts can be motivated. Although the studies provide immense information, the analysis can be extended in the future to include longitudinal data, cross-country and application of AI in a single industry. All in all, this paper is in favor of the prospect of AI as the engine of an efficient, eco-friendly and globally-competitive textile industry.

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Enhanced Extraction Practice of Natural Dyes for the Sustainable Textile Industry

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Abstract:

Efficient extraction solutions for both natural and synthetic dyes are of great interest due to the growing demand for environmentally sustainable textile processing. The main contemporary dye extraction methods, such as solid-phase extraction (SPE), surfactant-mediated extraction, supercritical fluid extraction (SFE), ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), and enzymatic and fermentation-based techniques, are reviewed and evaluated in this study. A critical analysis is conducted of each technique's principles, mechanisms, benefits, and industrial applicability. By means of efficient adsorbent–analyte interactions, SPE and its microextraction variations exhibit great selectivity, little solvent consumption, and superior recovery. For the concentration of hydrophobic dyes, surfactant-based methods like cloud-point extraction and coacervate extraction offer easy and environmentally suitable substitutes. Although SFE's low polarity limits its use to non-polar chemicals, it allows for quick and solvent-free extraction, especially with supercritical CO2. Specifically, when combined, UAE and MAE greatly improve mass transfer, shorten processing times, and boost extraction effectiveness. While fermentation methods, particularly for the creation of indigo, enable the natural biotransformation of dye precursors, enzyme-assisted extraction provides a gentle and sustainable method for plant-based colours. Overall, the results show that hybrid and integrated extraction techniques have a promising future for increasing dye yield while minimising environmental impact. It is believed that ongoing developments in these technologies will aid in the creation of more environmentally friendly and sustainable textile dyeing techniques.

Keywords: *Enzymatic Extraction, Innovative Extraction of Colourants, Solid phase, Supercritical fluid, Surfactants-mediated, Ultrasound and Microwave-Assisted*

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1. Introduction

In the textile business, a variety of synthetic dyes are used for colour materials. Globally, approximately 800,000 tons of synthetic dyes are produced annually, with the textile industry accounting for 75% of this quantity. [1] During the dying process, the synthetic dye is bonded to the cloth, and the remaining dye is discharged into the environment via wastewater, accounting for an estimated 10-15% [1]. Wastewater from the dyeing process has a variety of unfixed compounds, including auxiliaries, fixing agents, defoamers, oxidizing or reducing agents, and diluents [2]. It is found that typical dye discharges have an excessive biological oxygen demand (BOD) and chemical oxygen demand (COD), as well as a significant amount of organic and inorganic contaminants such as chlorinated chemicals, heavy metals, sulfur, nitrates, naphthol, soaps, chromium compounds, formaldehyde, benzidine, sequestering agents, dyes, and pigments. Throughout every stage of the supply chain, the worldwide textile sector is accountable for having a major adverse effect on the environment due to its astounding annual greenhouse gas emissions, such as carbon (more than 3.3 billion metric tons), large land and water intake, contamination of the soil, air, and water, and rising waste output [3]. Along with environmental impacts, researchers have found potential effects on human health, including skin sensitisation, allergic reactions, and allergic contact dermatitis in both industry workers and consumers. We should follow the latest method to reduce carbon emissions [4]. 36% of the textile supply chain is made up of dyeing, which contributes to the clothing industry, according to a UNEP assessment on sustainability.

Waterless dyeing techniques used in material synthesis are promising innovations that are beginning to emerge to reduce the adverse effects of the dyeing stage. Natural dyes are becoming increasingly popular as a greener option for synthetic colours [5]. However, their restricted and non-reproducible brighter hues, inappropriateness for machine use, and lack of availability in standard form, natural dyes make up just around 1% of the textile industry overall.

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Researchers and academics are working to find sustainable solutions for these problems.

Indians are the first to master the art of natural dying. Utilising novel technology [6, 7], textiles can now extract colourant from natural sources like plants, insects, animals, and minerals without harmful chemical extraction. Textile wastewater has the most harmful effluent composition. Natural dyeing of various fabrics and leathers has continued due to the distinct advantages and disadvantages of both natural and synthetic dyes. This is particularly evident in the decentralised sector for specialised products, whereas large-scale industries rely on chemical dyes for common clothing and textiles. Numerous scholars have examined diverse techniques for eliminating harmful colours from wastewater [8, 9].

2. Materials and Methods

2.1 Extraction Technique of Natural Dyes

The extraction of colorants from natural sources is a crucial step in the preparation of purified natural dyes, as plant matrices typically contain only a small proportion of dye, usually between 0.5% and 5%. The use of natural dyes on a large industrial scale will necessitate the resolution of several technical obstacles, such as improving extraction and application procedures to maximise cost-effectiveness.

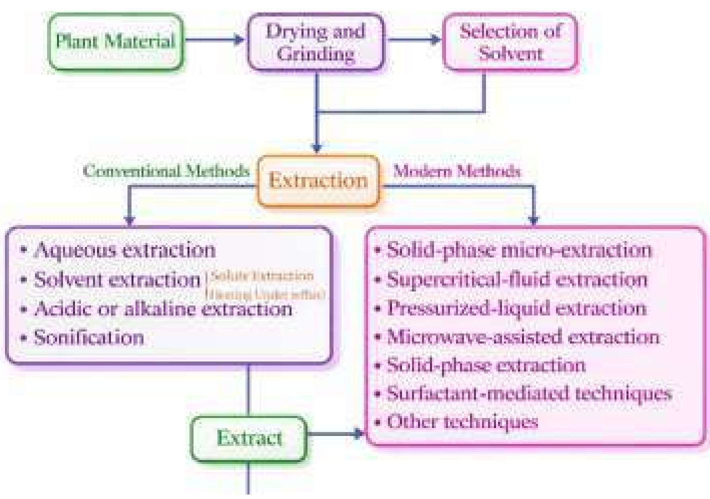

Figure 1: Extraction methods of natural dye [10]

Chromatographic techniques are used to separate the target isolated compounds used for dyeing, and spectroscopic techniques are employed to describe the separated compounds (Figure 1) [10].

A) Traditional Extraction Methods

Aqueous extraction is a conventional method in which colouring matter is ground or powdered before being immersed in water to relax the cell structure and improve process efficiency. The dye solution is prepared by boiling and then filtering [11]. Aqueous extraction has a long extraction period, a considerable volume of water required, and a low dye yield because only water-soluble dye components are extracted. Additionally, sugars and other water-soluble components are removed alongside the dye. High temperatures lower the yields of heat-sensitive dyes [11]. Extraction with organic solvents such as ethanol or methanol, or a combination of the two, is like aqueous extraction but yields a greater yield. Lower temperatures can be employed, reducing the risks of deterioration. Water/alcohol extraction can extract both water-soluble and insoluble compounds. Furthermore, the solvents can be easily extracted by distillation and reused. A disadvantage is the existence of harmful leftover solvents. Furthermore, the extracted material is not readily soluble in water, and co-extraction of other substances such as chlorophylls and waxy components may occur [11]. By comparing the effectiveness of nine solvents, namely n-hexane, ethanol, acetonitrile, chloroform, ethyl ether, ethyl acetate, petroleum ether, n-butyl alcohol, and methanol, to extract natural dyes from cordyline, pandan, and dragon fruit, and assessing the best extraction conditions. The results showed that methanol, ethanol, and water were the most acceptable solvents for dye extraction from the plants studied. Many dyes contain glycosides; extraction under alkaline or acidic conditions can accelerate glycoside hydrolysis and result in better extraction yields. Alkaline extraction is useful for colours with phenolic groups in alkaline conditions. One downside of this extraction procedure is that alkaline conditions may harm the colouring material, as many dyes are pH sensitive [12]. The alkaline extraction of natural colour from grape pomace, a by-product of wine manufacturing, was compared to aqueous extraction. The results revealed that alkaline extraction produced a greater extraction yield.

B) Modern Extraction Technique

The extraction of colouring ingredients from dye material was a critical step. There are numerous scientific ways of dye extraction procedures, which are mostly determined by the dye source, dye concentration, colour, end use of the extract, cost, and equipment required in the process [13]. As a result, environmentally safe and low-cost extraction technologies are critical for keeping the biomaterial without deterioration while not compromising extraction conditions. Several natural dye extraction technologies that comply with both customer demand and regulatory control are cost-effective and growing more popular. The optimal extraction process should be determined after considering the composition and solubility of the colouring components [11]. The following are the extraction processes used for natural dyes.Table 1 compares the main dye extraction methods based on their extraction process, target chemicals, benefits, drawbacks, and real-world uses. An overview of traditional and environmentally friendly extraction techniques for the recovery of synthetic and natural dyes is given in this comparison.

Table 1. Comparative Summary of Different Dye Extraction Techniques

Extraction Technique	Different DyesExtracted	Source Material	Key Advantages	Major Limitations	Typical Applications
Solid-Phase Extraction (SPE)	Acid, basic, reactive, azo, anthraquinone dyes	Textile wastewater; synthetic dye mixtures	High selectivity, excellent recovery, low solvent consumption, easy automation	Cost of sorbents; limited adsorption capacity	Dye monitoring, wastewater treatment, analytical sample preparation
Surfactant-Mediated Extraction (Cloud Point/Coacervate Extraction)	Hydrophobic dyes, disperse dyes, vat dyes	Textile effluents, aqueous dye solutions	Green solvent alternative, inexpensive, low toxicity, high enrichment factors	Sensitive to temperature and surfactant concentration	Dye preconcentration, wastewater remediation, environmental analysis
Supercritical Fluid Extraction (SFE)	Non-polar natural pigments (carotenoids, chlorophylls), hydrophobic dyes	Plant materials, natural dye sources	Solvent-free residues, rapid extraction, tunable selectivity, environmentally friendly	High equipment cost; less effective for polar dyes unless modifiers are used	Natural pigment extraction, food, pharmaceutical and textile industries
Ultrasound-Assisted Extraction (UAE)	Curcumin, anthocyanins, flavonoids, tannins, indigo precursors	Roots, bark, flowers, leaves, fruits	Reduced extraction time, lower solvent requirement, enhanced mass transfer, high extraction efficiency	Possible degradation under prolonged sonication; scale-up challenges	Extraction of natural textile dyes and bioactive compounds
Microwave-Assisted Extraction (MAE)	Curcumin, anthocyanins, flavonoids, polyphenolic dyes	Plant biomass	Rapid heating, short extraction time, high extraction yield, reduced energy consumption	Risk of thermal degradation of heat-sensitive compounds; specialized equipment	Industrial extraction of natural colorants and phytochemicals
Combined UAE–MAE (Hybrid Extraction)	Polyphenols, anthocyanins, flavonoids, mixed natural dyes	Plant-derived dye sources	Synergistic improvement in extraction efficiency, higher yields, reduced solvent and energy consumption	Process optimization required; higher capital investment	Large-scale sustainable extraction of natural dyes
Enzyme-Assisted Extraction (EAE)	Anthocyanins, flavonoids, tannins, betalains, carotenoids	Fruits, leaves, bark, seeds, flowers	Mild operating conditions, improved cell-wall disruption, higher purity, environmentally benign	Enzyme cost; sensitivity to pH and temperature	Green extraction of natural dyes and functional biomolecules
Fermentation-Based Extraction/Biotransformation	Indigo, indirubin and other microbial pigments	Indigofera spp.; microbial cultures	Renewable process, low chemical consumption, sustainable production, high product quality	Longer processing time; process control required	Natural indigo production and sustainable textile dyeing

a) Solid phase extraction

Solid-phase extraction (SPE) is an effective method for extracting materials. It requires no additional preparation processes, such as dilution or pH correction [14]. SPE does not need the mixing of two liquid phases; rather, the analyte is dispersed between two liquid phases (sample medium and adsorbent). The liquid sample is passed through adsorbent particles with a higher affinity for the analysts than the bulk liquid. Solid phase extraction uses an adsorbent based on the target dye compounds. In both liquid and solid phase extraction procedures, a single species is divided into two phases.

This method involves the use of a variety of adsorbents, such as resins that consist of silica, carbon, or clay. The components are purified, and their purity is increased by a solid adsorbent. Due to its higher recoveries, reduced emulsion, and simpler procedure, this approach has some advantages over liquid-liquid extraction. However, there are several shortcomings to SPE technologies that have been addressed by the development of new microextraction techniques such as magnetic SPE (MSPE), solid phase microextraction (SPME), and kinetic adsorption extraction [15]. SPME equilibrates analytes with both the matrix and the fibre, allowing for non-exhaustive microextraction. Microextraction involves exposing a tiny amount of extracted phase (fused-silica fibre) coated with a thin layer (7-100 µm thick) of immobilised polymer or solid adsorbent [16]. SPME has three fundamental operating modes: direct extraction, headspace SPME, and membrane-protected SPME (Figure 2).

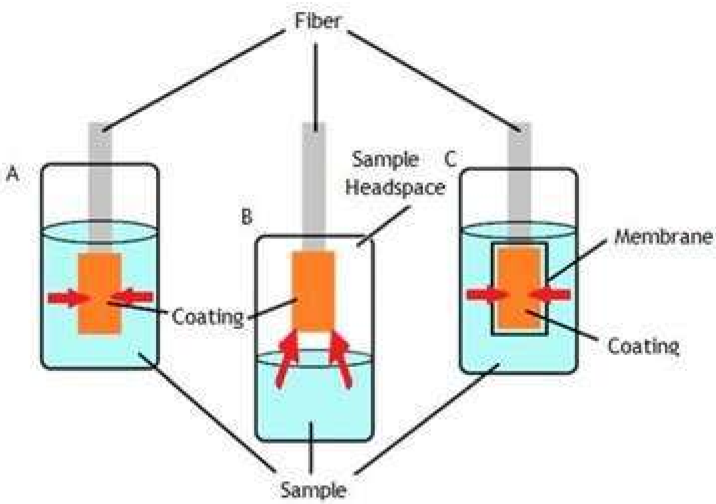

Figure 2: SPE extraction modes: (A) Direct immersion; (B) headspace mode; (C) membrane protection [16]

In the direct extraction mode and headspace, an adsorbent polymer coats the fibre rod. However, in direct extraction, the fibre is put into the sample solution, and the analytes are removed straight to the coated sorbent. During the headspace mode, the fibre is put above the sample solution to remove volatile chemicals, which is critical for decreasing macromolecule interference effects. The membrane-protected SPME is the most popular because of the selective-access membrane's ability to shield the coated polymer from interference. SPME procedures can be performed manually or automatically, and they can be combined with chromatographic systems to maximise efficiency.

b) Surfactant-mediated techniques

The surfactant-based extraction methods are classified into two types: cloud-point extraction (CPE) and coacervative extraction (CAE). Surfactant-based extraction methods separate solutions of surfactant aggregates into two phases: one rich in surfactant and one rich in water. CPE is the temperature-induced phase separation of neutrally charged (non-ionic or zwitterionic) surfactants, whereas CAE is the phase separation of ionic amphiphiles induced by other parameters. The extraction process in CPE and CAE involves solubilising solutes or analytes in aqueous micelles, separating a surfactant-rich phase from the aqueous bulk through changing conditions, and recovering or quantifying the analyte in the surfactant-rich phase [17]. Surfactants are amphiphilic compounds with separate hydrophobic and hydrophilic moieties - a polar or ionic group linked to a lengthy hydrocarbon tail.

Non-ionic surfactants are used in this procedure to remove and concentrate the hydrophobic component from water. Aqueous medium gives way to surfactant medium when constituents enter it. These days, this method is applied with microwaves or ultrasonography. Several authors suggested mechanisms based on the phase separation phenomena. It was proposed that above Tc, temperature-induced dehydration occurred in the exterior layer of the micelles of non-ionic surfactants. This is due to a decrease in water's dielectric constant with increasing temperature, which lowers the contact between the hydrophilic component of the surfactant and water [18]. With increasing temperature, surfactant molecules become more hydrophobic, and phase separation begins (Figure 3).

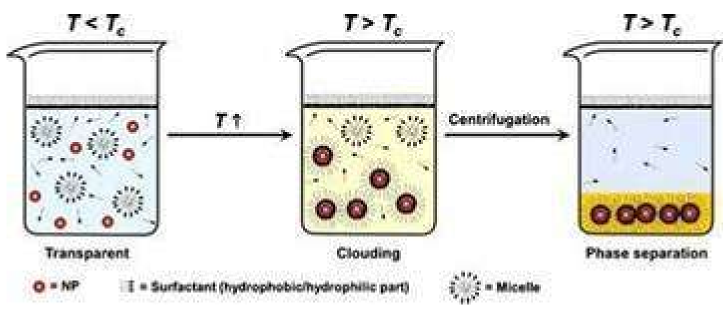

Figure 3: Surfactant-mediated phase separation process [19]

c) Supercritical- fluid extraction

Supercritical fluids are substances with qualities of both liquids and gases that exist above their critical pressure and temperature. The critical values vary depending on the material. These features enable rapid mass transfer in supercritical fluids. Several solvents can be utilized as supercritical fluids, such as carbon dioxide, ethane, ethene, methanol, nitrous oxide, n-butene, n-pentane, sulfur hexafluoride, and water.

Supercritical fluid extraction consists of two primary steps: solubilising the extract in the supercritical solvent and then separating the extract from the solvent. In the first stage, the plant matrix absorbs the supercritical solvent, causing swelling of the cellular membranes and a decrease in mass transfer resistance. Simultaneously, the extracted chemicals are solubilised and transported to the cell's surface. Afterwards, the solubilised chemicals are transferred from the cell's surface to the solvent. In the final stage, they are extracted from the supercritical solvent [20].

Carbon dioxide is the most used, for more than 90% of all supercritical fluid extractions (SFEs). Carbon dioxide is non-toxic and non-flammable, and it is considered safe for human health and the environment in terms of manipulation and value ranges. Second, it is high-purity, inexpensive, and easy to remove from the extract. Furthermore, its low critical pressure and temperature (73 atm and 31.2 ◦C, respectively) promote the preservation of bioactive components in extracts [21]. The fundamental disadvantage of using CO2 as a supercritical solvent is that it has low polarity, making it an efficient solvent for extracting molecules with no or low polarity, but useless for extracting polar chemicals. The [22] supercritical fluid extraction used for dyeing of PET fabric with curcuminoid dyes derived from turmeric, in which natural dye extraction and dyeing were carried out simultaneously in the same supercritical bath using carbon dioxide. Figure 4 illustrates the process of extracting PET using supercritical CO2. The conditions employed were set at 150 ◦C, 20 MPa, and 1 hour. The resulting samples were compared to those obtained through traditional dyeing using ethanol-extracted dyestuff, and it was discovered that PET samples dyed with a supercritical carbon dioxide approach had the highest dye exhaustion, K/S, and fastness values. The thermodynamics (the solubility of the compounds to be extracted or the undesirable compounds) and kinetics (mass transfer resistance) must be considered for the extraction of compounds.

Supercritical fluid extraction has many advantages, such as high yields and short extraction times, requiring low or room temperatures, and using solvents that are generally considered safe (GRAS); the extract contains no residual solvent. This extraction process can be directly coupled with analytical chromatographic techniques such as gas chromatography (GC) or supercritical fluid chromatography (SFC) [23]. The main disadvantages include the high expense of the technique, ineffective extraction of polar compounds, and worker safety issues because supercritical fluids operate at extremely high pressures.

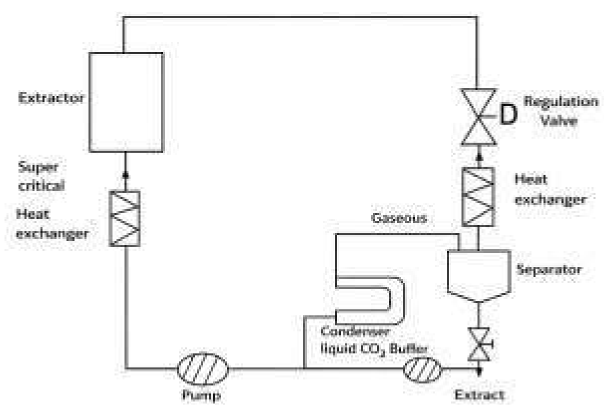

Figure 4: Diagram of the supercritical carbon dioxide extraction [23]

d) Ultrasound and Microwave-Assisted Extraction

Ultrasound-assisted dye extraction is the most effective method [24] and can be used on many textile substrates, including natural, regenerated, and synthetic. Ultrasound technology was used in conjunction with microwaves to improve extraction efficiency. Furthermore, the effects of several solvents were examined. The extracts were then used to colour wool and cotton. The results revealed that using a 70:30 ethanol: water mixture (v/v) with HCl resulted in a higher colour strength. The dyed wool and cotton materials showed good resistance to washing, crocking, and light. Furthermore, it was discovered that extracts using different solvents produced distinct hues on wool and cotton materials.

