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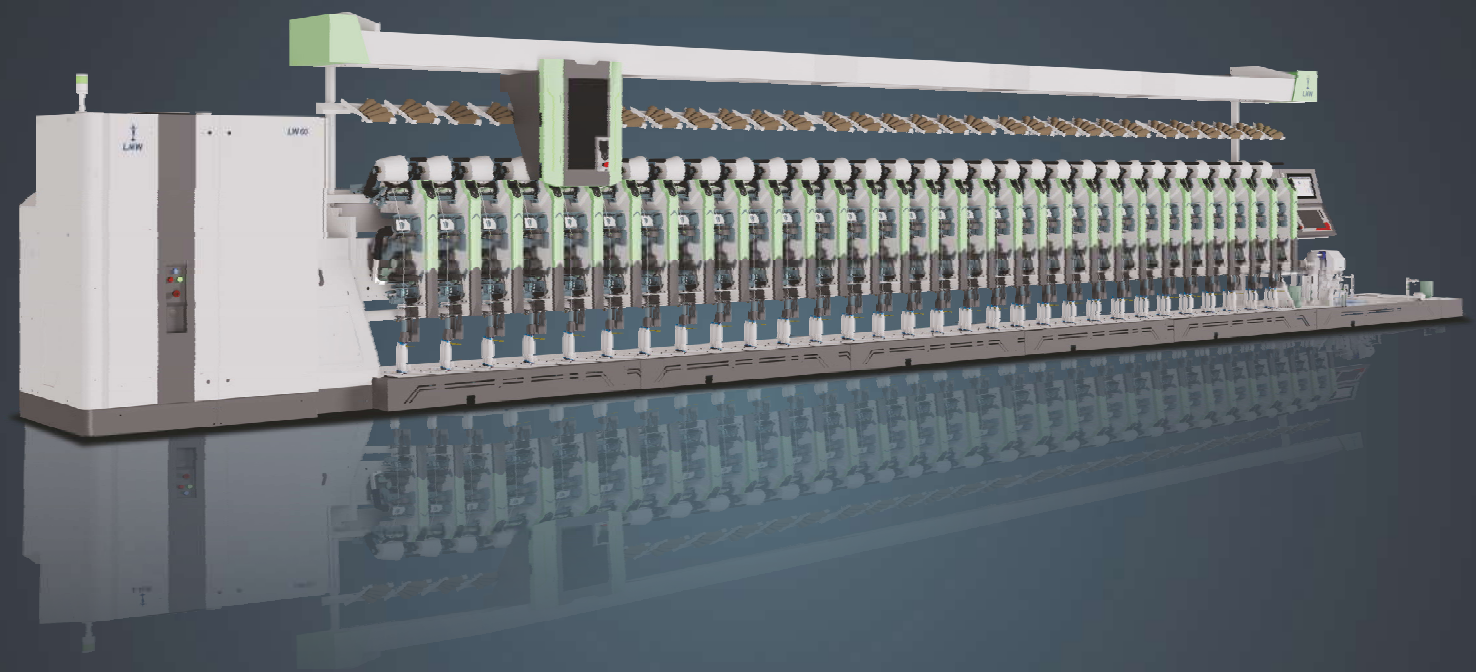
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THE TEXTILE ASSOCIATION (INDIA)
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Indian Textiles:
Turning Potential into Global Leadership

Dear Readers,
Greetings!!

I am pleased to inform you that I am appointed as Chairman of the JTA Editorial Board. I am sincerely thankful to all TAI Office Bearers and the Governing Council Members for showing faith in me for this position.

The Indian textile industry stands at a crucial juncture, balancing significant growth opportunities with intensifying global competition, volatile input costs and evolving sustainability requirements. With the sector valued at nearly US$190 billion in 2025–26 and an ambitious target of US$350 billion by 2030, the opportunity is immense. However, export growth, productivity and global competitiveness must keep pace with these aspirations.

Government initiatives such as PM MITRA Parks, the PLI Scheme, the Mission for Cotton Productivity and the Tex-Eco Initiative reflect a welcome commitment to manufacturing, investment and sustainable growth.
Recent trade agreements with UK, EU and some other countries also offer opportunities to expand market access.