Compared to conventional heating, heating through microwaves is more efficient (up to 50%) and results in significantly lower energy consumption. The microwave-assisted extraction allows for significantly lower consumption of organic solvents [25]. In the microwave-assisted extraction (MAE) of plant metabolites, the main mechanism induced by microwaves is the generation of heating and dipole rotation in organic. In this procedure, solvents are used along with varying microwave powers (264, 400, and 600 W) to conduct extraction. By heating the material and selecting a suitable solvent, the dye part is extracted. It is a quick extraction method that works with thermally unstable molecules. The target compound, temperature, time, solvent, extraction medium, and microwave power all affect this procedure. The potential of ultrasound-assisted extraction in combination with microwave-assisted extraction (MAE), as microwave irradiation provides fast and efficient extraction but in homogeneous heating (Figure 5) [26, 27].

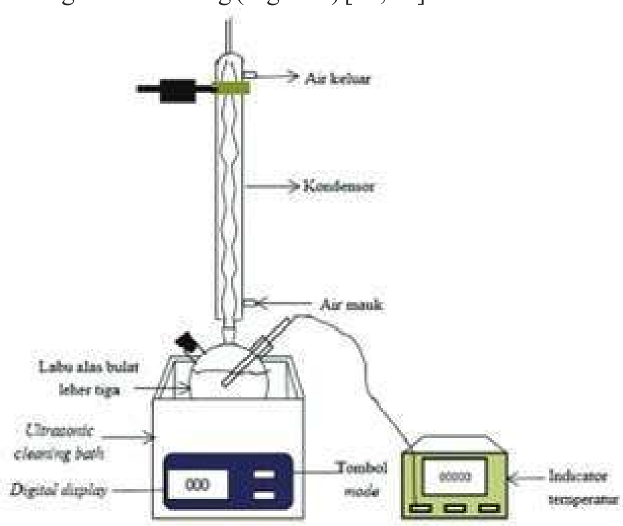

Figure 5: Diagram of the ultrasonic extraction method

e) Enzymatic Extraction and Fermentation

Enzyme-assisted extraction is a developing technique for more efficient exploitation of natural materials. It is an attractive alternative to conventional extraction techniques since it is a sustainable and eco-friendly technology. Enzyme-based extraction is regarded as a solvent-free, environmentally acceptable method of removing active chemicals from plant matrices. Enzymatic reactions proceed effectively at a relatively low temperature and moderate pH and in a relatively short time (up to a few hours) and do not require expensive equipment. Under mild circumstances, plant tissues are broken down with the aid of appropriate enzymes such as cellulase, amylase, and pectinase, which aid in the release of active chemicals and speed up the extraction process. The two primary variables that influence an enzyme's activity are pH and temperature. Hard plant materials like the bark and roots are especially well-suited for these methods. The blend of enzymes and ultrasounds produced the highest results in terms of colour yield when Tiwari and associates [29] compared enzymatic extraction with pectinase and cellulase, ultrasound extraction and enzyme-assisted extraction, and the enzyme-mediated ultrasonic-assisted extraction of natural colourants from pomegranate rind. Optimising essential conditions can reduce extraction costs and energy usage [30].

The fermentation extraction method employs enzymes produced by bacteria. The entire process takes 10 to 15 hours. Indigo dye extraction is the most prevalent type of fermentation extraction technique. Freshly collected indigo leaves are immersed in warm water at 32 degrees Celsius. Indimulsin enzyme degrades the colorless indigo glucoside, indican and converts it into glucose and indoxyl after 10-15 hours. Indimulsin, an enzyme, can also be found in indigo dye leaves. After 10-15 hours, yellow fluid containing indoxyl is transferred to the beating vats. In the beating vats, indoxyl is oxidised by the air, turning blue. After draining all extra water, indigo dyes were discovered in cake form.

3. Results and Discussion

The comparative assessment of different extraction techniques reveals significant variations in efficiency, selectivity, operational requirements, and environmental performance. Solid-phase extraction (SPE) proved high recovery rates and minimal solvent use, attributable to the strong affinity between adsorbents and dye molecules. Its microextraction variants SPME and MSPE further enhanced sensitivity and reduced sample handling, although limitations such as fiber fragility and non-exhaustive extraction remain challenges. Surfactant-mediated techniques, including cloud-point extraction (CPE) and coacervative extraction (CAE), showed strong potential for concentrating hydrophobic dyes through micellar solubilization. These approaches are relatively simple, cost-effective, and compatible with green chemistry principles, though phase separation can be sensitive to temperature and solution conditions.

Supercritical fluid extraction (SFE), especially with CO_2, provided high yields, short extraction times, and solvent-free extracts. Its efficacy in dyeing PET with curcuminoid dyes proves its dual extraction–dyeing capability. However, SFE is limited by the low polarity of CO_2 and higher equipment costs, which restrict its suitability for more polar dye compounds. Ultrasound-assisted extraction (UAE) and microwave-assisted extraction (MAE) showed the greatest improvements in extraction kinetics by accelerating cell disruption and heat transfer. Combined UAE–MAE systems further enhanced color strength and reduced solvent use, although uneven heating in microwave systems is still a concern. Enzyme-assisted extraction proved particularly effective for plant-based dyes, offering mild reaction conditions, high selectivity, and reduced environmental impact. The combination of enzymes with ultrasound significantly increased color yield, highlighting strong synergistic potential. Fermentation-based extraction, particularly for indigo, produced high-quality dyes through natural enzymatic conversion, though its longer processing time limits scalability. The results show that although each method possesses unique operational benefits, hybrid techniques such as enzyme-ultrasound extraction or integrated supercritical and dyeing systems present the most potential avenues for effective and sustainable color extraction. The choice of technique ultimately depends on dye polarity, substrate characteristics, cost considerations, and targeted industrial applications.

4. Conclusion

Natural dyes are derived from renewable resources, making them environmentally friendly. Their extraction methods have evolved to minimise ecological impact. Many contemporary techniques, such as pressurised liquid extraction, enzymatic, supercritical, microwave, and ultrasonication, have been shown to get natural colours more successfully. This information will thus contribute to environmental sustainability, eco-friendliness, and efficient resource use without sacrificing industrial advantages. Their Modern production generates minimal toxic waste compared to synthetic dyes. Using natural dyes contributes to a healthier planet. Modern extraction methods allow for efficient utilisation of natural dye materials. These methods optimize colour yield while minimizing solvent usage and extraction time. Unlike synthetic dyes, natural dyes do not release harmful chemicals into water bodies during the dyeing process. This reduces pollution and benefits aquatic ecosystems. Natural dyes are generally safer for human use, as they lack the toxic components found in synthetic dyes. They pose fewer health hazards to dyers, textile workers, and consumers. While natural dyes don't have these negative consequences, their low output and low binding ability still need to be taken into consideration. Therefore, it is imperative to do additional studies and optimize the output of natural resources. From an Indian standpoint, there are plenty of plants, minerals, and animals that can provide dyes; these can be cultivated or processed to produce enormous quantities. It is possible to investigate using bacteria and insects to produce colorants. Additionally, the effectiveness of colorants can be enhanced by investigating the usage of naturally occurring mordants.

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Microbial Dyes for Textiles: Advances, Challenges, and Sustainable Paths – A Review

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Abstract:

The application of synthetic dyes by the global textile industry, which are well known to be non-environmentally friendly and non-biodegradable, has triggered the search for effective sustainable alternatives. Microbial dyes isolated from the microbes such as bacteria, fungi, yeasts, and algae are an effective green substitute for synthetic dyes. Microbial pigments are renewable and biodegradable and contain functional properties like antimicrobial, antifungal, antibacterial action and UV protection for fabrics. This comprehensive review considers the recent developments in microbial pigment production, with focus on progress in fermentation methods, the application of crop wastes as green substrates, and the contribution of genetic engineering in optimizing the pigment production. The work delves deeply into dyeing processes for use on different textile substrates like cellulose, protein and synthetic, materials with an emphasis on the significance of green mordants and new dyeing technologies which are used to improve the colour fastness. It also discusses the major challenges that are limiting commercialization of microbial pigments, for example, poor pigment yield, extraction difficulties, and regulatory issues. This review gives a summary overview of microbial dyes as a promising and innovative approach to sustainable textile dyeing by assessing the environmental concerns, techno-economic feasibility, and opportunities in intelligent textiles.

Keywords: *Bacterial pigments, bio-colorants, eco-dyeing, microbial dyes, sustainable textile*

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1. Introduction

A linchpin of the world economy, the world textile industry has, for decades, relied heavily on synthetic dyes to produce the enormous range of bright, vibrant colors required. Yet, the environment impact of the petroleum-based colorants stands severe, marked by water usage at great volume, contamination of water bodies by hazardous and possibly carcinogenic chemicals, and the accumulation of persistent chemical residues [1, 2]. Increasingly rigid regulatory demand and maturing customer pressure to market sustainable products have now triggered a hasty shift in paradigms to greener alternatives. Microbial dyes have now come up as a leading contender. Extracted from bacteria, yeast, fungi, and algae, the pigments provide for the textile dyer a green, biodegradable, and nontoxic vehicle for colorization [3, 4]. Besides the colorization possibilities, they commonly bring inherent ancillary functions like antimicrobial, antioxidant, and UV-protective effects, providing substantial value addition to the finished textile product [5, 6]. The present review work presents a panoramic and timely overview of the current situation in the field of microbial dye research. The work goes into recent production processes, sophisticated post-treatment methodology on various textile support media, and the multifunctional benefit value they bring. Importantly, the discussion also encompasses the longstanding technical, financial, and regulatory hitches to be surmounted in order to allow their successful large-scale commercialization and their large-scale uptake by the industry [7, 8].

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2. Sources and Production of Microbial Dyes

Microbial dyes are derived from a vast and diverse array of microorganisms, including bacteria, fungi, yeasts, and algae (Table 1) [9, 13]. These biological factories listed in Table 1 are capable of synthesizing a broad spectrum of vivid pigments such as carotenoids, melanins, prodigiosin, violacein, phycocyanin, and indigoidine that serve as sustainable and functional alternatives to synthetic colorants [14, 16].

This strategy not only decreases production costs but also supports a circular bioeconomy by optimizing waste streams [17-19]. Post-fermentation, innovative and sustainable extraction methods including ultrasound assisted extraction (UAE), microwave assisted extraction (MAE), and enzymatic extraction are applied to effectively retrieve pigments to walk in the sustainable path [20, 21]. The comprehensive pipeline for the production and extraction of microbial pigments, from the selection of sources to the final characterization, is shown in Figure 1.

To further maximize the yield and stability of pigments, novel biotechnological approaches are being adopted. Strain improvement by mutagenesis and adaptive evolution today complemented by precision tools like CRISPR-Cas9 gene editing and synthetic biology enable the overexpression of

Table 1 - Pigments from Microorganisms and their Properties

Pigment Name	Source Microorganism	Type	Colour	Key Properties	Primary Textile Application
Prodigiosin	*Serratia marcescens*	Bacteria	Red to Pink	Antibacterial, Antifungal	Cotton, Silk
Violacein	*Chromobacterium violaceum*	Bacteria	Violet	Antifungal, Antibacterial	Wool, Cotton
Pyocyanin	*Pseudomonas aeruginosa*	Bacteria	Blue-Green	Antimicrobial	Cotton, silk, wool & blends,
Melanin	*Streptomyces* spp., *Bacillus* spp.	Bacteria	Brown to Black	Antibacterial, better lightfastness	Natural fibres
Indigodine	*Streptomyces* spp.	Bacteria	Deep Blue	Water-insoluble	Denim/cotton dyeing
Monascin	*Monascus purpureus*	Fungi	Yellow	Antioxidant	Cotton, wool, silk fibres
β-Carotene	*Dunaliella salina* (Algae)	Algae	Yellow-Orange	Antioxidant	Cellulosic fibres
Fucoxanthin	*Fucus*, *Sargassum* spp. (Brown Algae)	Algae	Yellowish brown to Olive	Antioxidant, Antimicrobial	Cotton, silk fabrics

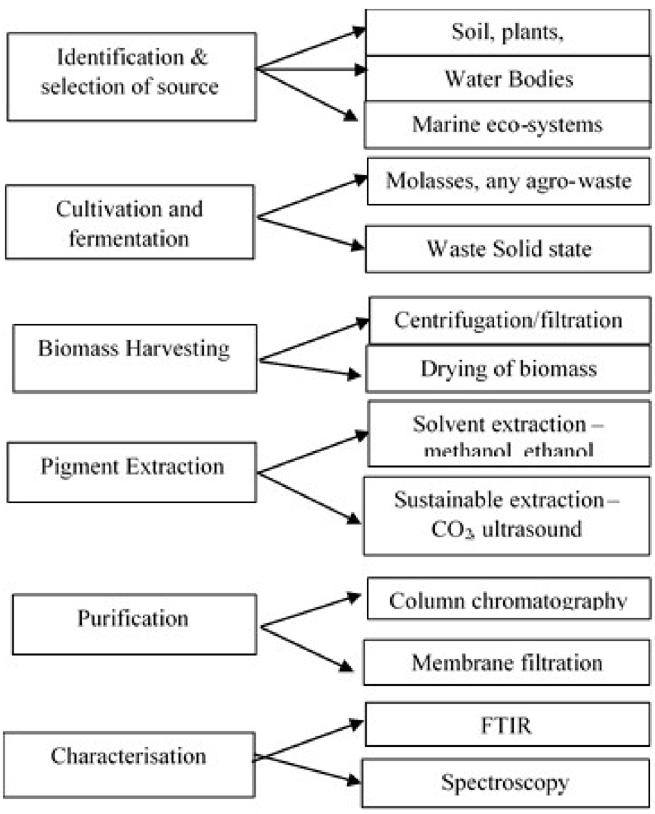

Figure 1 - Schematic Overview of Microbial Pigment Production and Extraction

the key biosynthetic genes and creation of new metabolic pathways [22, 23]. Scaling up production to an industrial level involves stringent control over conditions of fermentation (pH, aeration, temperature, C/N ratio) and introduction of efficient downstream processing techniques such as ultrafiltration, chromatography, and green solvent extraction for economic viability and product purity levels [24, 25].

3. Dyeing Processes and Applications on Textiles

The efficient application of microbial dyes on fabrics requires adjusting both traditional and current dyeing procedures to match the unique properties of these biological pigments. Exhaust dyeing, pad-dry-cure, and screen printing are common techniques, but studies are increasingly focusing on energy efficient methods such as ultrasonic assisted and microwave-assisted dyeing to improve pigment diffusion and fixation while reducing process duration and temperature [26-29]. The main fibre composition significantly effects dye absorption and durability properties [30, 31], which requires tailored application procedures for each kind of fiber [32]. The careful examination of dyeing methods and identifying methods to improve the fastness properties are discussed.

Fabric pre-treatment is an important step in achieving high-quality coloration. Pre-treatments are needed for cellulosic fibers such as cotton, which have a limited affinity for many microbial pigments. Enzymatic scouring, plasma activation, and cationization all introduce positive charges onto the fiber surface, significantly increasing ionic interaction with anionic pigment molecules [33, 34]. Recent developments have focused on chitosan-based biopolymer coatings and anionic alterations to establish high affinity binding sites. It was found that cotton treated with sulfhydryl groups had considerably better prodigiosin exhaustion, resulting in greater color fastness and UV protection [35].

The mordant used is also critical in the process of achieving an eco-friendly dyeing process. As a replacement for harmful metal salts such as copper and chromium, the sector is shifting aggressively towards green mordants such as alum, ferrous sulphate, and bio-mordants derived from plants (e.g., pomegranate peel, tannic acid). These mordants not only improve wash, rub, and light fastness, but darken the shade and can give other functional properties such as

Table 2 - Advanced Application Techniques for Microbial Dyes on Textiles

Application Technique	Key Mechanism	Advantages	Example Microbial Dye	Recent Finding
Ultrasonic Dyeing	High frequency sound waves-ultra sonic cavitation improves diffusion	Green process, improved dyeing, cost effective	Prodigiosin	30% reduction in process time and 15% increase in dye uptake on silk[6]
Chitosan Pre-treatment	Cationized fabric dyed with pigments	Enhanced adhesion, inherent antibacterial property	Violacein, Anthraquinones	showed a 40% increase in dye exhaustion on chitosan-treated cotton.
Bio-Mordanting	Natural compounds	Non-toxic technique, improves fastness	Monascin, Curcumin	Tannin from pomegranate rind improved wash fastness of fungal yellow dye by 1-2 grades
Digital Printing	Pigment-based inkjet inks with bio-binders	Precision, reduced waste, design flexibility	Indigoidine, Pyocyanin	Farag[41] developed a stable nano-emulsion ink from bacterial blue pigments for inkjet printing.
Micro-encapsulation	Pigments enclosed in shells	Improved light fastness	Melanin, Carotenoids	Chitosan-alginate encapsulated melanin showed no fading after 48 hours of light exposure [46]

improved antioxidant activity [36, 37]. Dyeing with Serratia marcescens derived prodigiosin and tannin mordant, produces excellent colour depth and antimicrobial stability, whereas Spirulina-derived phycocyanin on cotton produces vivid blues with good lightfastness when alum is used [38, 39].

Printing is an application value sector for microbial pigments. Screen and digital print formulations are under development, with thickeners and environmentally friendly binders stabilizing the pigments for excellent prints and adhesion on textile surfaces [40, 41]. Microbial dyes like violacein and indigoidine, due to their intrinsic pH responsiveness, are being developed as wearable sensor inks to change colour based on sweat or wound pH changes [42, 43].

Additionally, microbial dye application to blends such as P/C is subject to close scrutiny to meet industry requirements. Differential dye sorption and migration are problems to be solved through improved dyeing processes, which may be multistage or utilize special dye carriers to ensure uniform coloration of the different fibre components [44, 45]. The different advanced application techniques currently under development for microbial dyes are illustrated in Table 2 with focus on the new techniques applied to improve dye incorporation, activity, and eco-friendliness.

4. Functional and Bioactive Properties of Microbial Dyes in Textiles

Microbial dyes' value proposition is much more than their sustainable character and coloration function. The bio-pigments confer apparel with a host of inherent functional properties, which make them ideal enablers for future-generation high-performance and value-added applications. These range from robust antimicrobial, antioxidant, and UV-protection activities, in addition to pH-responsivity and inherent biocompatibility [47-49]. This multifunctionality, lacking in the bulk of synthetic dyes, opens up new markets for medical, wellness, protective, and smart textiles (Figure 2).

Figure 2 - Multifunctional applications of microbial pigments

4.1 Antimicrobial Activity

Prodigiosin, violacein, melanin, and phenazines are pigments with broad-spectrum antibacterial characteristics that break microbial cell membranes and interfere with biological activities. These metabolites have been shown to inhibit a diverse array of pathogens, such as Gram-positive (Staphylococcus aureus) and Gram-negative (Escherichia coli, Pseudomonas aeruginosa) bacteria and Candida albicans species of fungi [50]. Recent studies confirm the efficacy of treated fabrics; for example, prodigiosin-dyed cotton inhibited S. aureus and E. coli by more than >99% (>3-log inhibition) after 24 hours of treatment [51].

4.2 Antiviral Activity

COVID-19 has sped up the evolution of antiviral surfaces. Recent studies have shown encouraging antiviral effectiveness in specific microbial pigments. Melanin, especially from genetically modified Streptomyces, has demonstrated strong effectiveness against enveloped viruses such as influenza A (H1N1) and SARS-CoV-2, with research indicating a more than 90% decrease in viral interaction on treated fabrics [52]. Likewise, prodigiosin and violacein demonstrated outstanding antiviral capabilities against the Herpes Simplex Virus (HSV-1) by inhibiting viral entry and replication [53]. This offers a transparent route for creating protective medical textiles, face masks, and frequently contacted surfaces in healthcare environments.