Equally important is the growing policy focus on man-made fibres (MMF) and technical textiles, supported by incentives, research and product development, to diversify India's product portfolio and capture emerging global opportunities.

There is also a significant transition towards recycling and circularity. India generates substantial textile waste, creating opportunities for textile-to-textile recycling, recycled fibres and value-added products. Government initiatives promoting recycled and upcycled textiles through public procurement can help develop viable markets. Greater investment in collection, segregation, advanced recycling technologies and eco-design is essential to close the loop.

The way forward demands modernisation, innovation, skill development and decarbonisation. India must transform its traditional strengths into a technology-driven, circular and globally competitive textile powerhouse.

With best wishes,
Mr. J. B. Soma
Chairman
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R. K. VIJ, President

Indian MMF industry, an outlook and suggestions for its sustainable growth

As we enter the final quarter of 2026, the state of India's polyester and man-made fibre (MMF) industry is transitioning into a phase of structural growth mixed with near-term margin calibration. With the increase in consumer demand coupled with the Government's backing, we hope, the long-term outlook will materially strengthen, though volatility in upstream raw material supply / pricing remains a persistent headwind. The Government has also announced schemes like PLI-1, PLI-2, National Technical Textile Mission (NTTM), The Seven PM MITRA (Prime Minister Mega Integrated Textile Region and Apparel) Scheme, Extension of RoDTEP, Rebate of State and Central Taxes and Levies (RoSCTL) Scheme till December 2026 which will also help textile industry to grow in times to come.

The ongoing unrest arisen due to war between US led forces and Iran in West Asia has caused havoc supply shock across India's petrochemical value chain leading to disruptions over shipping corridors like the Strait of Hormuz, coupled with rising global crude oil and naphtha prices, have triggered severe upward cost pressures and volatility on supply / prices of PTA / MEG / Cotton and the downstream synthetic polyester prices.

We should use alternative sea routes / trade routes and shipping channels so that India's dependency on shipping routes through the Strait of Hormuz can be neutralized. If the freight costs, insurance costs are optimal in case of Alternative trade and energy routes, bypassing the Strait of Hormuz, it will be highly beneficial for India, offering crucial security and supply chain continuity during regional conflicts and chokepoint disruptions and it will definitely help Indian MMF industry to build a more resilient polyester supply chain in near future

Customs-duty exemption on PTA, MEG and Cotton has assumed greater significance amid continuing global supply and price disruptions as PTA, MEG and Cotton are critical raw materials for MMF / Cotton downstream industry and are short supply in India. Due to continuing global supply and price disruptions, prices of PTA, MEG and Cotton have increased which further pushes the prices of Indian downstream MMF and Blended products further putting Indian spinners / fabric manufacturers under margin pressure.

When the Government reduced Customs Duty on PTA and MEG from 5% to 0% for three and a half months and on Cotton from 11% to 0% till October 2026, the availability and prices of these major raw materials improved giving Indian MMF / Cotton downstream products manufacturers much relief on pricing front of their raw materials i.e. PTA, MEG and Cotton, strengthening knitting, weaving and processing units to augment production for the garment manufacturers. However, the Government has withdrawn the benefit of 0% Customs Duty on PTA / MEG from 15th July 2026 pushing prices of raw materials again on the higher side for the downstream MMF products.

Indian domestic supply of PTA and MEG also remains volatile due to PTA plants remaining under maintenance which creates a vacuum in supply / demand situation among Fibre / Filament / Yarn manufacturers. Since PTA and MEG are in short supply in India, downstream MMF manufacturers have to depend on import of PTA / MEG. Higher prices of domestic PTA and MEG push the prices of Fibre / Filament / Yarn. Keeping 0% Customs Duty on PTA / MEG till supply / demand does not match in India will work as a cushion for the downstream MMF producers.

As per information, GAIL PTA plant is now expected by November 2026. IOCL's PTA plant may take one more year to start. RIL's PTA plant may take two years to start. So, we suggest the Government reduce Customs Duty on PTA and MEG from 5% to 2.5%, if not 0% till 31st December 2026 or till the time supply / demand situation is improved in India.

Downstream MMF industry welcomes the Government of India's historic decision to rationalize MMF GST structure, including bringing MMF Fibre / Filament / Yarns to 5% GST. This correction is a significant move to encourage production of MMF in India and to strengthen the polyester textile value chain. However, the Government has kept PTA & MEG, the two critical raw materials used for the manufacture of downstream MMF products out of this rationalization initiative and these two products remain within the GST Tax Slab of 18% creating GST inversion. So, the Industry suggests that the Government should bring down the GST on PTA / MEG from 18% to 5% in line with PSF, POY, FDY, DTY. This will further bring ease of doing business in MMF textiles.

There should be a single GST rate across the textile value chain so that there remains no GST inversion and no blockage of working capital. GST Central Committee, however, recommends for early refund but still industry wants no inversion for ease

of doing MMF business. The Govt. can also keep GST on PET Chips either at 5% or at 18% itself. If kept the same at 18%, then PET Chips manufacturers will deposit the value-added GST to the Government as their downstream products are all at 18%.

Government should consider restoration of GST refund on Imitation Zari type plastic film threads / yarns at the stage of selling yarns which is lying blocked after implementation of Notification No. 20/2023 Central Tax (Rate) dated 19/10/2023 issued by Department of Revenue, Ministry of Finance, Government of India. This will create more small, small factories and jobs in the downstream textile industry.

The Government should also consider Cut Weaving Fabric (which is not a Stitched ready to wear Garment) under the category of Fabric GST rates itself and not under the category of Garment GST rates. Also, the Government should consider charging a 5% GST rate on Garments up to Rs. 3,500/- each value from the present Rs. 2,500/- each for the benefit of the common man.

We also suggest to the Government of India to also implement Reverse Charge Mechanism (RCM) for the Bottle Scrap B2B Users Industry and Recycled Fibre manufacturing industry like it did in Steel Scrap Waste to avoid harassment. The Bottle Waste Sellers work in the unorganized sector, some of them even do not have their registered companies and even do not pay GST while selling Bottle Scrap to the manufacturers of Recycled Fibre / Recycled PET / Recycled Bottles. This causes problems while getting GST adjusted by the Bottle Scrap Users Industry. Government revenue will also increase both for the State as well as for the Central Government if RCM also applies to the Bottle Scrap Sellers and Users Industry in line with the Steel Scrap Selling ecosystem.

While MMF accounts for roughly 70–75% of global apparel trade, India's textile ecosystem remains heavily skewed toward cotton. This textile ecosystem needs to be revamped so as to give MMF a growth impetus as cotton has limited growth potential due to its inherent weather dependent nature of cultivation.

The Indian MMF Fabrics and Garment industry is highly fragmented. Small small units constitute the industry which often faces capital crunch and is not able to avail of the government's initiatives fully. They constitute Micro, Small Manufacturing Units (MSME) and lack the desired scale to compete in international markets.

In order to preserve effectiveness of existing safeguards, the Government should consider imposing a uniform Specific Duty of Rs.115/- per kg across all relevant knitted fabric HS Codes under Chapter 60. This would simplify enforcement and effectively neutralize under-invoicing as even fabrics declared at artificially low values would attract minimum duty incidence thereby filtering out misclassified and undervalued imports while allowing genuine trade to continue. This will also increase the revenue of the Government and stop illegal trade.

European Union markets demand certain trade rules / norms to be complied with by the exporters. To cope up with these challenging market forces, innovation in technologies including judicious use of AI on the shop floors should be adopted to check the desired quality norms, production parameters, carbon footprints and if these initiatives are implemented, Indian textile exporters will definitely gain unhindered access in the UK / European markets and compete with other countries.

Incentivizing mega textile parks (such as Seven PM MITRA Parks) helps lower logistical and overhead costs through centralized infrastructure. With the new FTA with the UK, EU and other countries, our textile exports will increase and hope to achieve USD 100 Billion in next four to five years. The Production Linked Incentive (PLI -1 & PLI- 2) Scheme for the textile industry covers three main categories: Man-Made Fibre (MMF) Apparel, MMF Fabrics, and Technical Textiles. Investing in the Fabrics and Apparel sector will successfully drive growth in the upscale Fibre, Filament, and Yarn sector.