4.3 Antioxidant Properties

Some microbial pigments, including carotenoids like β-carotene and zeanthin, monascorubrin and phycobiliproteins phycocyanin, have strong antioxidant properties. They can protect against oxidative stress and cellular damage by free radical scavenging. If these pigments are used in textiles, they can be useful for the skincare garments, healing dressings, and anti-aging clothes. As an illustration, fabrics dyed with Monascus pigments have demonstrated strong free radical scavenging activity (up to 85% DPPH inhibition), indicating potential benefits for dermatological use in wearable textiles [54].

4.4 UV Protection

Pigments produced by microorganisms such as Streptomyces, Monascus, and Rhodotorula (melanin and carotenoids) have intrinsic UV absorbing biological functions because of their conjugated molecular structure. The fabrics colored with such microorganisms achieve excellent UPF (Ultraviolet Protection Factor) ratings, often surpassing UPF 40+ which is the threshold value recommended for outdoor and professional clothing [55, 56]. Moreover, melanin-dyed fabrics outperform all other types with regard to UVA and UVB radiation, making them sun-protective garments and needing no chemical UV absorbers.

4.5 Smart and Responsive Textiles

The chemical characteristics of microbial pigments are suitable for smart textile technology. Violacein and indigoidine pigments are known for their color changing pH responsive behaviors of changing within an interval of pH. This technology is being utilized for developing wearable health monitoring sensors like sports apparel that track hydration levels through pH of sweat, and pH responsive color changing wound dressings that indicate infection [57]. These pigments have lately been successfully incorporated into inkjet printing recipes for patch sensors [41].

4.6 Biocompatibility and Skin-Friendliness

An important benefit for wearable technologies is the relative non-toxicity and biocompatibility of microbial dyes, especially when produced in controlled conditions and purified to remove fermentation metabolites. Purified prodigiosin and phycocyanin pigments have undergone cytotoxicity testing on human skin cell lines, including HaCaT keratinocytes, and have consistently shown over 90% cell viability [58, 59]. Such skin friendliness is advantageous in the manufacture of sensitive products, which include the garments for infants, intimate apparel, and materials for the chronic wounds.

Table 3 - Recent Advances in Microbial Dye Application

Microbial Pigment	Source	Key Innovation	Textile Application & Result	Reference
Prodigiosin	*Serratia marcescens*	Encapsulation in chitosan-alginate nanoparticles	Silk dyeing and has shown improved light fastness	Farag [41] et al., 2024
Melanin	*Streptomyces* sp.	Engineered overproduction and coating	Antiviral textiles; >90% reduction in SARS-CoV-2 and influenza viral load	Petruk [52] et al., 2023
Violacein	*C. violaceum*	Application on chitosan-pretreated cotton	Enhanced dye uptake (40% increase) and improved antibacterial properties	El-Naggar [6] et al., 2023
Indigo	Engineered *E. coli*	De novo synthesis pathway from glucose; no precursor needed	Denim dyeing, achieved high titers of 8.3 g/L, direct reduction and dyeing	Liu [23] et al., 2023
Blue Pigment	*Streptomyces* sp.	Pilot-scale production in 500L airlift bioreactor	Successfully scaled fermentation while maintaining yield consistency for cotton dyeing	Gokhale [25] et al., 2023

As summarized in Table 3, recent research breakthroughs (2023-2024) continue to demonstrate the vast potential of microbial dyes for creating high value, multifunctional textiles.

5. Challenges in the Commercial Adoption of Microbial Dyes

Despite their enormous promise, commercializing microbial dyes presents a number of hurdles across technological, economic, and regulatory areas. Addressing these hurdles is critical to market penetration.

5.1 Low Pigment Yield and Productivity

A major economic barrier is the poor pigment output per unit biomass from wild-type strains, which frequently leads to extended fermentation durations and unsustainable production costs [60, 61]. For example, many natural pigment manufacturers direct carbon flow towards growth rather than secondary metabolite production. According to recent techno-economic analyses, achieving a minimum of more than 5 g/L is frequently required for economic feasibility at an industrial scale, a threshold that many processes still fail to meet [62].

5.2 Extraction and Purification Difficulties

Downstream processing remains a significant bottleneck contributing often over 60-70% to the total cost of production. The conventional processes using large volumes of organic solvents are harmful to the environment and are highly priced [68]. While greener technologies could be supercritical CO_2 extraction, microwave-assisted extraction (MAE), or ultrasound-assisted extraction (UAE), they commonly prove to be optimized on just a lab scale and also suffer first from energy efficiency and then from scalability to continuous industrial operations [63, 64].

5.3 Regulatory and Safety Concerns

Safety considerations take precedence in wearable textiles. Certain pigment-producing strains, mainly fungi like Monascus (which can produce citrinin), and some bacteria may sometimes co-synthesize other toxic secondary metabolites or endotoxins [65, 66]. Due to the absence of a Generally Recognized as Safe (GRAS) status in most microbial pigments intended for textile use, a strict safety assessment on a case-by-case basis has to be undertaken along with the application of expensive purification protocols-a factor inhibiting investment [67, 68]

5.4 Stability and Colour Fastness

Due to the negative effect of photodegradation or fading during washing with alkaline detergents, microbial pigments generally differ in inferior ratings of wash fastness, light fastness, and rub fastness from their synthetic counterparts [2]. Nonetheless, the stability could be improved along with mordanting and nano-encapsulation methods, for example, by encapsulating pigments in silica or chitosan matrices [48, 69] so, picking up yet another point of complexity and costs.

5.5 Lack of Industrial Infrastructure

The sector somehow suffers a "Death Valley" between laboratory-scale innovation and industrial-scale production. A scarcity of pilot-scale facilities for process validation, fermentation protocols lacking standardization, and no well-established channels for bulk supply of microbial dyes have been grave concerns [70]. The field holds an urgent much-needed space for bioreactor design, especially tuned to high-density pigment-producing cultures and standardization of product quality across the industry [25, 71].

5.6 Awareness and Acceptance among the Consumers

A major market barrier remains a lack of awareness and some "bio-skepticism" from consumers and brands. If transparent labelling ("microbially dyed" and the like) and educational marketing campaigns supported by credible third-party certifications (like GOTS, Cradle to Cradle) are not pursued, the demand among consumers will continue to stagnate, thereby holding back brands from making proper investments [37, 59].

6. Future Prospects and Opportunities

The interaction between biotechnology, sustainability, and market dynamics is creating numerous opportunities for microbial dyes to transition from experimental status to mainstream acceptance.

6.1 Synthetic Biology and Engineering at the Systems Level

Aside from CRISPR-Cas9, the future will focus on systems metabolic engineering and synthetic co-cultures. Referred to as a groundbreaking event, in 2023, a synthetic group of E. coli strains reinvented the metabolic process for indigoidine production, resulting in remarkable improvements in yield [72]. AI and machine learning modelling techniques are currently used to forecast optimal fermentation conditions and to create new enzymatic pathways for pigment synthesis [73].

6.2 Integrated Biorefineries and Circular Economy

The incorporation of biorefineries, transforming agricultural waste into multiple high-value products, represents the future of cost-effective manufacturing. For example, a method might be developed in which citrus peel waste is utilized at the same time to generate microbial pigments, bioethanol, and limonene, benefiting the overall economics and fully supporting the idea of a circular economy [74].

6.3 Advanced Applications in Smart and Technical Textiles

The functional properties of microbial dyes make them ideal for high-value technical textiles. Research is moving beyond basic pH-response to developing pigments that respond to specific biomarkers or environmental toxins. Furthermore, their inherent biocompatibility is being leveraged for advanced wound care products where the dye provides both colour and therapeutic benefits

6.4 *Strengthening the Innovation Ecosystem*

To speed up commercialization, targeted policy measures, including grants, tax benefits and pilot plant funding are necessary. Pre-competitive partnership among industry players (such as dye supplies and textile brands) and academia will be the key factor to de-risk technologies and produce international standards and safety certification frameworks for bio-based dyes [75].

7. Conclusion

Microbial dyes and pigments promise to provide an alternative solution to the significant environmental issues associated with synthetic dyes, due to their strong environmental compatibility and sustainability. The immense potential they hold is further demonstrated by this review, rooted not only in their renewable and biodegradable source but also in their intrinsic multifunctional activity. The capacity to afford vivid colours together with intrinsic anti-microbial, -viral, UV-protective and pH-responsive properties makes these bio-pigments the key materials for future high-performance and smart textiles. Through advances in synthetic biology, especially the development of CRISPR-Cas9 and metabolic engineering, historic yield constraints are becoming less of an issue, while intelligent valorisation of agro-industrial waste lends itself to circular economy notions. However, the transformation of an invention within the laboratory into one well adopted by the masses presents common great barriers. Technical hurdles are posed for downstream processing and purification, as does colour fastness. Subsequently, a lack of present established regulatory frameworks, defined industrial-scale infrastructure, and increased consumer awareness has been hampering further commercial success. To overcome these challenges, a concerted effort must be undertaken by academics, industry stakeholders, and governmental agencies. The future of microbial dyes looks exceptionally bright. As faster genetic, fermentation, and application technologies progress, these sustainable dyes will shift from a niche novelty to a mainstream commodity. Provided that interdisciplinary research continues being supported and with a strong commitment to the principles of green chemistry, microbial dyes will not be just an alternative, but should surely change the way textiles are manufactured, thus setting the foundation to a truly sustainable and functionally enhanced textile industry.

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Assessment of Dyeing Properties of *Couroupita guianensis* Extracts on Eri Silk

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Abstract:

Background: *Natural dye extracted from the leaves and flowers of Couroupita guianensis, also known as cannonball tree, was used to investigate its dyeing, fastness, and antimicrobial properties on eri silk.*

Methods: *A beaker dyeing machine was used to dye Eri silk fabrics with the obtained dye extracts. The effect of two mordants, namely potassium aluminium sulphate and zirconium oxychloride, on the colour co-ordinates, colour strength and fastness properties was studied. Pre-mordanting and post-mordanting techniques were adopted. The antibacterial property of the extracts on silk was also assessed.*

Results: *Eri silk fabrics dyed with zirconium oxychloride and potassium aluminium sulphate produced a variety of shades in the yellow range with a slight reddish undertone. Although the mordants resulted in varying shades, flower extracts showed little improvement in colour strength, except for potash alum pre-mordanted samples, which exhibited enhanced colour strength when compared to the unmordanted samples. However, the fabric samples dyed with leaf extract showed improved colour values on mordanting. All the dyed fabric samples, regardless of the mordants and mordanting techniques used, resulted in acceptable fastness properties. The samples dyed without mordants also exhibited acceptable fastness properties, barring light fastness. The dyed substrates also exhibited acceptable antimicrobial activity.*

Conclusion: *Colour strength, fastness ratings and shades obtained on eri silk demonstrate the use of flower and leaf extracts of Couroupita guianensis as a potential natural dye source for natural fibre-based textile substrates.*

Keywords: *Colour fastness, Couroupita guianensis, eri silk, mordant, natural dye*

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1. Introduction

The importance of colour in textiles has been recognised for thousands of years, and ancient writings contain frequent references to it. Natural dyes and dyeing are as old as textiles themselves. The arrival of synthetic dyes led to the decline of natural dyes, as they offered several advantages over natural dyes, including superior colour fastness, better reproducibility of shades, colour brilliance, and ease of use. Of late, there has been an increasing focus on natural dyes due to the growing demand for environmentally friendly clothing [1]. The dyes, if extracted from renewable sources such as leaves and flowers, would make the entire process sustainable and beneficial to the environment. Dyes extracted from the leaves [2, 3] and flowers [4, 5] for application on various textile substrates have been reported earlier. It becomes more important when such a source of natural dye is used to dye eri silk, obtained from silkworms grown in the wild or semi-domestically. Eri silk is considered environmentally friendly because the process of raising silkworms and silk processing does not involve any harmful substances. Additionally, the pupae are not killed and are allowed to emerge as moths before processing, making the process more ethical and sustainable.

Couroupita guianensis (also known as the Cannonball tree) is a perennial tree extensively grown in tropical and subtropical regions, including India. It flourishes under cultivation and is also used as animal feed [6]. Leaves and flowers of *Couroupita guianensis* have also been reported to possess medicinal properties [7]. The main colouring constituent of flowers is known to be quercetin [8], and leaves are known to possess quercetin and rutin [9]. The dyeing potential of indigo extracted from the fruits of Cannonball is reported [10], but the flower and leaf extracts have yet to be explored. The present study reports the utilization of leaves and flowers of the cannonball tree for the extraction of dye and its application to khadi eri silk fabric. The influence of mordants, viz., potassium aluminium sulphate and zirconium oxychloride, on the colour values and fastness properties were determined.

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2. Materials and Methods

2.1 Material

2.1.1 Dye source

The fallen leaves and flowers of cannonball tree were gathered from the gardens in Bangalore, dried at room temperature, powdered and used for the extraction of the dye.

2.1.2 Fabric

Plain woven khadi eri silk fabric, weighing 230 g/m^2, thickness of 1.04mm, an EPI of 46, and a PPI of 24, procured from Barkhetri Unnayan Saniti, Mukalmua, Assam was used.

2.1.3 Chemicals

Acetic acid and Sodium carbonate were used to maintain the dyebath pH. Laboratory grade Potassium aluminium sulphate and zirconium oxychloride were used as mordants.

2.2 Methods

2.2.1 Dye extraction from the leaves and flowers of Cannonball tree

The dye extraction was performed by mixing 25 g of powder in 250 ml of water and boiling for an hour at neutral pH. The extracts were allowed to cool, filtered and used for dyeing.

2.2.2 Mordanting

Pre-mordanting and post mordanting of eri silk fabrics was carried out in an aqueous solution of the mordants. Zirconium oxychloride at concentrations 0.5, 1.0, 1.5, 2.0 and 2.5%, potassium aluminum sulphate at 5, 7, 10, 12 and 15% maintaining the bath temperature at 70^0C and liquor ratio 1:30 for 30 minutes. The pre-mordanted fabrics were then separately dyed while the dyed fabrics were mordanted for post mordanting.

2.2.3 Dyeing of eri silk fabrics

A beaker dyeing machine with temperature control was used for dyeing eri silk fabrics. Dyeing was started at 40^0C with 10% dye solution and the temperature was raised to 85^0 C and continued for 45 minutes with the dye bath pH 5 and MLR 1:30. The dyed fabrics were rinsed in cold water and subjected to soaping with 1gpl non-ionic soap at 70^0 C for 10 minutes followed by rinsing and drying.

2.2.4 Colour Measurement

Colour strength and colour co-ordinates (L, a*, b*, C & h) were obtained by measuring the reflectance of dyed fabrics using reflectance spectrophotometer [1]. The colour difference (ΔE) and relative colour strength of the dyed fabrics were also calculated.

Kubelka Munk (K/S) function is given by:

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

Where K = absorption coefficient, S = scattering coefficient and R = reflectance at complete opacity.

Colour difference (ΔE)= $\sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2}$

Where ΔL, Δa and Δb are the differences in L, a* and b* values respectively between mordant dyed and unmordanted dyed fabric samples.

Relative Colour strength (%)= $\frac{K/S\ of\ mordanted\ sample}{K/S\ of\ unmordanted\ sample} \ x\ 100$

2.2.5 Colour fastness tests

Colour fastness of all the dyed eri silk fabrics to light was determined using ISO 105-B02 method (xenon-arc apparatus) wherein samples measuring 10x50 mm were exposed along with the blue wool standards and the fastness assessed using grey scales [11]. Washing fastness was determined using Launder-o-meter (ISO 105 C02 method) with 5 gpl soap at 40^0C for 30 min followed by assessment using grey scales [12].

2.2.6 Antibacterial Activity

The parallel streak method, as described in AATCC TM 147-2004 [13] was used to determine the antibacterial activity of the dyed eri silk fabrics. Specimens measuring 25x50mm were placed across 5 parallel streaks of the test bacteria and incubated for 24h at 37^0C and the zone of inhibition was measured. Staphylococcus aureus and Escherichia coli, were considered for the study.

3. Results and Discussion

3.1 Colour characteristics

Colour strength expressed as K/S values, colour co-ordinates and the values pertaining to colour difference of the fabrics dyed with the extract of leaves without mordanting and with varying concentration of mordants, viz., Zirconium oxychloride and potassium aluminium sulphate, are summarized in Table 1. The colour strength values of the mordanted dyed samples were found to be better than those of the unmordanted fabric, indicating that the mordant influences the improvement of colour strength. Post-mordanting resulted in increased colour strength values compared to pre-mordanting with Zirconium oxychloride, while with potassium aluminium sulphate, pre-mordanting resulted in improved colour strength compared to post-mordanting. This is also evident with the increased relative colour strength and ΔE values. The colour strength values increased with the increase in Zirconium oxychloride concentration, whereas this was not the case with potassium aluminium sulphate. The ΔE and relative colour strength were maximum for Zirconium oxychloride post-mordanted and potassium alum pre-mordanted samples.

The colour co-ordinates of all the dyed samples, both mordanted and unmordanted, were +ve with respect to a* and b* and hence, all the dyed silk samples are in the yellow-red quadrant of the colour space diagram. The mordanted samples, especially those treated with potassium aluminium sulphate, were found to shift towards yellow co-ordinate with increased b* values. Chroma and hue angles were also found to be increased for potassium aluminium sulphate-treated samples.

The colorimetric attributes of the eri silk fabric samples dyed with flower extract are presented in Table 2. The fabrics dyed with different concentrations of mordants did not result in any improvement in colour strength when compared to the unmordanted dyed sample, as demonstrated by the K/S values and ΔE. Only the samples pre-mordanted using potassium aluminium sulphate resulted in an increase in colour strength values, ΔE and relative colour strength recording slightly lower L values and a* values, while the b* value (yellowness) increased. The colour co-ordinates of all

Table 1 - Colour attributes of eri silk fabric dyed with flower extract at varying mordant concentrations

Type of mordants	Mordant conc. (%)	K/S	L*	a*	b*	c*	h^0	ΔE	Relative Colour Strength	Dyed Sample
Nil	-	7.76	52.85	6.87	16.89	18.24	67.84	-	-	
ZrOCl3 Pre-mordanting	0.5%	7.96	53.17	7.36	16.52	18.09	65.97	0.69	102.63	
	1%	8.09	53.46	7.47	16.83	18.42	66.07	0.86	104.31	
	1.5%	8.66	53.86	8.06	19.04	20.68	67	2.66	111.62	
	2%	9.24	51.68	7.69	18.03	19.61	66.88	1.82	119.13	
	2.5%	10.09	49.6	7.81	18.12	19.73	66.67	3.6	130.04	
ZrOCl3 Post-mordanting	0.5%	9.51	50.22	7.95	17.59	19.31	65.67	2.92	122.55	
	1%	11.08	47.4	7.79	17.11	18.8	65.51	5.49	142.8	
	1.5%	11.47	46.05	7.95	17.07	18.83	65.01	6.89	147.76	
	2%	11.74	45.91	8.17	17.75	19.55	65.28	7.11	151.25	
	2.5%	11.6	47.39	7.73	18.42	19.97	67.23	5.72	149.48	
Potash Alum Pre-mordanting	5%	11.34	50.52	6.14	20.91	21.8	73.61	4.7	146.07	
	7%	11.31	49.14	6.53	21.15	22.14	72.83	5.66	145.74	
	10%	10.96	47.71	6.88	20.99	22.09	71.84	6.57	141.23	
	12%	10.17	49.73	6.5	21.57	22.53	73.21	5.64	131.11	
	15%	11.96	48.16	6.92	22.1	23.16	72.6	7.01	154.12	
Potash Alum Post-mordanting	5%	8.98	54.89	5.89	21.54	22.33	74.7	5.18	115.67	
	7%	8.3	54.93	4.89	19.68	20.28	76.03	4.01	106.94	
	10%	9.83	51.66	5.66	20.24	21.02	74.38	3.76	126.69	
	12%	8.9	53.333	5.16	20.05	20.7	75.56	3.63	114.7	
	15%	8.75	53.317	4.88	19.63	20.23	76.03	3.43	112.8	

Table 2 - Colour attributes of eri silk fabric dyed with flower extract at varying mordant concentrations

Type of mordants	Mordant conc. (%)	K/S	L*	a*	b*	c*	h^0	ΔE	Relative Colour Strength	Dyed Sample
Nil	-	12.96	49.87	5.17	16	16.81	72.08	-	-	
ZrOCl3 Pre-mordanting	0.5%	13.17	51	5.61	17.8	18.66	72.5	2.17	101.59	
	1%	12.23	53.6	5.18	17.35	8.11	73.36	3.97	94.35	
	1.5%	11.49	53.98	4.86	16.9	17.58	73.95	4.21	88.68	
	2%	12.86	51.8	5.46	17.95	18.77	73.06	2.76	99.23	
	2.5%	13.98	49.56	5.63	17.54	18.43	72.19	1.64	107.87	
ZrOCl3 Post-mordanting	0.5%	10.54	53.42	4.7	16.8	17.45	74.37	3.67	81.34	
	1%	13.35	49.13	4.94	18.08	18.75	74.75	2.23	102.95	
	1.5%	13.6	49.24	5.04	18.05	18.74	74.39	2.15	104.92	
	2%	13.6	48.87	4.43	20.01	20.49	77.5	4.2	104.92	
	2.5%	13.83	49.47	4.61	18.88	19.44	76.26	2.96	106.67	
Potash Alum Pre-mordanting	5%	17.52	46.17	5.02	22.26	22.82	77.27	7.27	135.18	
	7%	16.01	48.41	4.46	22.85	23.28	78.95	7.04	123.47	
	10%	16.48	46.59	4.25	22.17	22.57	79.13	7.05	127.14	
	12%	16.65	47.38	4.56	22.59	23.05	78.58	7.07	128.41	
	15%	16.82	48.28	4.15	22.65	23.02	79.6	6.91	129.71	
Potash Alum Post-mordanting	5%	12.63	52.73	4.14	20.05	20.47	78.31	5.06	97.46	
	7%	10.84	55.79	3.69	19.62	19.97	79.34	7.09	83.63	
	10%	12.63	51.11	4.18	19.05	19.5	77.62	3.44	97.46	
	12%	13.24	50.86	4.14	19.58	20.02	78.04	3.86	102.13	
	15%	11.29	54.09	3.85	19.88	20.35	79.07	5.88	87.07	

the flower extract dyed samples, both mordanted and unmordanted, were +ve with respect to a* and b* and hence, all the dyed eri silk fabric samples lie in the yellow-red quadrant of the colour space diagram.