The Department of Chemicals and Petrochemicals should also come up with some scheme like PLI, in line with the Ministry of Textiles, in manufacturing of Fibre / Filament so that future demand could be met with installation of new plants. As of today, there are no Fibre / Filament new plants in the pipeline. A new plant takes around two to three years to be commissioned. With new polyester plants in place, this will generate new employment opportunities in India and produce cheaper products for the downstream MMF industry.

China, once world's most threatening market sucker, is losing its shine over a period of time as the economic benefits which it enjoyed over the period of time in terms of having cheap labor, lower production cost and export benefits from the Government are diminishing. But it still continues to dominate the global polyester and MMF textile value chain through scales and integration. India has the capacity and scale to compete with China globally, but the Government of India has to be less reliant on cotton centric approach and turn its attention to the growth of Man-made Fibre production which ultimately help to build a sustainable competitive advantage in the global markets and of course over China.

India should also develop processing hubs like China which are as of today on demand. There should be a time bound one

window system to approve all licenses like China and other countries have in their textile hubs. Four priority actions the Government should do in collaboration of the industry for substantially increasing India's polyester consumption, downstream value addition and MMF exports by 2030 include:

i. The basic raw material PTA and MEG are costly by Rs.4.00 to Rs.5.00 per kg and they are also short in supply in India. The main reason is the Customs Duty on PTA / MEG which is at present 5.5% whereas the same in Vietnam, Indonesia and Thailand is 0%. So, PTA and MEG which are the critical and major raw materials and about 90 to 95% are used in the production of Man-made Fibre, Yarns, Filaments becomes costlier by Rs.4.00 – Rs.5.00 per kg.

   The Government of India should reduce Customs Duty on PTA and MEG from the present 5% to 2.5%, if not 0% till the MMF downstream industry becomes self-sufficient in demand / supply. Another justifying point is that the customs duty on Paraxylene, which is the basic feedstock for the manufacture of PTA, is 0%.

ii. The power cost also in India is around Rs.7.00 – Rs.8.50 per unit whereas in China and other countries it is Rs.5.00 per unit. We bring to your kind attention that to produce 1 kg of Man-made Fibre or Filament, we need at-least 1.0 unit of power. So, we are costlier by Rs.2.00 – Rs.2.50 per kg.

iii. The present GST rate on PTA / MEG is 18% in India whereas the Man-made Fibre, Filament, Yarns attract 5% GST rate, thereby creating GST duty inversion at the hands of Man-made Fibre, Filament, Yarn manufacturers. For ease of doing business, we need one GST rate of 5% on PTA & MEG as proposed.

Sr. No.	Products	Present GST Rate (%)	Proposed GST Rate (%)
1	Purified Terephthalic Acid	18	5
2.	Mono Ethylene Glycol	18	5
3.	Polyester Chips	5	5
4.	Man-made Polyester Fibre (PSF)	5	5
5.	Partially Oriented Yarn (POY)	5	5
6.	Draw Texturized Yarn (DTY)	5	5
7.	Fully Drawn Yarn (FDY)	5	5
8.	Industrial Yarn (IDY)	5	5

iv. In China and other countries, the interest cost on borrowed working capital and investment is around 5% whereas in India it is 9.0 to 10.0% which means Rs.2.00 per kg additional cost the company has to bear. The Government has to bring down the interest cost on borrowed capital – either for working capital purposes or for new investments to 5% in line with international rates.

These all four facts make our product costlier by around Rs.9.00 per kg as compared to China, and other countries.