3.2 Colour Fastness

The washing and light fastness properties of unmordanted and mordanted dyed eri silk fabrics are presented in Table 3. The unmordanted leaf extract dyed sample exhibited good washing fastness, while the fastness to light was found to be fair. A light fastness grade 3 observed in the case of unmordanted silk fabric may be due to the 3-hydroxy groups present in quercetin, which is known to lower the light fastness due to decreased photo-stability [14]. Mordanting with Zirconium oxychloride and potassium aluminium sulphate showed an improvement in the light fastness ratings. Both the mordants and techniques were successful in improving the light fastness. The unmordanted sample dyed with the flower extract exhibited good washing fastness, but slightly inferior light fastness, which improved with mordanting. Overall, the colour fastness attributes were found to be similar to those of the fabrics dyed with the leaf extract.

Table 3 - Colour fastness of the eri silk fabrics dyed with the extract at varying mordant concentrations

Type of mordants	Mordant conc. (%)	Leaf extract dyed samples			Flower extract dyed samples		
		Washing fastness		Light fastness	Washing fastness		Light fastness
		Cc	Cs	Cc	Cc	Cs	Cc
Nil	-	4	4-5	3	4	4-5	3
ZrOCl3 pre-mordanting	0.5%	4-5	4-5	4	4-5	4-5	4
	1%	4	4-5	4	4-5	4-5	4
	1.5%	4	4-5	4	4	4-5	4
	2%	4	4-5	4	4	4-5	4
	2.5%	4	4-5	4	4	4	4
ZrOCl3 post-mordanting	0.5%	4	4-5	4	4	4	4
	1%	4-5	4-5	4	4	4-5	4
	1.5%	4-5	4-5	4	4-5	4-5	4
	2%	4	4-5	4	4-5	4-5	4
	2.5%	4	4-5	4	4-5	4-5	4
Potash Alum pre-mordanting	5%	4	4-5	4	5	4-5	4
	7%	4	4-5	4	5	4-5	4
	10%	4	4-5	4	5	4-5	4
	12%	4	4-5	4	5	4-5	4
	15%	4	4-5	4	5	4-5	4
Potash Alum post-mordanting	5%	4-5	4-5	4	4	4-5	4
	7%	4-5	5	4	4-5	4-5	4
	10%	4-5	5	4	4-5	4-5	4
	12%	4-5	4-5	4	4-5	4-5	4
	15%	4	5	4	4-5	4-5	4

3.3 Antibacterial activity:

Extracts of *Couroupita guianensis* were found to be effective against the bacteria, *Staphylococcus aureus* and *Escherichia coli*. The unmordanted dyed samples showed inhibition zones in both cases, with a minimum of 1mm recorded for the samples dyed with leaf extract, while the samples dyed with flower extract recorded a 2.5 mm inhibition zone (Table 4). The antibacterial activity of the dyed samples could be due to the active ingredients of *Couroupita guianensis*, which are potent antimicrobial agents [6, 15].

Table 4- Antimicrobial activity of the unmordanted dyed eri silk fabrics

Sl. No.	Sample	*S. aureus* (Inhibition zone in mm)	*E. coli* (Inhibition zone in mm)
1	Undyed sample	Nil	Nil
2	Dyed with leaves extract	1.2	1
3	Dyed with flower extract	2.5	2.5

4. Conclusion

The extraction of dye from *Couroupita guianens* is leaves and flowers, and its subsequent application to silk, is environmentally friendly process. The present findings demonstrate the dyeing potential of *Couroupita guianensis* extracts on eri silk. The extracted dyes were found to have a good affinity for silk, even without the use of mordants, exhibiting good washing fastness and improved light fastness when mordants were used. Zirconium oxychloride when used as post mordant and potash alum when used as pre-mordant resulted in better colour values with both the leaves and flower extract dyed samples. As the leaves and flowers are obtained from a renewable source and are abundantly available, *Couroupita guianensis* may be considered a prospective source for obtaining various shades using safe mordants on an eco-friendly substrate such as eri silk.

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Reviving Mukka Embroidery: A Systematic Policy Review

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Abstract:

Background: *Mukka embroidery, locally known as Mukke-ka-kaam, is a traditional metal-thread craft associated with women artisans in Barmer, Rajasthan and adjoining craft regions. The craft has cultural value, yet it faces livelihood pressures linked to low returns, dependence on intermediaries, limited formal recognition, weak market access and declining transmission of skills.*

Methods: *The paper uses a systematic policy review to examine government interventions relevant to Mukka embroidery and related handicraft livelihoods during 2006-2026. Academic literature, policy guidelines, official statistics, institutional reports and credible grey literature were screened and synthesized around policy design, implementation mechanisms, reported outcomes and evidence gaps.*

Results: *The review finds a broad but uneven policy environment covering artisan identification, skill development, MUDRA-linked credit, cluster development, market promotion, welfare access and GI-related cultural recognition. The evidence is strongest at national, state and scheme levels, but remains thin at the Mukka-specific and artisan-household levels. The key issue is weak conversion of policy inputs into income security, bargaining power, direct market access and cultural continuity.*

Conclusion: *Mukka embroidery requires an integrated, cluster-based and artisan-led policy pathway that connects Pehchan registration, skill development, safe credit, SHG or cooperative organization, craft documentation, branding clarity and direct market linkages. This approach can support the craft as a living livelihood practice rather than treating it only as a heritage object.*

Keywords: *Artisan livelihoods, Cluster development, Cultural sustainability, Geographical indication, Handicraft policy, Mukka embroidery*

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1. Introduction

Mukka embroidery, locally known as Mukke-ka-kaam, is a traditional metal-thread embroidery practice associated with western Rajasthan and adjoining craft regions. The craft uses gold- and silver-toned thread effects to create decorative motifs on textiles, ceremonial garments, traditional attire and community-based textile objects [1]. In Barmer and nearby craft pockets, Mukka embroidery is practiced largely by women artisans, including members of historically situated craft communities. It is therefore not only a textile technique but also a form of livelihood, cultural memory and inherited artisanal knowledge [1, 2].

The importance of Mukka embroidery lies in its dual character. On one side, it is a cultural resource that carries motifs, techniques, aesthetic codes and regional identity. On the other side, it is a livelihood activity embedded in household labour, informal production and gendered craft work, a condition shared by many rural handicraft artisans whose economic returns remain low despite their skills [4]. This dual character makes it unsuitable to evaluate the craft only as an object of heritage preservation or only as a commodity shaped by global-local market dynamics [3]. A policy review must examine how cultural value, income generation, market access and institutional support interact in the everyday lives of artisans.

These challenges are particularly relevant for Mukka embroidery because the craft remains less documented than several better-known women-led embroidery traditions such as Lucknow Chikankari [5]. Small and geographically concentrated craft groups may be present within the broader handicraft policy ecosystem but remain underrepresented in policy data, market platforms and impact evaluations. For such crafts, the question is not only whether government schemes exist, but whether artisans can identify, access and convert those schemes into income, bargaining power, cultural recognition and intergenerational continuity.

During the review period, national schemes such as NHDP, AHVY, Pehchan and MUDRA provided support across key areas of the handicraft sector, including artisan registration, skill development, credit access, market linkage, infrastructure, product diversification and GI-related recognition [6, 7]. The policy concern around Mukka embroidery arises from the gap between available schemes and their actual reach among artisans. While national programmes provide support for training, marketing, credit,

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welfare and infrastructure, clear evidence on how these benefits reach Mukka artisans remains limited. This paper therefore reviews national and state-led interventions related to Mukka embroidery and allied handicraft livelihoods during 2006–2026, with attention to policy influence, implementation processes, reported outcomes and evidence gaps.

The review is guided by three research questions: first, what public policies and institutional interventions have been implemented for Mukka embroidery and related handicraft livelihoods between 2006 and 2026? Second, what evidence exists regarding the socio-economic, cultural, and market-related outcomes of these interventions for Mukka artisans? Third, what implementation gaps, policy limitations, and enabling conditions shape the effectiveness of these interventions, and what integrated policy framework can strengthen Mukka embroidery's sustainability?

The paper contributes to textile and craft policy scholarship by reframing Mukka embroidery as a livelihood-sensitive heritage system. It argues that cultural preservation cannot be separated from income security, producer organization, market access and value-chain governance. This approach is relevant for policymakers, textile researchers, craft institutions and development agencies concerned with sustaining traditional crafts as viable rural livelihoods.

2. Materials and Methods

A systematic review approach was adopted studying the existing literature and relevant documents. The review followed the broad principles of transparent source identification, screening, eligibility assessment, data extraction and thematic synthesis used in systematic review research [12, 13].

To build a comprehensive dataset, literature was gathered from academic databases including Scopus, Web of Science, and Google Scholar alongside official portals, institutional websites, and sector-specific repositories. Primary organizational material was retrieved from key entities - Ministry of Textiles, Office of the Development Commissioner (Handicrafts), Press Information Bureau, Geographical Indications Registry, Export Promotion Council for Handicrafts, Micro Units Development and Refinance Agency and Indian Institute of Crafts and Design. The search strategy employed targeted keywords to capture regional craft variations such as Mukka, Mukke-ka-kaam, Barmer, and metal embroidery alongside broader socio-economic themes like artisan livelihoods, women creators in Rajasthan, and sectoral policy frameworks. Query strings also featured specific public programs, including the Pehchan identity card, MUDRA loans, the National Handicrafts Development Programme, cluster initiatives, and Geographical Indication (GI) protections. The review spans literature published between 2006 and 2026, a 20-year window that captures a period of intense structural evolution for the craft sector. This timeline encompasses major milestones, including the rollout of formalized identity registration, expanded credit access, cluster development models, legal GI recognitions, and recent state-level initiatives in Rajasthan. Older literature was excluded from the search unless strictly necessary to anchor the study's analytical framework specifically regarding livelihood theory, cultural capital, and value-chain governance.

The screening process was conducted in three stages. First, titles, abstracts, summaries and executive notes were reviewed to remove sources unrelated to handicrafts, textile crafts, artisan livelihoods or public policy. Second, full texts were assessed to identify sources directly relevant to Mukka embroidery, Rajasthan handicrafts, cluster development, GI protection, credit access, marketing support, women artisans or livelihood outcomes. Third, eligible sources were categorized according to policy domain, evidence type and relevance to the research questions.

Data were extracted using a structured policy-review template. For each source, information was recorded on policy objectives, implementing agency, target beneficiaries, intervention mechanism, geographical relevance, reported outcomes and limitations. Particular attention was given to whether the evidence was Mukka-specific, Rajasthan-specific, craft-sector level or general handicraft-sector level. This distinction was necessary because several official sources provide national or state-level data but do not disaggregate outcomes by craft, district, gender, or artisan group.

The quality of sources was assessed through credibility, relevance and evidence strength. Peer-reviewed literature was assessed for conceptual and methodological relevance. Government documents were assessed for official status, policy specificity and data usefulness. Grey literature was included only when it provided relevant institutional or field-level information and could be triangulated with academic or official sources. Promotional material, unverified web content and Wikipedia entries were excluded from the final evidence base.

The interpretation was guided by Sustainable Livelihoods Theory, Cultural Capital Theory and Value Chain Governance Theory. Sustainable Livelihoods Theory helped examine policy effects on human, financial, social and market-linked assets [14]. Cultural Capital Theory helped interpret Mukka embroidery as a repository of symbolic value, embodied knowledge and cultural identity [15]. Value Chain Governance Theory helped assess how pricing, orders, raw materials, branding and buyer relationships shape value capture in craft production systems [10, 11].

Because several sources were policy documents rather than empirical studies, a PRISMA-style numerical flow could not be applied in the same way as in a clinical systematic review. However, the review used a transparent screening logic to separate directly relevant sources from contextual sources and excluded sources.

Table 1 - Search strategy and eligibility framework

Review component	Criteria used in the study
Review period	2006-2026, with older conceptual sources retained where theoretically necessary
Source types	Peer-reviewed articles, books, working papers, government documents, policy guidelines, trade statistics, institutional reports and credible grey literature
Databases and portals	Scopus, Web of Science, Google Scholar, Ministry of Textiles, Development Commissioner (Handicrafts), Press Information Bureau, GI Registry, EPCH, MUDRA and IICD
Inclusion criteria	Sources related to Mukka embroidery, Rajasthan handicrafts, textile crafts, women artisans, handicraft policy, GI protection, credit support, cluster development, market linkage, livelihood assets or value-chain governance
Exclusion criteria	Promotional material, duplicate sources, non-relevant craft studies, unverified web sources, Wikipedia entries and documents without usable policy or livelihood evidence
Main data extracted	Policy name, year, implementing agency, objective, beneficiary group, intervention mechanism, geographical relevance, reported outcome, evidence type and implementation gap
Synthesis approach	Thematic policy synthesis and comparative interpretation using livelihood, cultural capital and value-chain lenses

Table 2 - Source selection and evidence classification

Stage	Review action	Use in the study
Identification	Academic databases, official policy portals, institutional websites and sector reports were searched using craft, policy and livelihood keywords	Built the initial evidence pool
Screening	Sources unrelated to textile crafts, handicrafts, policy, artisan livelihoods, GI, credit or cluster development were removed	Reduced topic drift
Eligibility	Full texts were examined for relevance to Mukka embroidery, Rajasthan, women artisans, handicraft schemes or value-chain issues	Established direct or contextual relevance
Classification	Sources were grouped as Mukka-specific, Rajasthan-specific, handicraft-sector level, policy-level or conceptual	Prevented overclaiming from broad data
Synthesis	Evidence was coded around identification, skills, credit, clusters, markets, GI, welfare and implementation gaps	Generated the review findings

3. Results and Discussion :

This section presents the policy mapping and thematic synthesis. Table 3 summarises the main schemes and their relevance to Mukka embroidery, followed by discussion of implementation gaps and evidence strength.

Table 3 - Policy mapping and evidence synthesis for Mukka embroidery

Policy/intervention	Main mechanism	Relevance to Mukka embroidery	Review finding
National Handicrafts Development Programme	Skill development, design support, marketing assistance and welfare-linked support	Provides the broad national framework for artisan support	Relevant but generic; Mukka-specific outcome data are limited [6]
Ambedkar Hastshilp Vikas Yojana	Cluster-based mobilization, design support and market linkage	Useful for geographically concentrated craft communities	Strong conceptual relevance, but limited Mukka-specific evidence [6]
Pehchan ID card scheme	Formal artisan identification and access to schemes	Can help women artisans enter formal policy systems	National and Rajasthan data exist, but craft-wise Mukka data are unavailable [7]
MUDRA-linked support	Credit, interest subvention and margin-money assistance	Can support raw material purchase and small production orders	Useful only when linked with financial literacy and assured market access [16]
Comprehensive Handicrafts Cluster Development Scheme	Infrastructure, technology, training, product diversification and market linkage	Highly relevant for artisan collectives and local craft clusters	Strong policy design, but artisan-level evaluation is needed [17]
Mukka Craft Cluster Development Program, Barmer	SHG formation, design training, exhibitions, website development and online marketing	Most directly relevant intervention for Mukka artisans	Promising craft-specific initiative, but long-term livelihood outcomes remain unverified [18]
Kutch Embroidery GI	Legal and cultural recognition of Kutch embroidery	Indirect relevance to regional embroidery traditions	Cannot be assumed to directly protect Barmer Mukka embroidery without legal clarification [19]

The policy architecture can be described as broad but thin. It is broad because support exists for skill development, identification, credit, marketing and cluster work. It is thin because the evidence rarely traces the same artisan from registration to training, from training to production, from production to market access and from market access to income change. For Mukka embroidery, meaningful evaluation should therefore examine income, paid workdays, repeat orders, price realization, strength of collectives and reduction in intermediary dependence, not only scheme coverage.

A major finding concerns artisan identification. Pehchan is potentially important because formal recognition can make artisans visible to the state and enable access to schemes. Official reporting shows national and Rajasthan-level registration under Pehchan [7]. However, the review could not identify publicly available craft-wise data showing how many Mukka artisans in Barmer possess Pehchan cards or use them to access benefits. This is an important gap because artisan identity is the first step in a policy chain. If the identity system does not record craft type, gender, location and market channel, the policy system cannot accurately identify who is being supported.

Skill development is another important but incomplete domain. NHDP and cluster-oriented initiatives support skill upgradation, design innovation and market exposure [6, 17]. For Mukka embroidery, such support can help artisans adapt metal-thread techniques to contemporary products, improve finishing and expand beyond ceremonial uses. Yet training has limited livelihood value unless it is linked with product costing, buyer feedback, quality standards and repeat orders. Without a market pathway, training may create skilled artisans who remain underpaid. Credit support has similar limitations. MUDRA-linked assistance, including credit categories, interest subvention and margin-money support, can help artisans purchase raw materials, accept orders and manage production cycles [16]. Yet credit is useful only when repayment is supported by demand. For home-based women artisans, loans may become risky if orders are irregular, payments are delayed or prices are controlled by intermediaries. Therefore, credit policy should be bundled with financial literacy, SHG-based support, documentation assistance and order-linked repayment planning.

Cluster development appears to be the strongest policy route because it can combine several interventions in one place. CHCDS seeks to address infrastructure, productivity, market access and product diversification in unorganized clusters [17]. The Barmer Mukka Craft Cluster Development Program is notable because it works with women artisans, SHG mobilization, design development, exhibitions and online marketing [18]. This is closer to the needs of Mukka embroidery than isolated workshops or occasional exhibitions. Its effectiveness, however, should be judged through artisan-level indicators rather than programme completion alone.

Cultural recognition is necessary but must be handled carefully. The official GI record shows that Kutch Embroidery is registered for Gujarat under Application No. 103 [19]. This registration is relevant for understanding regional embroidery branding, but it should not be treated as direct legal protection for Barmer-based Mukka embroidery unless geographical coverage, authorized-user status and craft classification are verified. GI literature also indicates that recognition alone does not guarantee producer benefit unless it is supported by organization, quality standards, marketing, enforcement and value-chain governance [8-10].

Market access remains the deepest bottleneck. Marketing support under national schemes, together with the export-promotion infrastructure maintained by the Export Promotion Council for Handicrafts, includes exhibitions, buyer-seller meets, virtual platforms and market promotion [20, 21]. These platforms are useful only when artisans can participate directly, understand product costing, negotiate prices, maintain quality and build repeat buyer relationships. If traders or contractors continue to control raw materials, designs, orders, pricing and customer access, market promotion may increase product circulation without improving artisan value capture. This is why the review treats value-chain governance as central to policy effectiveness [10, 11, 23, 24].

The theoretical interpretation reinforces this point. From a Sustainable Livelihoods perspective, Mukka artisans require simultaneous strengthening of human capital, financial capital, social capital and market-linked assets [14]. From a Cultural Capital perspective, motifs, techniques and inherited knowledge need institutional support to become economically meaningful [15]. From a Value Chain Governance perspective, policy success depends on who controls pricing, orders, branding and buyer relationships [10, 11, 23, 24]. These lenses converge on one conclusion: isolated interventions are not enough. The review also links the embroidery form to broader debates on craft clusters and heritage preservation. Cluster literature suggests that geographically concentrated artisan systems can benefit from common facilities, collective marketing, training and institutional coordination when artisans are organized as active participants rather than passive beneficiaries [22, 25]. Heritage policy also emphasizes that living traditions require community participation and transmission, not only documentation [26]. Mukka embroidery therefore requires a policy model that connects cultural safeguarding with livelihood viability.

Table 4 indicates that the available evidence is stronger at the scheme and sector levels than at the artisan or household levels. This limits the extent to which the real benefits for Mukka artisans can be assessed. The findings suggest that policy support needs to move in a clear sequence, beginning with registration and training, followed by credit access, cultural recognition and stronger direct market linkages.

Table 4 - Evidence strength and policy gaps across review domains

Policy domain	Evidence strength	Main finding	Key gap
Sector growth and promotion	Moderate to strong at national level	Handicraft promotion infrastructure exists through national schemes and export institutions	No Mukka-specific export, sales or order-volume data
Artisan identification	Strong at national and state level	Pehchan can formalize artisans and connect them to schemes	No publicly available Mukka-wise Pehchan data
Skill and design development	Moderate	Training can improve human capital and product adaptation	Weak evidence on post-training income and repeat orders
Credit and financial inclusion	Moderate policy evidence	MUDRA-linked support can provide working capital	No Mukka-specific uptake, repayment or income evidence
Cluster development	Strong policy design evidence	Cluster approach can integrate SHGs, skills, design and markets	Barmer cluster needs independent outcome evaluation
GI and cultural recognition	Strong legal evidence for Kutch GI	GI can support branding and cultural recognition	Direct legal relevance to Barmer Mukka embroidery is unclear
Value-chain governance	Strong conceptual evidence	Intermediary control can limit artisan value capture	Need Mukka-specific value-chain mapping

Integrated Policy-to-Livelihood Model for Mukka Embroidery

Stage #	Model Dimension / Level	Primary Components & Initiatives	Key Outcomes & Strategic Focus
Step 1	**Policy Inputs**	• Pehchan registration • NHDP training • MUDRA credit	• Cluster development • GI / branding • Market promotion
Step 2	**Access Mechanisms**	• Local facilitation • SHGs / cooperatives • Documentation support	• Financial literacy • Scheme awareness
Step 3	**Capability Building**	• Skill upgradation • Design innovation • Product costing	• Digital readiness • Quality improvement
Step 4	**Market and Cultural Conversion**	• Direct buyers • E-commerce • Exhibitions	• Craft documentation • Authenticity branding
Step 5	**Artisan-level Outcomes**	• Higher income • Better bargaining power	• Reduced intermediary dependence • Youth participation
Step 6	**Long-term Result**	**Livelihood-sensitive preservation of Mukka embroidery**	

Source: Author's synthesis based on the systematic policy review

Figure 1 - Integrated policy-to-livelihood model for Mukka embroidery

Figure 1 brings the main findings together as a policy-to-livelihood pathway for Mukka embroidery. It shows that schemes such as registration, training, credit, cluster support, branding and market promotion can improve artisan livelihoods only when they are supported by local facilitation, SHGs, financial literacy and design guidance. Through this linkage, policy support can move beyond scheme access and contribute to better income, stronger bargaining power and continuity of the craft.

The model is intended to keep two concerns together: the economic life of artisans and the cultural life of the craft. It cautions against preserving Mukka embroidery without improving earnings, and against commercializing it without protecting community knowledge and craft identity. In this sense, it links welfare, enterprise, heritage and market reform.

Monitoring is the next policy concern. Existing documentation is richer on scheme design than on outcomes. Annual tracking of income, workdays, direct sales, Pehchan coverage, credit uptake, SHG strength, youth participation, product diversification and intermediary dependence would help distinguish participation from real livelihood improvement.

A third implication concerns GI and craft identity. Since the Kutch Embroidery GI cannot automatically be assumed to protect Barmer Mukka embroidery, the first requirement is legal and ethnographic clarification [19]. This should include documentation of motifs, techniques, production communities, geography, raw materials, product types and market identity. Only after this should policymakers decide whether Mukka embroidery requires separate GI recognition, authorized-user linkage or another form of formal cultural documentation.

Table 5 - Policy action matrix for Mukka embroidery

Policy gap	Recommended action	Expected outcome
Lack of craft-specific artisan data	Create a Mukka artisan registry linked with Pehchan, recording craft type, location, gender, skill level, income range and market channel	Better targeting and monitoring
Weak income impact of training	Link training with product costing, buyer feedback, order placement and post-training income tracking	Training becomes livelihood-oriented
Dependence on intermediaries	Develop SHG federations, cooperatives or producer collectives with transparent pricing and order allocation	Higher value capture and bargaining power
Risky credit access	Bundle MUDRA support with financial literacy, documentation help, order-linked repayment planning and SHG support	Safer and more productive credit use
Weak market linkage	Establish direct buyer networks, e-commerce support, exhibition handholding and institutional procurement channels	Sustained orders and reduced trader dependence
Unclear cultural/legal identity	Conduct ethnographic and legal assessment of Mukka embroidery for GI, authorized-user linkage or formal craft documentation	Stronger branding and heritage protection
Limited outcome evaluation	Monitor income, workdays, direct sales, credit uptake, youth participation, SHG strength and craft transmission annually	Evidence-based policy correction

A fourth implication is that direct market access must be treated as a governance issue. E-commerce, exhibitions and buyer-seller meets are useful only when artisans can control pricing, quality, branding and buyer relationships. Producer collectives, SHG federations or cooperatives can help shift bargaining power toward artisans. Without this, intermediaries may continue to capture most of the value even when the craft receives visibility.

Finally, the review identifies a clear research agenda. Future studies should conduct field surveys, interviews, time-use studies, income tracking and value-chain mapping in Barmer and adjoining Mukka-practicing areas. Longitudinal studies are especially needed to test whether cluster development, credit support, digital marketing and craft documentation produce sustained livelihood gains or only short-term visibility. Such research would be valuable for textile scholars, policy researchers, design institutions and government agencies.

This model transforms the craft from a passive cultural asset into the basis of a dynamic, formalized economy. It has been divided into three measurable priorities:

i. A registry linked to the Pehchan identity system is suggested to strengthen the targeting and monitoring of artisan support. It would capture basic artisan details such as craft type, location, skill level, market linkages, and participation in government programmes, thereby helping to organise and track policy delivery more effectively.

ii. Training programs are restructured from isolated events into measurable economic pipelines. Every skill and design workshop must integrate three commercial deliverables: a verified product-costing matrix, direct buyer feedback loops, and a formalized mechanism for tracking follow-up orders. Similarly, credit initiatives shift from stand-alone loans to demand-linked working capital. By integrating financial literacy modules and Self-Help Group (SHG) mutual-repayment frameworks, the model aims to reduce loan default risks while scaling credit utilization.

iii. To improve market equity, the model aggregates artisans into structured producer collectives, cooperatives, or SHG federations capable of managing high-volume orders, quality assurance protocols, standardized pricing, and client communications. This shift leverages direct market linkages, transparent costing structures, and producer-owned intellectual property to systematically reduce intermediary dependencies and improve the profit margins retained by creators.

4. Conclusions

This systematic policy review shows that Mukka embroidery is supported by several government interventions, including artisan identification, skill development, credit assistance, cluster development, market promotion and cultural recognition. However, the major challenge is not the absence of schemes, but their weak conversion into measurable livelihood gains for artisans. The review finds that isolated interventions have limited value unless they are integrated through a cluster-based, artisan-led model. Mukka embroidery should therefore be treated as a livelihood-sensitive heritage system, where cultural preservation is linked with income security, producer organization, safe credit, transparent pricing and direct market access. Future policy evaluation should focus on artisan-level indicators such as income, workdays, Pehchan coverage, credit uptake, direct sales, youth participation and reduced intermediary dependence. Such an approach can help sustain Mukka embroidery as both a cultural tradition and a dignified livelihood.

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Natural Fibre Based Leather Alternatives: A Review

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Abstract:

Leather made life style products are very popular in the commercial market. However, natural leather processing involves larger quantity of chemical consumption and effluent generation. Therefore, in the way of sustainable development, concept of natural leather mimicking technology emerged and current review highlights the different engineering techniques employed by the researchers for the development of agricultural biomass, bacterial cellulose based sustainable flexible composite for the usage as alternative to leather like material. It emphasizes research effort on the exploration of different natural fibres like jute, ramie, hemp, pineapple, bamboo, cotton etc. for making leather like products by using natural rubber and different polymeric matrices. This article also elaborates the methodology; mechanism used for engineering leather like products from natural fibre and other Agri-Resources. Current compilation registered surface morphologies, essential physical and performance properties of natural fibres and engineered leather products prepared from natural fibres. Besides, it also elucidates a detail review of manufacturing process conditions, chemicals, auxiliaries used for engineering natural fibre-based leather and compared it with the animal leather and marketed synthetic leather.

Keywords: *Cellulose, natural fibre, natural leather, Plant based leather, Physical properties*

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1. Introduction

Natural leather is a true gift of the nature and it is a highly precious material for making different life style items, apparel grade products, footwear etc., for day-to-day usage. However, processing of natural leather is not sustainable as series of cumbersome chemical treatments like salt treatment, lime treatment, pickling, acid treatment, chrome tanning etc., have been involved for processing of natural leather material in leather industries [1-3]. In general, effluent discharged by leather industries contains a larger quantity of inorganic salts, heavy metals, acid, alkali and other toxic deposition. All of these chemicals have directly and indirectly polluted discharged water and affect hygienic parameters of it. It affects aquatic life, flora and fauna of water bodies of country. Certainly, slaughtering of animals for raw hide extraction is also a critical social issue, as per government legislation. However, world wise, different research work is already going on for sustainable approaches of animal hide processing. Moreover, many multinational companies are also assisting to alter leather processing sequences with sustainable chemicals. Main elegancy of natural leather is that it has high tensile properties, impact and puncture resistance, chemical resistance, inherent fire resistance and also biodegradable in nature. Because of these high-end adjectives and cumbersome process conditions, products manufactured from natural leather are not economical and somehow difficult to afford by all class of people of society. Therefore, for meeting socio-economic demand, different products prepared from petroleum-based leathers are coming into the market, and the major advantages associated with the products developed from this technique are that they are economical [3]. Most of the synthetic leathers have been prepared by using synthetic fibre-based structure as backing material, coated with polyurethane or polyvinyl chloride based upper coating, however, not biodegradable and eco-friendly in nature. Indeed, different grade (cost wise different) polyurethane-based leather material is available in the commercial market as per demand and end uses [4]. Synthetic leathers don't have great tensile properties like natural leather but its production capacity and market availability are in higher range [5-7]. It is widely used in the domain of home furnishing, automotive, footwear and other technical textile grade applications. However, these products are not eco-friendly due to usage of synthetic polymers during manufacturing [7-9]. As discussed earlier, for footwear application, this might cause effects on the feet of the users due to the presence of microbes, fungus generation, and bad odor development due to continuous usage because of non-breathability and water vapor permeability [7-9]. Moreover, it is not biodegradable in nature [10, 11].

As the world is moving towards sustainable directions, developmental work on the field of mimicking natural leather was going on from last one decade. Researchers have taken multi technological approaches by using plant products, vegetables, regenerated bacterial cellulose, natural fibres etc., for mimicking natural leather by sustainable means [12-19]. Researchers and industrialists have developed cactus plant-based leather alternative, leaf-based leather, mushroom based leather, bacterial cellulose-based leather, mango peel-based leather alternative [12, 20 & 21] etc. Some of those engineered leathers are soft, flexible and have good mechanical properties, however availability of raw material,

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cost of engineering with sustainable polymer matrices are the major concern for product commercialization and scaling up [13, 20 & 21]. In this direction, the development of the leather alternative based on the natural fibre material is a good and appropriate development in the line of development. From earlier days, natural fibre like jute, ramie, hemp, bamboo, flax etc., have been used for making apparel, home textiles, different life style items etc., and it is close attached with our day to day social and cultural life [22-25]. Cellulosic and ligno-cellulosic fibres have good tensile properties and they are completely biodegradable [26, 27]. Elegant mechanical properties attracted researchers to use it as raw material for making leather like products. On the other hand, natural fibre of proteinous background is soft, non-conductive and extensible [27]. From last few years, different companies are marketing vegan leather, Agri-biomass like cactus, fruit, apple, fish scale-based leather in the market. Major advantage is that, no animal products or by products has been used directly or indirectly inside the finished leather products, however, in most of the cases availability of the resources is a big challenge. Moreover, synthetic polymers, synthetic resins also have been explored for getting leather like texture of final products. So, biodegradability is a major concern for the end products. In this way, plant-based adhesives, resin, natural rubber with natural fibre, Agri-biomass based reinforcement may be a suitable alternative for making the final leather like material [15-17, 28 & 29]. Incorporation of the cellulose and ligno-cellulosic biomass inside a biodegradable matrix improved tensile properties and other performance behavior of the composite materials. Leather alternatives made from protein fibre improved resiliency of the final product [1,12 & 13].

2. Biodegradable leather alternatives

Different natural resources have been explored for making sustainable leather like flexible composite materials. Researchers are also developing natural fibre -based leather. They have used different natural fibres like ramie, hemp, banana, jute etc., for making leather like materials. Even bacterial cellulose-based leather alternative is also emerging as upcoming development. Total classification chart of leather alternative is represented in Figure 1.

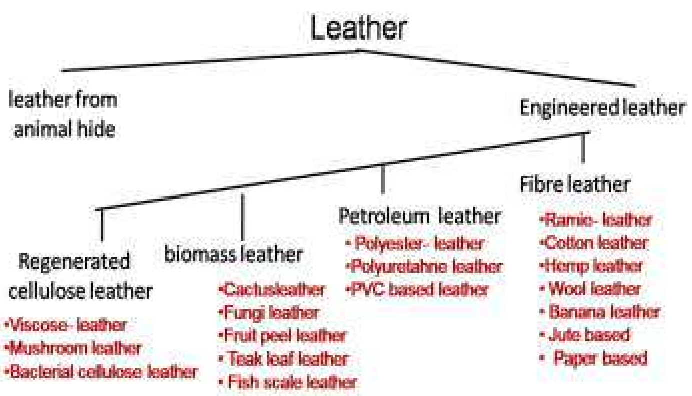


Figure 1 - Different kind of engineered leather available in the commercial market [1, 2, 15, 16, 29-32]

2.1 Different plant-based leather alternative

2.1.1 Fruit leather and cactus leather

Fruit skin based vegan leather has been developed by an Italian factory named FRUMAT and they are marketing it in the trade name Apple Skin™. Production firm adopted an innovative approach of exploration of the wastage of apple sauce and fruit juice industries. As per mentioned procedure, peels and juices of waste fruit materials have turned into powder mass and mixed with resin to give it a proper leather like shape and texture. However, polyurethane like synthetic polymer is one of the major ingredients of it and developed material is not biodegradable in nature [33]. Mango leather also has been prepared from pulp of mango peel and by using biodegradable polymeric matrices. Luxtra, a London based company launched new addition in the vegan domain by inclusion of mango pulp based sustainable leather like products in collaboration with Dutch company Fruit Leather Rotterdam [34]. They have made use of the wastage mangoes available in the commercial market to produce the leather. Like apple leather, wastage of mango pulp industries has been collected and dried into powder like materials to prevent bacteria, fungus or other toxic contaminations. Pulps of the mangoes are mixed with the other chemical auxiliaries, act as carrier material and dried, cured and pressed. Finally, pressed material was calendared at suitable temperature to get leather alternative product. However, the detailed technology of producing the leather is not registered with the researcher on the open platform [20].

2.1.2 Mushroom leather

Mushroom and mycelium are mainly glucose and chitosan-based material and it forms leather like layer on different kind of Agri-biomass, wood etc., on deposition for a long time period [23,36]. Mainly it is composed of polysaccharide glucoses and nitrogen-based chitin. Mycelia based leather could be produced by using ligno-cellulosic material saw dust etc. It supports mycelium growth into a thick fabric like composite sheet having good compressive strength. After certain time period of exposure in particular temperature and humidity mycelium spores are harvested from saw dust and mechanically and chemically processed. Mycelium sheet was treated with glycerol or sorbitol for moisture absorbency, fungal protection and dipped with alkali and acid for a specific time period. This treatment assists to remove carbohydrate and protein and deacetylation of chitin with the creation of cross-linking sites. Treated material was pressed and plasticizer was added for improving flexibility and stretch ability of the developed leather. Thereafter different color or pattern could be added on its surface [23,36]. Pictorial depiction of mushroom leather is represented in Figure 2. As of physical properties are concerned, mycelia leather is soft, flexible, however, tear strength, impact and tensile strength is comparatively lower as it has no strength reinforcement support inside the flexible structure. Mycelia fibres have lower length and low strength due to lack of chain molecule orientation in its structure.

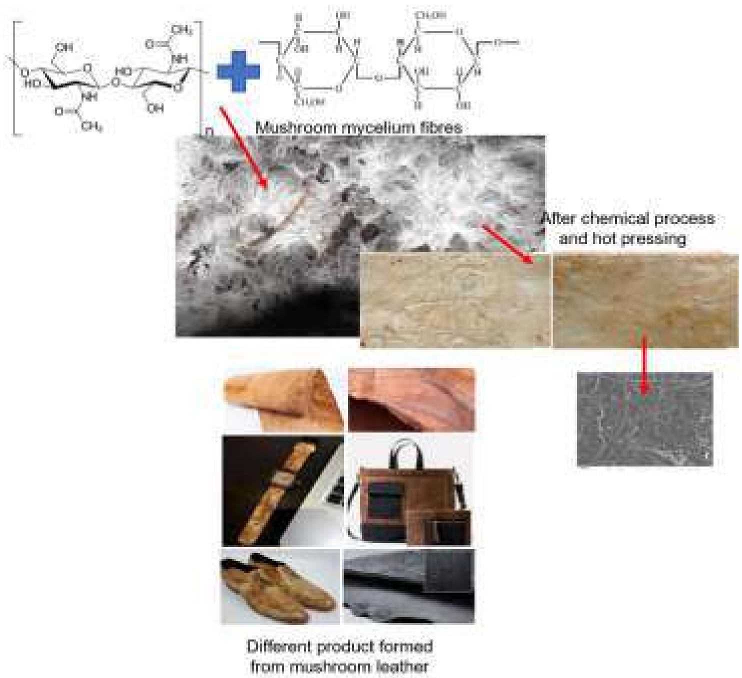


Figure 2 - Development of mushroom leather and different products made from it [23, 36 & 37]

2.1.3 Snap-pap and teak leaf leather

Snap pap leather is one of the fashionable leathers like product available in the western market. Mainly it is composed of 60% cellulose and 40% natural adhesive. The thickness of the snap pap leather is around 0.5mm - 0.6 mm. Different colors like light brown, dark brown, black etc., could be possible on snap pap leather. Developed leather product could be easily washed in Luke warm water and ironed [38]. Teak leaf leather is another type of leaf based vegan leather. Mainly it is made with wastage leaf and laminated coatings. Wastage leaves are used for the development of teak leaf leather. Leaves are dyed with different shades of color. After dyeing, leaves are coated with a non-toxic lamination coating. In addition, teak leaf leather can be developed using a combination of plant leaves and cotton fibers. Moreover, it is also developed using a combination of plant leaves, cotton fibers, and eco-friendly resin adhesive. The developed composite material is similar to leather. In addition, it is a waterproof, lightweight, and high tear resistant composite material [38].