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

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Sustainable Local Materials of Natural Fibre-based Composite for Optimizing Acoustic Performance in Aerospace Applications

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Abstract:

The rising demand for sustainable and lightweight materials for noise-control applications has motivated researchers to search for environment-friendly alternatives to traditional synthetic acoustic materials. Local materials of natural fiber-reinforced composites (NFRC) are the natural reinforcements for composites that are being used, which have great applications for sound absorption in aerospace (one of the basic services), paving the pathway to development assistance and sustainable industrialization by using this in civil engineering and automotive applications. They act as eco-friendly, sustainable composites with economical viable alternative in place of synthetic composites. This research on NFRC analyzes the production and acoustic characteristics of natural resources like sisal, banana and bamboo fibers composites and aims to improve global resource efficiency. The sound absorption coefficient (SAC) was measured on composite samples with a thickness of 20 mm and 40 mm using the impedance tube method in the frequency range of 200 Hz to 1600 Hz. Research shows that sisal fibre composites have a significant sound absorption coefficient, which is up to 0.91 at 1280 Hz. According to ANOVA, the material type (sisal, banana, bamboo) significantly influences SAC. Thickness also has some impact, but it is not as strong as the material. Furthermore, the study also examines the optimization of acoustic qualities. The results revealed that the composite has appreciable acoustic performance, and its strength-to-weight ratio can support improving energy efficiency.

Keywords: *Basic services, Development assistance, global resource efficiency, Human rights, Local materials, Sustainable industrialization*

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1. Introduction

Noise pollution has to be checked by looking into the procedures of sound dampening. There are granular and many spongy SACs. Fibrous and cellular classes for different uses. The environmental benefits, the cost-effectiveness and the global resource efficiency of sustainable acoustic composites produced with local materials and agricultural waste has attracted attention. Recent research has enhanced the strength, stability, and acoustics of hybrid composites to aid the sustainable sector. They blended glass with the calamus rotang fibre. Better mechanical, acoustic and vibrational properties. Tensile strength: 85 ± 1.2. SEM and finite element modeling validated the bending strength of 132 ± 2.3 MPa and MPa [1]. It makes good automobile parts and good building insulation. Holes on panels. Polyurethane foam enhances frequency acoustics. Hz significance was validated by impedance tube testing and COMSOL Multiphysics. Material and geometric optimization [2]. Biodegradable composites of polyethylene ANN improved integration of Nelumbo Nucifera fiber and banana peel filler. Taguchi-based CRITIC-EDAS was used to optimize flexural strength parameters to obtain a lightweight, ecological material with tensile strength of 24.75 MPa 31.25 MPa (4500 psi) [3]. These efforts contribute to achieving international sustainable industrialization objectives by reducing the usage of synthetic and non-renewable materials. Machine learning and multi-objective approaches (ARAS-GA) with 35% bamboo–madar hybrid fiber, 10% nano-SiO2, 24 mm fiber length and 9% NaOH treatment improved natural fiber-based composites for vehicle applications to develop a lightweight structure [4]. Renewable resources and waste-derived reinforcements reduce carbon emissions and improve resource efficiency. The composite is low in carbon emission and durable in structure and can substitute conventional automotive materials.

Hybrid polymer composites reinforced with PALF/sisal fibers and SiO2 nanoparticles with 4 wt.% SiO2 showed enhancement in tensile, flexural and impact strengths and decrease in volumetric degradation [5]. Anova, JCA and Delany-Bazley based predictive models validated the performance trends in water hyacinth fiber composites, where the lower density samples maximized sound absorption (SAA = 0.63) and higher density samples enhanced transmission loss (TLA = 32.5 dB) [6]. Needle-punched nonwovens with mixed recycled PET with jute and flax at 50% jute:25% flax:25% PET and increased fabric weight reduced sound significantly [7], thus showing promise for industrial acoustics using jute-based materials. The fibre length and weight fractions were modified to improve the mechanical and acoustic properties of the banana/epoxy composites. The maximum sound absorption coefficient (α = 0.997) was obtained at 5% fiber content and