2.1.4 Leather from bacteria regenerated cellulose

Bacterial cellulose-based leather is another scientific approach to mimic natural animal leather. Recently [21]. has produced bacterial cellulose-based leather. They have produced bacterial cellulose-based leather by taking the coconut water. They have kept the coconuts in sterilized water for the growth of bacteria. Jelly-like substances have been produced after 12-14 days of impregnation in the water. They have then mixed the substance with banana fibres or gum and produced continuous 3D sheet of natural leather like material. They have then dried the sheet and made it soft for the usage of the produced material into different products like footwear, bags [21]. Apart from coconut shell cellulose fibres also could be produced by members of the genera komagatacibacter, members of K. Xylinium (bacteria ingested as part of Kombucha Tea). This bacterium may produce pellicles of cellulose, either alone or in combination with other bacteria [39]. Generated cellulose accumulated in the extra cellular medium, dried and develop leather like structure as shown in Figure 3. Bacterial cellulose could be bleached by hydrogen peroxide and can be dyed with natural coffee extract. Bacterial cellulose treated with coffee extract could also be dyed with basic methylene blue dye to get different range of shades in the leather product. One carbon source and nitrogen source is required on Kombucha culture for bacteria growth at around 26°C for 7-8 days with a fixed material to liquor ratio. Developed cellulose is washed with acid and alkali, acetylated and pressed at higher temperature for getting leather alternative [40].

Bacterial cellulose also has been used for making vegan leather. Bacterial cellulose film was synthesized from AcetobacterXylinum, a common bacteria found in soil. Synthesized bacterial cellulose is almost look like animal leather [39]. Komagataeibacte (genre) bacteria also has been used for cellulose synthesize and it forms bacterial colony in presence of tea leaves. Cellulose film produced by those bacteria has been dried and look like a soft leather like material [19, 39]. Bacterial cellulose based leather could be very much useful for making inner footwear parts and softness of this leather can attract orthopedic patients.

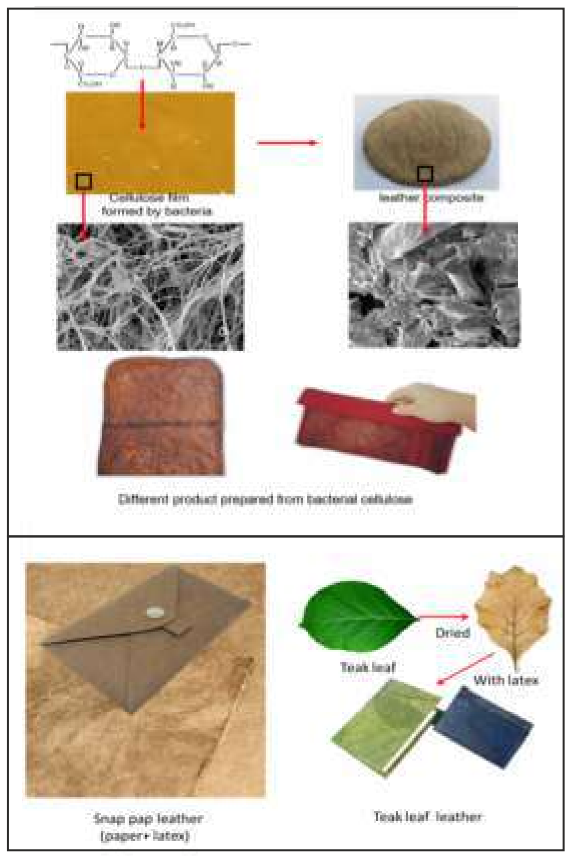
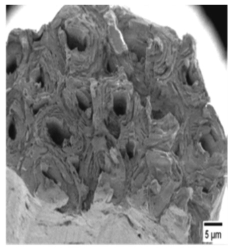
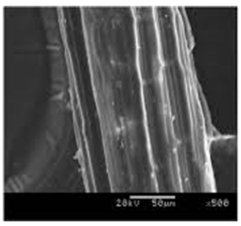
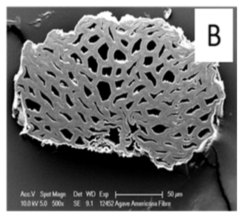
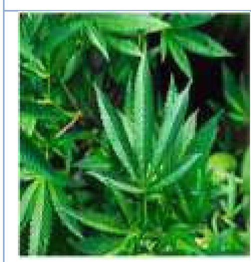
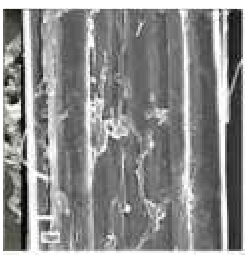
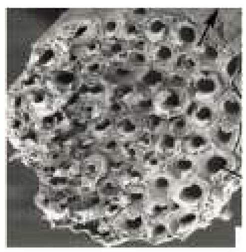
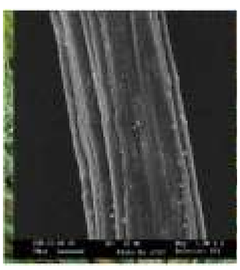
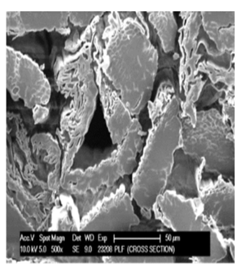
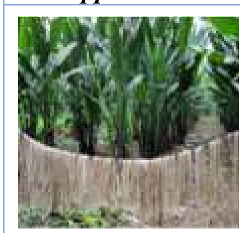
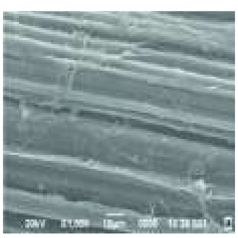
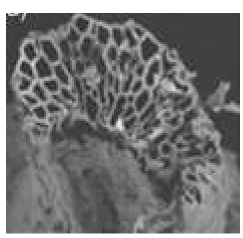


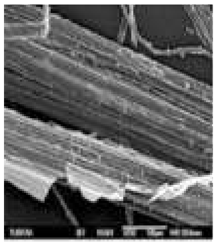
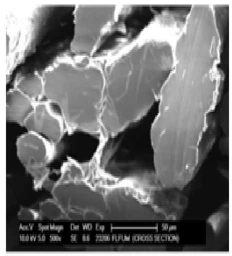
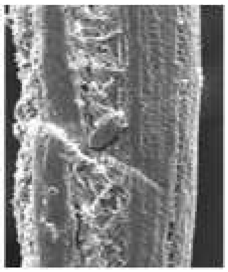
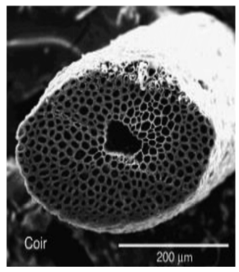
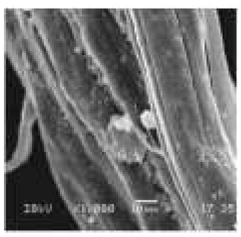
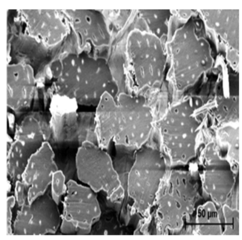
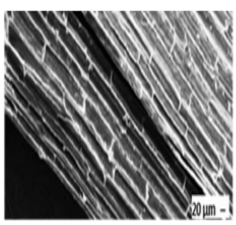
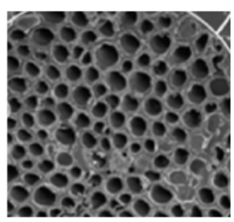
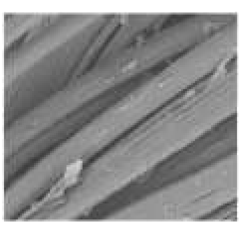
Figure 3 - Bacterial cellulose based, waste paper, plant leaf-based leather like products [21, 38-40]

2.2 Different Natural fibres and fibre-based leather alternatives

Some of the natural fibres have very good potential to be used as leather alternative products which are completely biodegradable. Properties of the natural fibres are mentioned and leather alternative prepared from those fibres are also registered in the context. A brief technical description is represented on the explored ligno-cellulosic fibres in Table 1 as under:

Table 1- Different natural fibre used for making leather alternative and its properties [41-44]

Plant Appearance [4,15,20]	SEM Appearance [41,43]	Cross sectional Appearance [41,43]	Chemical composition [41,43,44]	Physical properties [41,42]
 ***Ramie***			68-75% cellulose, 13-15% hemi-cellulose, 3% lignin, pectin and sugar-based material and 5-7% water soluble extractives, little fat and greases	Elongation (%):3.0-4.0% Density (g/cc): 1.50-1.55 Fineness (tex): 0.4-0.8 Tensile Strength: 40-65 g/tex
 ***Sisal***			composed of cellulose 65-68%, hemi-cellulose 13-15%, lignin9-10% and wax, pectin is around 1%	Elongation (%):2.5-4.5 Density(g/cc): 1.30-1.45 Fineness (tex): 16-35 Tensile Strength: 40-50 g/tex
 ***Hemp***			composed of cellulose 65-68%, hemi-cellulose 13-15% lignin, 9-10% and wax, pectin is around 1%	Elongation (%): 2.5-4.5 Density (g/cc): 1.30-1.45 Fineness (tex): 5-15 Tensile Strength: 40-50 g/tex
 ***Pineapple***			80% cellulose, 6–12% hemicellulose, and 5–12% lignin	Elongation (%): 2.5-4 Density (g/cc): 1.35-1.38 Fineness (tex): 2.5-6 Tensile Strength: 25-45 g/tex
 ***Banana***			60-65% cellulose, banana fiber also contains 6-19 percent of hemicellulose, 5-10 percent of lignin and 3-5 percent of pectin.	Elongation (%): 1.8-3.5 Density (g/cc): 1.35-1.38 Fineness (tex) :3-12 Tensile Strength: 30-40 g/tex

Plant Appearance [4,15,20]	SEM Appearance [41,43]	Cross sectional Appearance [41,43]	Chemical composition [41,43,44]	Physical properties [41,42]
 ***Flax***			70-85% cellulose, 11-20% hemicelluloses, 2-12% pectin, and about 2% lignin with several minor extractives, such as fat, wax, protein, tannins, dyes, inorganic salts etc.	Elongation (%) 2.5-3.5 Density (g/cc): 1.28-1.3gm/cc Fineness (tex): 2.5-6 Tensile Strength: 45-55 g/tex
 ***Coir***			40-45% cellulose, 45-48% lignin and 2.2% ash content	Elongation (%): 20-30% Density(g/cc): 1.40-1.43 Fineness (tex): 8-10 Tensile Strength: 10-12 g/tex
 ***Jute***			60-64% cellulose, 10-12% lignin and 20-22% hemi-cellulose	Elongation (%):1-1.8 Density (g/cc): 1.52-1.55 Fineness (tex): 0.9-4.0 Tensile Strength: 30-45 g/tex
 ***Sunhemp***			60-64% cellulose, 14-15% lignin and 18-19% hemi-cellulose	Elongation (%):2.5-3.5 Density (g/cc): 1.22-1.30 Fineness (tex): 1-1.5 Tensile Strength: 30-40 g/tex
 ***Nettle***			80-86% cellulose, 3-4% lignin and 8-9% hemi-cellulose	Elongation (%)3.5-4.5% Density (g/cc) 1.4-1.5 Fineness (tex): Tensile Strength: 75-78 cN/tex

2.2.1 Ramie and hemp fibre-based leather alternative

In the last few years, different research work is going on the development of natural fibre-based biodegradable vegan leather. In this direction, recently a group of scientists of ICAR-NINFET have developed vegan leather from ramie fibre. Indeed, decorticated ramie fibre comprises 25-30% gum predominantly of hemi-cellulose, pectin, and other lignin- and tannin-based polyphenolic compounds. Therefore, pristine ramie fibre is harsh in nature and its surface was modified by using alkali-based formulation.

Table 2 - Tensile and other physical properties of the leather alternative [4]

Physical parameters	Control ramie non-woven	Ramie fibre and natural rubber-based leather alternative with varying hot pressing/ curing time			Natural leather
		4 min	6 min	8 min	
Tenacity (N/mm^2) in length direction*	1.02 (7.4%)	4.10 (3.4%)	5.05(2.3%)	5.51 (3.2%)	12-13 (0.5%)
Tensile strain at break* (%)	42.11(7.5%)	28.17 (2.5%)	27.32 (2.8%)	32.08 (3.1%)	70.48 (0.3%)
Tear strength (N/mm)*	36.45 (4.7%)	74.21(2.2%)	75.13 (2.1%)	65.2 (4.2%)	276 (0.6%)
Puncture resistance (N/mm)	137 (6.8%)	210 (3.4%)	200 (4.5%)	220 (5.4%)	585 (0.4%)
Energy for puncture (mJ)**	768 (6.9%)	820 (2.2%)	830 (2.2%)	725 (3.2%)	4090 (0.5%)
Swelling (wt%)	300% (10%)	27.70 (2.5%)	47.40 (2.4%)	60.63 (4.4%)	32 (0.8%)
Hot water shrinkage (%)	Length wise 4.5% and width wise 5.26%	No shrinkage in both direction	No shrinkage in both direction	No shrinkage in both direction	Length wise it is 3% and width wise 2%

*Note: *Mean value of three samples, **Mean value of five samples*
Parentheses elucidate CV% of all data represented in the Table 2

Degummed ramie fibre is finer, light weight and having less fibre diameter. Mechanically interlocked fibrous structure has been prepared from surface modified ramie fibre and was coated with the mixed formulation of natural rubber, Sulphur dispersion, accelerator, activator, stabilizer, natural filler antioxidant etc., and vulcanized in different temperature and time period [4]. Performance parameters of the developed soft composite material are represented in Table 2. Research work also has been performed by using bleached ramie fibre blended with scoured proteinous wool fiber in different percentages (10, 20, 30 percent of fibre weight/volume) for making the non-woven structure having area density of 250 g/m2. Front side of the developed natural fibre-based composite was coated with pigment and polyurethane resin-based formulation so that the percentage of synthetic polymer present on the upside of the sample is only bound within1% [12].

Hemp fibre also has been used by same research group for development of vegan leather. Hemp fibre has been extracted by following alkali based (1-2% w/w) gum removal treatment. Extracted hemp fibre is finer and having light weight as compared to the common ligno-cellulosic fibre like jute. Hemp fibre surface was modified by using enzyme treatment so that it can easily form bridging groups with natural rubber-based formulation. Henceforth, hemp matt coated with natural rubber has been developed and performance properties of the composite are almost equal to the cotton fibre based flexible composite.

2.2.2 Pineapple fibre-based leather alternative

Pineapple waste and pineapple leaf fibre also has been used for making leather like flexible composite materials. Annas Anam a famous brand launched pineapple waste-based leather in the commercial market whereas Hugo Boss a western fashion house introduced Pinatex, a pineapple fibre-based leather. They have used Pinatex for making upper part of the shoe and other footwear products like sneakers, chappal etc. Pinatex leather is vegan, however, they did not claim that the Pinatex based products developed by them is biodegradable in nature [12, 46 & 47].

They have prepared the shoe upper using “Pinatex.” The upper part is prepared using pineapple leaf fibre, which is dyed using natural dyes. Fibre yield percentage from pineapple leaf is around 1-2%. Pinatex was prepared by cellulose fibres extracted from pineapple leaf, poly lactic acid and petroleum resin. Pinatex fibre was used for making different shoe parts and footwear upper materials. Main elegancy of Pinatex is that it is soft, light weight and it has good moisture vapour permeation property. Manufacturer also made it water and dust repellent for commercial usage [46].

2.2.3 Banana and jute fibre-based leather

Banana leather is an edible semi-pliant sheet derived from a dried banana mixture. Banana stem fibers mixed with biodegradable matrices and dried to create a leather alternative. The environmental impact of this leather alternative is much lower compared to both animal and plastic leather. Five years before, scientists have prepared jute cotton fibre-based leather like flexible composite for using it in different footwear parts. According to the published document, union fabric was treated with the mixed formulation of polystyrene, polyvinyl alcohol, filler, plasticizer and solvent in suitable stoichiometric ratio. Finished material has been used for the preparation of toe puff, insole, etc. The researchers have claimed that the products prepared by the manufacturing process have more shape retention property than the natural leather [47].

Another research group prepared jute non-woven matt based flexible composite by using polyvinyl alcohol polymer as matrix. Treated jute based flexible composite has been pressed in hot press machine in presence of heat energy. Developed composite material has thickness 1-1.2 mm, has superior tensile properties, having tensile strength more than 8 N/mm2 and elongation beyond 10% and flexing sustains beyond 50000 cycles. Finally, developed flexible composite was used for making different life style products for daily usage.

3. Flexible composite based on cellulose, protein fibre and their blends

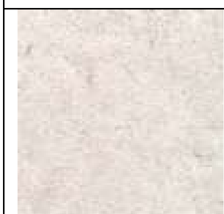
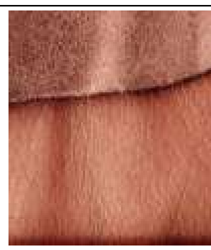
Combination of cellulosic natural fibre and triglyceride-based plant oil also has been used for making leather like material. According to their report, different viscosity oils like soybean oil, linseed oil, and fatty acid, and acrylate monomer-based coating have been done on the flax and kenaf fibre-based matt structure. The flexible composite structure is almost like the synthetic leather. Natural fibres like sisal, wool, pineapple, flax have been used for mimicking natural leather. One research group reported that sisal-wool and pineapple fibre-wool based flexible composite have shown almost similar tensile and performance properties like natural leather in terms of fullness, strength and resiliency. They also have claimed that the developed leather like material is biodegradable in nature [2]. Furthermore, the same research group have also developed wool fiber-based flexible composite using natural rubber-based formulation. In this context, the research group has pre-treated the wool fiber with sodium lignosulfonate to create the necessary functional groups on the wool fiber surface. The methyl group present in the lignin structure is able to react with the negatively charged carboxylic group present in the wool polymer chain. On the other hand, the lignin present is helpful to hold the rubber molecules on the wool fiber-based reinforcement [48]. As of performance properties, they have claimed that the developed product has shown excellent resiliency, softness and elongation properties, but tensile as well as tear strength is low compared to natural leather, synthetic leather, and reinforced leather like material based on cellulose alone. Recently, one more research group has adopted tertiary combination of hemp fabric, denim fabric, and cellulosic fibre matt and biodegradable resin for developing leather like material. Performance properties of the developed material have been compared with calf leather and pig leather of the same weight and thickness in terms of break force and total heat loss [2, 48].

Very recently, cellulose-protein fibre based (80: 20 and 70: 30 blend ratio) mechanically, which is locked in a fiber structure and then made into a composite for vegan leather production. According to the published report, the fiber structure locked composite has been coated with a natural rubber-based formulation and heat pressed for 3 to 5 minutes. Developed flexible composite has high resiliency and flexing action due to the presence of protein fibre as reinforcement combination. It may be due to the fact; that highly elastic polymer alpha keratin presents in wool fibre assist in flexibility of the resultant composite material. However, tensile strength of the flexible composite is around 10% lower as compared to a composite made from a cellulose fiber-based reinforcement material. Moreover, fullness and softness of the composite is also superior as compared to the pristine cellulose based flexible composite [12,49]. Figure 4 shows the variety of cotton fibre reinforced biodegradable vegan leather products developed.

Only cotton fibre based vegan leather also has been prepared by group of researchers at ICAR-NINFET. Main technical advantage is that cotton fibre based biodegradable leather shows high flex resistance of around 150000 cycles whereas tear strength is around 90-120 N/mm. High flexing resistance and tear strength may be attributed with the fineness, lower weight and length of cotton fibre. On the other hand, due to inherent softness of cotton fibre, it did not require any kind of chemical-based pretreatment for compatibility with natural rubber or other natural resin based biodegradable formulation. Therefore, total cost involved for manufacturing of cotton fibre reinforced vegan leather is much lower compared to the leather produced from ligno-cellulosic fibre, other Agri-biomass and cellulose-protein fibre-based combinations [49].

Figure 4 - Products prepared from cellulose and cellulose-protein fibre-based leather alternatives

Table 3 - Comparison of the performance properties of the natural fibre-based leathers with marketed synthetic leathers and natural leathers [4, 12]

Nonwoven Appearance	Physical properties of non-woven	Leather Appearance	Physical properties of the fibre-based leather alternatives			
			Tensile strength (N/mm^2)	Elongation (%)	Tear strength (N)	Flexing test
 Banana	Tenacity (N/mm^2): 0.5 N/mm^2 Elongation: 34% Tear strength: 2-3 N		2-3[3.4%]	14.6 [1.9%]	36.34 [2.4%]	5000 [6.7%]
 Jute	Tenacity (N/mm^2): 1-1.2 N/mm^2 Tear strength: 5-6 N Elongation: 24%		4-5[2.5%]	13 [2%]	74.2 [3%]	5000 [2.3%]
 Ramie	Tenacity (N/mm^2): 1.2-1.3 N/mm^2 Tear strength: 6-8 N Elongation: 40-45%		5-6 [0.95%]	22 [45.32%]	86.45 [40.23]	40,000 [1.2%]
 Hemp	Tenacity (N/mm^2): 1-1.5 N/mm^2 Elongation: 40% Tear strength: 5-7 N		6-8 [4%]	20 [2.2%]	105.12 [4%]	70,000 [4.6%]
Natural Leather	Tenacity (N/mm^2): 12-14 N/mm^2 Elongation: 70% Tear strength: 200 N		12-14 [1.5%]	70% [3%]	200 N [1.2%]	150000 [1.2%]
Synthetic Leather	Tenacity (N/mm^2): 3-4 N/mm^2 Elongation: 110% Tear strength: 45 N		3-4 [1.3%]	110 [3%]	45 [1.2%]	25000 [3.4%]

4. Mechanism of fibre based leather formation

Surface morphologies and cross-section of the natural fibres popularly and potentially used for making leather alternatives are represented in Table 1. As of published figures, cross-sectional morphologies of ramie and hemp fibre have shown holes inside fibre structure. It helps to obtain more soft leather alternative with the help of the fibre as compared to the jute fibre, which may be due to the presence of holes inside the fibre structure. It is also important to understand the mechanism lies behind the interaction of natural fibre and natural rubber molecules. The presence of cross-linked natural rubber structure attached with the -OH group of cellulose (main backbone of ramie) by formation of (C-O-C) ether linkage in alkaline condition. Accelerator and activator present in the latex formulation have controlled the scientific parameters like time, cross-linking rate of latex vulcanization process. The primary hydroxyl (-OH) group of cellulose is highly reactive in nature and is prone to react with the rubber chain with the help of the electron transfer reaction or the Vander walls force of attraction [12]. The latex and natural fibre based flexible composite was applied with the mixed formulation of polyurethane cross-linker, resin, hydrophobic silicon, and pigment for mimicking natural leather surface and texture. Total coating process on fibre reinforced flexible composite was performed in two to three steps. On the other hand, natural leather is made up of protein groups, amino acid groups, collagen fibers, etc. Natural wet blue leather includes a process known as the heavy metal treatment process, which is applied to the pickled leather. In this scientific process, a highly oriented proteinous structure was attached to the natural leather with a highly valent chromium. As mentioned in the earlier section, bio leathers also have been prepared from cactus pulp, fruit pulp, mango pulp etc., and in most of the cases with pulp, one crosslinking polymer like polyurethane, poly vinyl chloride or other resin has been used for getting proper tensile properties of the developed leather like material. Agri-pulp mainly contain cellulose and proteinous matter, act as reinforcement of the developed leather like composite material. Protein part assist to provide resiliency and softness of the final product developed from it. In the case of bacterial cellulose-based leather, the degree of polymerization of the cellulose is relatively lower compared to the fibre cellulose. Therefore, the leather product derived from bacterial cellulose-based reinforcement would have lower tensile properties unless a filler of value is added to the formulation.

5. Conclusion and future thrust

Natural leather processing used a high level of toxic chemical compounds and animal slaughter, although it provides advantages like bio-degradable, renewable nature, softness and breathable. On the other hand, synthetic leathers made by PVC and PU have emerged as alternatives to natural leather. However, the use of petroleum-based PVC and PU also poses a significant environment concern. For mitigating this effect, recently researchers have developed plant based and regenerated cellulose-based leather based on cactus, mango, mushroom and bacterial cellulose. Developed products are soft, flexible and biodegradable, and have gradually entered the commercial market. Researchers have used different scientific methods to develop the natural leather substitutes. Natural fibre based reinforcing material may be engineered in terms of woven, non-woven, knitted, layered structure. Fine fibres like ramie, hemp, cotton have provided better leather like appearance. Incorporation of wool fibre in combination of other cellulosic and ligno-cellulosic fibre has improved flexibility and softness. In spite of having immense potential of commercial success, this arena is suffering some serious technical issues. Softness, flexibility and surface appearance of the leather alternatives developed from coarser grade natural fibres like jute, banana, sisal etc., are real challenges. Only a limited number of studies have explored structural modifications in this field. The random orientation of protein fibres presents in natural leather contributes to vapour permeation through its structure and it is lighter as compared to the fibrous leather material. Chemical composition of natural fibres is varying with fibre to fibre and growing locations. Therefore, pretreatment methods must be optimized to improve compatibility with latex or other polymeric matrices. Finally, research work on thin PU coating (add-on% 1-2 on weight of material) is require to optimize coating layer quantification for better abrasion properties. Scientific intervention is also required to replace PU coating with natural bio based coating of natural fibre based flexible composite to achieve leather alternative material. This process will assist to achieve leather like coated, completely biodegradable, breathable, moisture vapour permeable flexible composite.

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Vilas Gharat

Mr. Vilas Gharat is working as a Managing Director, for Gharat & Associates, having over 50 years' experience in manufacturing function in all composite sectors of Textile Industry. Out of which more than a decade in Operations and HR with emphasis in Business Process Consulting,

Mr. Gharat is having Specialization in various field of textile value chain like;

- Change Management, Business Development and Project Management
- Project Management, Business Development
- Supply Chain Management
- Resource Allocation
- Process Reengineering
- Change Management, Production and Business
- Planning Function
- Training and Mentoring CEO's

He has wide experience in:

Business Consultant for Oswal Hammerle, for their upcoming state of art technology plant for manufacture of sophisticated Yarn Dyed Shirting Project, primarily catering to the needs of international garment manufacturers. This is a Joint Venture project of Oswal group and F.M. Hammerle (Austria)

His previous assignment involves restructuring and transformation of a large Textile units

He worked with various executive capacities as Executive Director -Suvin Advisors Pvt Ltd.; Senior President in S Kumar's., Technical & Commercial Advisor in J. K. Cotton Mills, Senior President in Morarjee Brembana Ltd., Birla's in Indonesia, Oswal Hammerle, Bhojsons, Nigeria etc.

Awards:

Mr. Gharat was awarded with Best General Manager Award in MSTC - National Award for energy conservation for Simplex Mills & MSTC and Best Vendor Award from Johnson & Johnson.

Mr. Gharat was awarded with FTA by The Textile Association (India) in 1999,

Mr. Vilas Gharat was a President of The Textile Association (India) - Mumbai Unit during 2017-2019 and 2019-2021. Now he is on the Board of Trustees of TAI – Mumbai Unit.

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Uniform Market 2026

By **Mr. Vilas Gharat**

Founder & M.D. (Gharat & Associates); Board Member of Trustees (The Textile Association (India) – Mumbai Unit; Gem of Mentor India (AIM – Niti Aayog, Govt. of India; Mentor (Women Entrepreneurs Platform; Expert Evaluator (Ministry of Education)

The Global Uniform Revolution: Technology, Sustainability, and the Shift Toward Performance Wear

The global uniform and workwear market is undergoing a profound structural transformation. No longer defined by rigid, one-size-fits-all designs, the modern uniform industry has evolved into a highly technical, multi-billion-dollar ecosystem.

Driven by rapid technological integration, corporate sustainability mandates, and a post-pandemic focus on worker comfort, the market is breaking away from traditional retail cycles to chart a highly lucrative, resilient growth path.

1. The Financial Architecture: Resilient Scale

The global uniform market enters 2026 split into three distinct, high-volume pillars, heavily insulated from standard economic downturns by institutional mandates.

GLOBAL UNIFORM MARKET (2026)

Corporate/Workwear	Healthcare Apparel	School Uniforms
$94.81 Billion	$55B - $130 Billion	$32B - $38.4 Billion
(Proj: $140.53B by 2035)	(CAGR: 6.7% - 10.5%)	(Proj: $60B- $90B by 2035)

Corporate & General Workwear

Valued at approximately USD 94.81 Billion, this segment is projected to scale to USD 140.53 Billion by 2035 at a steady 4.5% CAGR. Demand is led by general workwear for logistics and warehousing (41%), followed by specialized professional/safety gear (34%) and traditional service uniforms for aviation and hospitality (25%). Heavy industrial sectors driven by over 220 million construction workers globally command a dominant 34% market share.

Healthcare & Hospital Uniforms

Spurred by strict hygiene protocols and expanding medical workforces, the broader medical apparel market sits between USD 55 Billion and USD 130 Billion, expanding at an accelerated 6.7% to 10.5% CAGR. While North America remains the largest consumer zone (40% of global value), the Asia-Pacific region has emerged as the fastest-growing market and the primary global sourcing engine.

The School Uniform Market

A naturally resilient sector, the global school wear market enters the year valued at USD 32 Billion to USD 38.4 Billion, on track to skyrocket to between USD 60 Billion and USD 90 Billion by 2035 (7.3% to 10.4% CAGR). Volume consumption now exceeds 9.4 billion individual garments annually, with four emerging economies India, China, Nigeria, and Indonesia driving nearly half (49%) of the entire world's demand.

2. Next-Gen Textile Engineering & The Circular Economy

The fundamental chemistry of uniform fabric is being rewritten to balance environmental targets with industrial durability.

- The Circular Eco-Uniform Shift: Brand owners and educational trusts are aggressively migrating away from virgin polyester toward recycled polyester, organic cotton, and bamboo blends. Annually, over 765 million school uniform units are now manufactured using these sustainable materials, largely out of green production hubs in India, Bangladesh, and Vietnam. Furthermore, closed-loop garment take-back schemes are becoming standard practice to hit net-zero targets.

- Fluorocarbon Polymers & Advanced Protection: For industrial and tactical environments, textiles are being treated with invisible, microscopic fluorocarbon polymer films. This creates oil-, dust-, and chemical-proof surfaces that protect the worker while remaining entirely non-irritant during long shifts.
- Active Performance Weaves: Borrowing heavily from modern athletic wear, modern uniforms are embedding four-way stretch, moisture-wicking, and antimicrobial properties directly into everyday garments even formal school blazers and corporate suits.

3. Style Evolution: The Death of the "Boxy" Cut

A distinct aesthetic shift is occurring across all professional environments, prioritizing movement, climate adaptability, and modern branding.

- Athletic Scrubs: Spearheaded by direct-to-consumer digital brands, hospital uniforms have undergone a massive retail upgrade. The historical boxy, oversized cotton scrub has been replaced by athletic-style cuts, tapered jogger pants, and flexible performance fabric blends engineered for intense 12-hour shifts.
- The Premium Executive Look: For customer-facing roles in aviation, banking, and luxury hospitality, organizations are leaning into sharply tailored, poly-wool stretch blends. These garments maintain a crisp, wrinkle-free structural profile through extended wear while subtly reflecting corporate identity.
- Smart-Casual Tech Style: As offices adopt relaxed dress codes, the fastest-growing corporate segment features coordinated professional knit polos, lightweight structured vests, and comfortable chinos—blending athletic comfort with professional optics.

4. Digital Transformation & Structural Challenges

The operational backend of the uniform industry has successfully migrated from manual, fragmented ordering systems to sophisticated B2B e-commerce architectures.

Suppliers now build dedicated, private digital storefronts for enterprise clients. Whether managing a global airline with 50,000 employees or a regional hospital network, these platforms seamlessly handle automated point-allowance accounts, complex regional embroidery guidelines, and automated reorder triggers via direct ERP integration. In the retail school wear sector, virtual sizing tools have become vital to cutting down historical return rates for parents.

Market Vulnerabilities

Despite predictable bulk demand, the sector faces two key head-winds:

1. Raw Material Volatility: Squeezed profit margins, caused by fluctuating global textile input costs, affect nearly a third of worldwide manufacturers.

2. The Second-Hand Surge: Inflationary pressures have accelerated consumer adoption of peer-to-peer second-hand networks and institutional hand-me-down programs, capping the net volume expansion of primary retail sales.

Conclusion: The Path Forward

The uniform market has evolved past simple clothing to become a vital intersection of technical textiles, corporate identity, and digital logistics. Driven by state-sponsored equity programs—such as India's massive Samagra Shiksha initiative and rising corporate compliance, the manufacturers who master sustainable, high-performance fabric blends and seamless B2B digital delivery are set to lead this high-volume global market.

Scaling Sustainable Technical Textiles in India's Government Procurement

Transitioning state bulk procurement—such as the Samagra Shiksha school uniform mandate and the Ayushman Bharat healthcare lines into high-performance, circular technical textiles represents a multi-billion-dollar opportunity for India. It aligns national social equity initiatives with the National Technical

Textiles Mission (NTTM) and the Viksit Bharat Net-Zero targets.

UPSTREAM INDUSTRY | DOWNSTREAM IMPACT
• NTTM Research & R&D | • 100M+ School Students
• PM MITRA Textile Parks → • Strict Laboratory Specs
• 5F Vision Implementation | • Mass Economic Equity
FEEDBACK LOOP

Achieving this requires addressing distinct structural bottlenecks through an actionable roadmap.

1. Regulatory Overhaul: Upgrading standard specifications

Currently, government uniform tenders primarily focus on low-cost cotton-polyester weaves governed by rigid budget ceilings (e.g., ₹600 per child for two complete pairs under Samagra Shiksha). To scale technical textiles, the Bureau of Indian Standards (BIS) and the Ministry of Education must update tender criteria:

- Mandate Performance Metrics: Shift from simple thread-counts to active performance standards. Tenders should explicitly specify moisture-wicking indices, antimicrobial activity (IS 17584), and stain/fluid resistance via fluorocarbon-free formulations.
- Decentralized Lab Testing: Leverage the template set by progressive states (like Assam's use of the Assam Textile Institute) to build institutionalized, block-level quality control testing pipelines. This helps enforce strict compliance while filtering out substandard, short-lifecycle generic fabrics.

2. Supply Chain Mobilization via PM MITRA & MSMEs

India's technical textile infrastructure remains highly fragmented, with over 80% of capacity situated in the MSME sector. Government contracts can unify this supply chain through targeted manufacturing frameworks:

- Integrated Mega-Hubs: Utilize the PM MITRA (Mega Integrated Textile Region and Apparel) Parks to cluster recycling units, spinning mills, and performance-finishing facilities. This operationalizes the Government's 5F Vision (Farm to Fiber to Factory to Fashion to Foreign) by minimizing processing logistics and cutting input costs.
- Financial Subsidies for Green Tech: Deploy the capital incentives of the MSE-SPICE (Scheme for Promotion and Investment in Circular Economy) and MSE-GIFT schemes. Providing 25% capital support and interest subventions allows small-scale weavers to upgrade to the technical machinery needed for advanced synthetic blends.

3. Implementing a Circular Economy Framework

To offset the premium costs of technical textiles, procurement models must shift from a Linear Purchase mindset to a Closed-Loop Lifecycle:

[Virgin Raw Materials] → [Precision Manufacturing] → [Institutional Distribution]
↑ ↓
[Chemical/Mechanical] ← [Aggregation & Sorting] ← [Take-Back Mandates]

Recycling

- Institutional Take-Back Systems: Insert an Extended Producer Responsibility (EPR) clause into high-volume institutional contracts. At the end of an academic year or hospital cycle, used uniforms can be systematically collected via school management committees (SMCs) and regional civic bodies.

- Recycling Infrastructure: Divert gathered uniform waste into domestic mechanical and chemical recycling networks. This raw material directly feeds back into the value chain as recycled polyester (rPET) and blended insulation materials, supporting India's growing $3.5 billion textile recycling target.

4. Financial Restructuring & Life-Cycle Costing

The primary friction point for technical textiles is the initial price difference compared to cheap, unrefined fabrics. Resolving this requires a change in how public funds are evaluated:

- Value-Based Procurement (L1 vs. Quality): The General Financial Rules (GFR) should be adjusted for specific institutional wear, shifting the focus from the lowest upfront bidder (L1) to Life-Cycle Costing (LCC). A technical textile uniform that lasts 24 months' costs significantly less over time than a low-quality pair that tears or fades within 6 months.
- Green Labelling Integration: Standardize bulk purchases under the Eco-Mark Scheme. Awarding preferential points to bids featuring verified eco-labels, traceable sourcing (e.g., Kasturi Cotton), and zero-hazardous chemical footprints helps accelerate the adoption of sustainable practices.

Dr. Deepa Raisinghani re-elected as the Chairman of the JTA Editorial Board

The Textile Association (India) has been elected the JTA Editorial Board Members and JTA Advisory Panel for the term 2025-2027 during the Governing Council Meeting held on 22-11-2025 at Hotel Le Meridien, Coimbatore.

Dr. Deepa Raisinghani re-elected as the Chairman of the JTA Editorial Board. Also other members of the Editorial Board have been elected as under.

Dr. Deepa Raisinghani
Chairman

Dr. Aadhar Mandot
Hon. Editor

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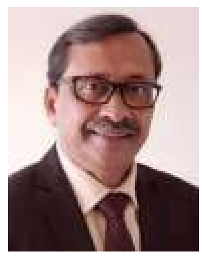

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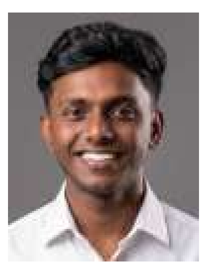

Shri Vinith Kanna K. R

AHMEDABAD UNIT

The Textile Association (India) Ahmedabad Unit arranged a visit to AI-Driven Innovation at the AI Centre of Excellence, GIFT City, Gandhinagar, Gujarat. A team of 15 Local Managing Committee members of the association visited the facility and got experience how AI is transforming industries and shaping the future of innovation.

Mr. Siddharth Kamat, Senior Associate- Industry Engagement, AI Centre of Excellence presented the Experience Zone at the CoE provides a hands-on showcase of AI-powered solutions, offering industry leaders and stakeholders the opportunity to explore real-world applications of AI and emerging technologies.

18th April 2026

The Textile Association (India) Ahmedabad Unit & Bharat Vikas Parishad jointly organized a Pravachan of Dr. Gyanvatsal Swamiji for their members and family members at Dinesh Hall auditorium. Dr. Gyanvatsal Swami is a most senior saint(Monk) of BAPS. The deliberation of the Swamiji was very much motivating for the audience. All the members and their family members took the blessings from Swamiji.

23rd May 2026

Under the society welfare activities the Association provided a financial help to Shri Mahendrabhai K. Patel a needy people in the society of Rs. 159000/- (one lakh fifty-nine thousand only) for one cycle treatment of his wife who has been suffering from cancer since 2018.

April & May 2026

Under the society welfare activities, the Association distributed nutrition kits to the pregnant women in the Ahmedabad (E) area who are suffering from malnutrition during the pregnancy period. About total 448 nutrition kits distributed in the month of April & May 2026.

Bharat Trivedi Earns Doctorate in Management

Colorant Limited proudly announces that Mr. Bharat Trivedi has successfully completed his Doctorate in International Trade & Marketing from GIBMS Business School (Global Institute of Business Management & Studies). The degree was formally conferred during the Convocation Ceremony held on 24th June, 2026.

Mr. Trivedi's doctoral thesis, titled "Dynamic Pricing Strategies in International Markets: An Empirical Study of Cost, Competition, and Compliance Factors among Indian Export-Oriented Chemical and Dyes Manufacturers," focuses on one of the most critical aspects of India's export industry.

The research provides valuable insights into how chemical and dyes manufacturers can develop effective international pricing strategies while balancing production costs, market competition, regulatory compliance, and global business challenges. The degree has been formally conferred during the Convocation Ceremony held on 24th June 2026 at Ahmedabad.

Dr. Bharat Trivedi is an experienced international trade and export management professional with an MBA in International Trade from the International School of Business Management and a Master of Commerce degree from North Maharashtra University. With over 22 years of industry experience, he currently serves as the Manager-Exports at COLORANT LIMITED, a leading manufacturer and exporter of Reactive Dyes.

Dr. Trivedi's contributions have led to significant export growth, earning the company numerous awards and recognitions from trade bodies and organizations. He has travelled to over 10 countries, enhancing his global understanding of Reactive Dyes markets. Additionally, Dr. Trivedi is a sought-after speaker on international trade and export management and has actively participated in international exhibitions and technical seminars throughout his career.

Dr. Bharat Trivedi expressed his heartfelt gratitude to Mr. Subhash Bhargava, Managing Director of Colorant Limited, and Mr. Vikas Bhargava, General Manager, for their constant encouragement, guidance, and unwavering support throughout his doctoral journey. He acknowledged that their trust, motivation, and leadership played a significant role in helping him successfully to complete this important academic milestone while continuing his professional responsibilities.

Colleagues, industry associates, and well-wishers have congratulated Dr. Bharat Trivedi on this significant academic achievement and wished him continued success in his professional, research, and leadership journey.

Grasim Industries Announces fresh investment of ₹3094 Crore to expand Lyocell Capacity

Post expansion, Total Cellulosic Staple Fibre (CSF) capacity would Surpass 1 million Tonnes Annually by 2030.

Grasim Industries Limited, the flagship company of the Aditya Birla Group and a global leader in cellulosic fibres, announced on 09-06-2026, an investment of ₹3,094 crore, for Phase II Lyocell capacity of 110K TPA at Harihar, Karnataka. This expansion will consist of 2 lines of 55K TPA (150 Tons per day) each. The first line is expected to be commissioned by 2028, and the second line is expected to be commissioned by 2030.

This additional capacity will complement the Phase I Lyocell plant of 55K TPA currently under construction at Harihar, which is expected to be commissioned by mid-2027. Upon completion, Grasim's total Lyocell capacity, will reach nearly 210K TPA, making it one of the largest Lyocell producers globally.

Mr. Kumar Mangalam Birla, Chairman, Aditya Birla Group, said, "The Aditya Birla Group has always demonstrated the willingness to invest ahead of the curve in sectors that will define India's future competitiveness and economic resilience. This investment carries forward that legacy. It is a vote of confidence in the scale and promise of the Indian market, aligns closely with the aspirations of Make in India, and will help position India as a more competitive and resilient force in the global textile industry." He added, "This investment also marks another significant step in Grasim's strategic expansion of advanced fibre capabilities, catering to the growing global demand for sustainable and high-performance textile materials. This fresh expansion will catapult Grasim's overall Cellulosic Fibres capacity beyond 1 million tonnes per annum, reinforcing its position as a global leader in sustainable Man-Made Cellulosic Fibres (MMCF)."

Mr. Vadiraj Kulkarni, Business Head, Grasim Pulp & Fibre added, "This expansion strengthens our position in the evolving MMCF landscape by scaling a high-value, future-ready fibre segment. By expanding Lyocell capacity, we are accelerating the shift towards high performance fibres with a lower environmental impact. Lyocell enhances our product mix, supports premium applications, and aligns with our focus on delivering differentiated, sustainable solutions to global markets."

Lyocell is a versatile, next-generation fibre widely used across apparel, home textiles, and technical textile applications. Manufactured through a highly efficient closed-loop process, Lyocell offers a compelling combination of durability, breathability, comfort, and lower environmental impact. The expansion would strengthen the Company's Specialty product portfolio and solidify its position as a key player in the global sustainable fibre industry. Grasim's Specialty portfolio share (including Lyocell, Modal, Dope-dyed and Recycled fibres) would increase to 35% by 2030.

USTER®

Recycled Fibers: The Vital Data for Quality and Profitability

Uster's new Recycling Opening Index guides spinners to the perfect blend

Uster AFIS 6 R Recycling Module measurement showing summary

Uster AFIS 6 – The fiber process control system

Uster AFIS 6 now offers the key data for better decisions when blending recycled fibers. Process control is decisive in determining the quality and economic outcome. The new R Recycling Module of AFIS 6 introduces the Recycling Opening Index (ROI), so spinners can optimize their circularity credentials. It is officially launched 09-06-2026 at ITM 2026 in Istanbul, Türkiye.

Cotton recycling has become a strategic priority for brands, regulators, and technology providers because it directly addresses the textile sector's biggest challenges: growing volumes of waste, resource scarcity, climate impact, and regulatory pressure.

Recycled waste and the use of it

Recent industry data shows that most textile waste is post-consumer waste (75% by volume) while post-industrial (pre-consumer) waste makes up around 25%. However, when it comes to recycling – turning this waste into quality new yarn – the situation is different.

Even though it's a smaller share of total waste, about 95-99% of post-industrial waste is already being reused. Almost every scrap of factory waste is already being collected and spun back into yarn. That's because it's clean, consistent, and relatively easy to process.

Spinners generally see it as the safer option to start their recycling activities with post-industrial waste. These raw materials are more predictable in their behaviour, so it's simpler to refine spinning techniques to suit them. An optimized process can then be developed for blending in pre- and/or post-consumer waste.

Controlling processes with recycled raw materials

Now, objective measurement data from Uster is available to give clear indicators of processability and profitability when using recycled raw materials. This comes with the Recycling Opening Index (ROI), together with the total yarn pieces' value. The ROI is a metric in the Uster AFIS 6 R Recycling Module, which describes the effectiveness of the opening process in the recycling of cotton fibers. It is defined as the ratio of opened fibers to remaining yarn pieces (hard ends). 'Total yarn pieces' means the sum of yarn fragments present in the raw material that have not yet been fully opened into individual fibers.

If a low ROI value is indicated, this suggests a poor degree of opening, which can disrupt the spinning process and cause issues such as yarn irregularity (IPI), weak spots and uneven surface structures.

So, the ROI is a vital metric for evaluating the quality of recycled cotton materials. For the first time, spinners can have a quantitative assessment of the opening process.

R Recycling Module of Uster AFIS 6

Uster AFIS 6 with the R Recycling Module supports better decisions through real measurements. The concept of the Recycling Opening Index (ROI) combined with the number of yarn pieces per gram, provides spinners with a more precise evaluation of recycled material processing. The R Recycling Module also offers advanced recycling parameter measurements, as well as a refined short fiber content analysis with < 6.35 mm indicating the non-spinnable fiber content. In addition, the module enhances fiber quality assessment by incorporating detailed nep and fiber length parameters. The R Recycling Module on AFIS 6 is an optional, on-demand feature designed exclusively for this latest model.

The new module fits perfectly within Uster AFIS 6, with its expanded measurement range for 100% synthetic fibers giving details of cut length and denier/fineness, to help spinners make proper raw material selections. The updated reporting package simplifies complex data analysis, and the integrated Uster Statistics remains the essential tool for spinners to optimize intermediate process steps finally empowering full control of their processes.

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H-Circle Product Innovation Awards returns for its Fifth Edition at Hgh India

The H-Circle Product Innovation Awards, instituted by HGH India to recognise outstanding design and innovation across home and lifestyle trade, return for their fifth edition at the 19th HGH India, scheduled from June 30 to July 3, 2026 at the Bombay Exhibition Centre, Mumbai.

The H-Circle Awards are open to all exhibitors specializing in Home Textiles, Home Decor, Home Furniture, Houseware, and Gifts. These awards are designed to honor individual products for their exceptional quality and innovation, ensuring that every recognition is based entirely on the product's own merit.

A key highlight of this edition is HGH India's strategic partnership with the Institute of Indian Interior Designers (IIID, MRC). IIID is directly integrated into the award evaluation and presentation framework. This collaboration also introduces dedicated knowledge-sharing programmes and formalises the participation of the national architecture and interior design community on the trade floor.

The independent five-member jury who will evaluate the nominations comprises prominent design academicians, interior designers, retail experts, and trade editors. Mapped across three primary exhibition zones Hall 6 for textiles and sleep products, Hall 2 for décor and lifestyle accessories, and Hall 4 for houseware and kitchen appliances the panel will evaluate physical entries based on an evolving framework of technical, functional, aesthetic, and ecological parameters. The evaluation process also weighs consumer utility and ecologcal compatibility, steering the industry toward sustainable design practices.

All nominated products will be featured in a curated central display zone, serving as a primary discovery point for commercial buyers, developers, and project specifiers during the event.

The final laureates will be celebrated during the official H-Circle Awards Night on the evening of June 30, 2026 attended by the industry, creating strong visibility and recognition.

KARL MAYER GROUP

The Fastest Path from Yarn to Champion Shoe

Footwear innovation enabled by warp knitting technology insights from New Balance

The future of the athletic shoe is increasingly being shaped on warp knitting machines. For KARL MAYER, the footwear industry is one of the most important growth markets – and one of the sectors where innovative textiles can realize their full potential. In his keynote address at the opening of KARL MAYER's TEXTILE INNOVATION CENTER in Obertshausen in April, Vishnu Prakash Muthusamy, Senior Textile and Materials Engineer at New Balance, explained the opportunities that warp knitting technology opens up for performance, sustainability, and faster development processes, and why textile manufacturers are transitioning from suppliers to development partners.

To succeed in the footwear market, you need technology

The footwear sector is one of the most demanding areas of the textile and apparel industry. Today's modern athletic shoes must meet a wide range of requirements simultaneously: they need to be lightweight and durable, offer optimal comfort, stabilize the foot, be breathable, and be produced sustainably. “From a technical standpoint, a modern athletic shoe is like a mini-car packed into a tiny space,” explained Vishnu Prakash Muthusamy in his presentation. In fact, a single shoe often contains up to 30 individual components that must work together perfectly to achieve the desired performance.

At the same time, pressure on manufacturers is growing. Development cycles are expected to become shorter, production more resource-efficient, and processes less complex. This is precisely where warp knitting technology offers new perspectives. It transforms textile manufacturers into far more than mere material suppliers: they become development partners and co-creators of the product.

“All the products we develop today are designed with a specific supplier and a specific material in mind,” says Vishnu Prakash Muthusamy.

For brands like New Balance, innovative textile solutions are thus becoming a decisive competitive factor – and warp knitting technology is becoming a key technology for the next generation of shoes.

Less complexity, more speed

Traditional athletic shoes consist of a multitude of individual components: upper parts, overlays, reinforcements, and appliqués are cut to size, glued together, and assembled in several steps. This makes production time-consuming, increases the shoe's weight, results in material waste, and lengthens development cycles.

Warp knitting technology takes a different approach: functions such as breathability or support, as well as aesthetic elements, are integrated directly into the textile structure rather than added later. This creates an integrated system instead of a collection of individual components. “It's not just about simplification and greater speed. By reducing complexity, we also improve the product's performance,” emphasized Vishnu Prakash Muthusamy.

For brands like New Balance, this is a decisive advantage. At the same time, warp knitted fabrics offer technical properties that are particularly in demand in performance footwear – including high dimensional stability, controlled stretch, and an excellent strength-to-weight ratio.

Multiple functions and designs in a single piece of fabric

New Balance sees particularly great potential in what is known as “Zonal Engineering.” On warp knitting machines, stitch density can be precisely controlled, and yarns can be placed with pinpoint accuracy using Jacquard technology. This allows different functional zones, textures, and designs to be specifically tailored within a single upper material to meet the shoe's requirements.

The result is breathable zones exactly where ventilation is needed. Reinforcements and varying levels of elasticity provide additional support in the midfoot area and greater stability at the heel. Around the lacing area, extra-strong sections prevent the fabric from tearing, while integrated graphic elements, patterns, and logos add a stylish touch to the look. All these features are created in a single production step directly on the machine. Additional printing, laminating, or application processes are eliminated. This saves time and resources while enhancing the product's durability.

Faster product development, shorter time-to-market

The enormous time savings achieved with design updates are particularly relevant for international footwear brands. Design adjustments can be made digitally and transferred directly to the production machines. Here, new patterns can be implemented in a matter of seconds using the EN pattern drive – without additional tools. At the same time, the product can be validated even during production.

This speed and flexibility are decisive advantages for New Balance in the race against time.

“We only have seven days to switch from Design A to Design B. Thanks to the EN function, we can seamlessly transfer the pattern without any new pattern discs or additional tools,” explains Vishnu Prakash Muthusamy. The new material must be evaluated within 14 days, and the shoe must be manufactured from it within 45 days. There is no room for wasting time here!

Greater Sustainability

In addition to performance and speed, warp knitting technology also excels in terms of sustainability.

"For us, warp knitting is at the top of the list of technologies we use to integrate sustainability into our products," confirms Vishnu Prakash Muthusamy.

A key advantage lies in what is known as near-net-shape production. In this process, textile components are manufactured in a form that is nearly identical to their final shape. Compared to traditional cut-and-sew processes, there is significantly less waste, which allows for more efficient use of materials and reduces waste.

At the same time, the entire value chain is simplified. Multiple components of a shoe – such as the upper, tongue, and collar – do not need to be manufactured separately and then assembled; instead, they can be produced as a single piece of fabric. Additional processing steps are eliminated, which reduces labor and energy costs and streamlines production processes.

Durability also benefits from this approach. Constructions made from a single piece are less prone to wear and tear, while mono-material solutions made from recycled or bio-based yarns facilitate the subsequent recycling of used shoes. Added to this is the technology's high energy efficiency. Thanks to the high production speed of modern warp knitting machines, warp knitting ranks among the most efficient textile manufacturing methods in terms of energy consumption per kilogram of fabric produced, according to Vishnu Prakash Muthusamy.

Material savings of up to 28 percent

Vishnu Prakash Muthusamy illustrated just how significant these savings can be in practice using a recent development project as an example. By optimizing the layout of the cut pieces within the material, the yield was increased from four to five pairs of shoes per yard of fabric.

The result is remarkable: material costs fell by up to 28 percent, while at the same time there was virtually no waste.

The basis for this efficiency is high-precision manufacturing. Thanks to Jacquard technology and "zonal engineering," upper material can be placed on the fabric with a precision of plus or minus 2 mm.

The Next Step: From 2D to 3D

Vishnu Prakash Muthusamy envisions a complete shift in the future from traditional two-dimensional design and manufacturing processes to three-dimensional, biomechanically optimized structures.

Since the human foot itself has a three-dimensional structure, shoe production must also be thought of in 3D in the future. Textile structures should be able to respond directly to movements, stresses, and pressure points by being tailored to real human biomechanical data.

"Warp knitting allows you to conceptually shift from 2D patterning to 3D structural engineering. Your machine should be capable of producing textiles in 3D form," Vishnu Prakash Muthusamy advised the audience.

For brands, this approach opens up entirely new possibilities for performance optimization, differentiation, and a competitive edge in the race for the world's best shoe. In this field, every thousandth of a second and every gram counts: In a 100-meter dash, as little as 0.09 milliseconds can decide the winner. If a shoe is just two grams lighter, that can be the decisive factor.

Conclusion: The future of the footwear industry lies in intelligent, functionally integrated, and three-dimensionally designed textile structures. Warp knitting technology is set to become one of the key technologies of the next generation.

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National Conference on Technical Textiles

PHDCCI, in collaboration with the Ministry of Textiles, hosted the "National Conference on Technical Textiles – Sportech Bharat Vision 2047" on 30th June, 2026 at PHD House, New Delhi. The event united stakeholders to strategize on positioning India as a global leader in Technical Textiles.

Key Speakers and Highlights:

- **Mr. R. K. Vij,** Co-Chair, PHDCCI Textile Committee; Secretary General, PATA; National President, The Textile Association (India), welcomed the gathering and lauded the National Technical Textiles Mission (NTTM) for accelerating industry innovation. He urged the Government to rationalize duties on key raw materials like PTA and MEG and address the GST inverted duty structure to boost sector competitiveness.

- **Mr. Pabitra Margherita,** Hon'ble Minister of State for Textiles emphasized that initiatives like Khelo India and Fit India are driving demand for high-performance sportech. He noted that India's Technical Textile exports surged from ₹8,827 crores in FY 2013–14 to ₹28,392 crore in FY 2024–25.

- **Ms. Manisha Chatterjee,** Joint Secretary, Ministry of Textiles stated that the NTTM is shifting toward commercialization, highlighting the PRAMAN guidelines and the approval of six research projects and one start-up under the Sportech segment.

- **Dr. Harish K. Chatterjee,** Director General, Wool Research Association, discussed the convergence of textiles with smart sensors and data analytics, asserting that India is poised to become a global hub for high- performance sports textiles.

- **Mr. Debabrata Ghosh,** Vice President & Sales Director, Barmag India Pvt. Ltd. projected that India's active wear yarn market will grow at a CAGR of over 10% between 2026 and 2035, significantly outpacing China.

- **Mr. Shantanu Agarwal,** Co-Chair, PHDCCI Textile Committee & Joint Managing Director, Maral Overseas Ltd. concluded the session by thanking the Ministry, NTTM, and industry partners for their support.The conference featured four thematic sessions and an innovation exhibition focused on indigenous manufacturing and R&D. The event concluded with the presentation of a WRA White Paper, providing a strategic roadmap for the NTTM to over 225 attending delegates.

Meeting with Hon'ble Finance Minister, Government of Gujarat on 07 July, 2026

Mr. Vij has attended the meeting with the delegation for representing the Man-Made Fibre (MMF) and Polyester Textile Industry and met the Hon'ble Finance Minister, Government of Gujarat on 07-07-2026. They presented the industry's concerns regarding the blockage of Input Tax Credit (ITC), particularly Capital Goods ITC, under the present GST framework.

Delegation was comprised with:

- Shri Jyotibhai (Chiripal Group)
- Shri Kulbhushan Gupta (Wellknown Polyesters)
- Shri Madhubhai and his team (Filatex India Ltd.)
- Shri Vij R. K.
- Debdutta Chatterjee (Garden Silk Mills Pvt. Ltd.)

The delegation was accompanied by a former Home Minister of Gujarat, who facilitated the meeting through his good offices. Although the appointment was scheduled for 11:00 AM, the Hon'ble Finance Minister met the delegation at around 12:15 PM and devoted adequate time to hear the industry's concerns.

Discussion with the Hon'ble Finance Minister

The delegation explained the issues arising from the inverted GST structure and the consequent accumulation of Input Tax Credit in the MMF and Polyester industry.

Particular emphasis was placed on the fact that the industry's principal concern is not merely the inverted duty structure. It was explained that even if GST rates on inputs and outputs are aligned in future, thereby preventing further accumulation of ITC, the substantial accumulated Capital Goods ITC would continue to remain blocked indefinitely. This represents a permanent lock-up of investment and acts as a disincentive for further capital expenditure in manufacturing.

The delegation also presented international practices demonstrating how several VAT/GST jurisdictions have adopted mechanisms to enable refund or utilization of Capital Goods ITC, thereby avoiding long-term blockage of investment-related tax credits.

The Hon'ble Finance Minister appreciated the concerns raised and observed that, in the interest of Gujarat's industrial development and the textile sector, the matter deserved to be pursued at the appropriate forum.

Accordingly, in the presence of the delegation, he called Shri Natrajan, IAS, Additional Chief Secretary (Finance), Government of Gujarat, and directed him to meet the delegation, examine the issue in detail, and prepare an appropriate note for consideration by the GST Council.

Meeting with Additional Chief Secretary (Finance)

Pursuant to the Finance Minister's directions, the delegation met Shri Natrajan, IAS, Additional Chief Secretary (Finance), and made a detailed presentation.

The discussion again focused on the distinction between:

- correcting the inverted duty structure for future transactions; and
- resolving the continuing blockage of accumulated Capital Goods ITC, which remains unaffected even after inversion is corrected.

International practices relating to Capital Goods ITC refunds were also presented in support of the industry's proposal.

A further issue highlighted was the interaction between Gujarat's Industrial Incentive Scheme and the present GST structure. It was explained that industries operating under an inverted duty structure have little or no SGST liability and are therefore unable to effectively avail the SGST incentives sanctioned under the State's industrial incentive policies.

Shri Natrajan appreciated the issue and immediately understood the practical implications of the present tax structure. He devoted considerable time to the discussion and indicated that these aspects would be examined while preparing Gujarat's note for the GST Council.

Further Action

The soft copies of the presentations and supporting reference material have been shared with Shri Vij for onward circulation to the concerned Government authorities.

Shri Vij is also scheduled to meet the Finance Ministers of Haryana and West Bengal prior to the GST Council meeting on 16th July, 2026 with the objective of building broader support among States for addressing the issue of accumulated Capital Goods ITC.

The Commissioner of State GST could not be met today due to his preoccupation. However, Shri Natrajan informed the delegation that he would personally brief the Commissioner, who would be involved in preparing the State's formal note for the GST Council.

Overall Assessment

The meetings were highly constructive and encouraging. Both the Hon'ble Finance Minister and the Additional Chief Secretary (Finance) devoted substantial time to understanding the industry's concerns. Most importantly, the discussion succeeded in shifting the focus from the inverted duty structure alone to the larger issue of permanent blockage of Capital Goods ITC and its adverse impact on industrial investment.