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10 mm length [8]. Banana fiber composites have the ability to absorb sound up to 0.604 [9] and hence are suitable for light weight acoustic applications. In article [10] it was found that nonwoven coffee husk with nettle and banana fibers had superior sound absorption. It exhibited better thermal properties compared to conventional polyester and polyurethane foams. Improved hydrophobicity, thermal stability and sound absorption (0.51–0.84) were obtained by using bamboo fibers with stearic acid and aluminium hydroxide nanoparticles, demonstrating that porous acoustic absorbers can be robust [11]. ZB-BC composite aerogels were obtained by sol-gel and freeze-drying. Aerogels exhibited an average sound absorption coefficient of 0.72 (800–6300 Hz), NRC 0.48, 30.31 dB transmission loss, 0.053 W/mK thermal conductivity, 30.6% LOI, and 0.28 MPa compressive strength, showing multipurpose occupant atrium with acoustic, thermal, and flame-retardant capabilities [12] These indigenous materials reduce environmental effect and provide up opportunities for rural economic development and agricultural waste value-added development aid projects. The NaOH treatment of the carbon/bamboo fiber hybrid composites improved the damping by 34.55% at medium and high frequencies, whereas the untreated composites exhibited better performance at low frequency sound absorption [13].

Bio-based polyurethane foams with 0.7%, 1.6% and 1.5% of nanoparticles (MWCNT, CuO, bamboo charcoal) showed considerable sound absorption and NRC, and are ideal for lightweight aerospace and defense applications [14]. The ideas foster more environmentally friendly production processes and global resource efficiency by using renewable and recycled resources. The typical sound absorption coefficients above 500 Hz were over 0.8, while the values of NRC were 0.5-0.73. Green sisal fibre with dextrinated starch binding acoustics benefits buildings [15]. A study found that adding plasterboards to Moroccan sisal woven fabrics improves their sound absorption. The greatest sound absorption coefficient was 0.39 for the three Basket 2-2 layers at 1700 Hz. This is a lot higher than plain plasterboards. Moreover, support vector regression models may predict their performance accurately [16]. The sound absorption effectiveness improved with 0.4 wt% Fe doped ZnO nanoparticle loading in sisal fiber reinforced hybrid composites for sound absorbing and thermal insulating bio-composite applications [17]. Co-fibrous composites of plant fibers (pineapple, hemp, sisal, agave) and recycled PET were characterized with NRC values >0.56 and high-frequency sound absorption coefficients (0.94–0.97), with potential for pineapple and hemp composites as sustainable commercial sound absorbers and insulators [18]. Peanut shells showed NRC values of 0.23–0.54 and average coefficients to 0.9 above 2000 Hz, demonstrating eco-friendliness [19]. Besides engineering advantages, eco-friendly acoustic materials contribute to environmental sustainability, health at work and community well-being. Safer living and working conditions with reduced exposure to noise are human rights to health, safety, and quality of life. Drivers for technical innovation and sustainable development are the responsible utilization of resources, sustainable industrialization and improved environmental conditions via natural fiber reinforced acoustic composites. Tests and analysis of the non-FRC system have shown its acoustic properties. The study employed sisal, banana and bamboo. In addition, epoxy was used as the matrix. A feedback ANOVA was performed to investigate the influence of thicknesses on SAC and composite acoustics.

2. Materials and Methods

Natural fiber reinforced composites are manufactured using natural fibers such as sisal, banana, bamboo, etc. due to their renewability, biodegradability, environmental sustainability, recyclability and affordability. A banana cultivar for animal feed rope, biofuel, insulation, paint, plastics, food, biodegradable, clothes, textiles and paper Cannabis musa. Bamboo is also known as java jute or Deccan banana and belongs to Malvaceae. Jute is as sturdy as bamboo. The natural fiber mat treated with sodium hydroxide (NaOH) is procured from Go Green Products Pvt. Ltd., Chennai, India.

2.1 Natural fiber-reinforced composite preparation

The test specimens for the sound absorption coefficient in the impedance tube were 100 mm in diameter and 20 and 40 mm in thickness. The natural fiber composite specimens were prepared using epoxy resin with Aradur HY 951 hardener to enhance the bonding of the fiber layers [20]. They were coated with the concoction. The test specimens were hand-laid-up with 20% natural fibre by volume. Epoxy resin was used as the matrix and Aradur HY 951 hardener as the curing agent (10:1) to prepare the test specimens of natural fiber-reinforced composite.2.2 NFRC Sound Absorption Evaluation. epoxy-to-hardener ratio, followed by processing at 80 °C for 30 min and subsequent room-temperature curing.

Evaluation of acoustic relevance of green composites by means of impedance specific A study of an AFD 1000 impedance tube following ISO 10534-2 was carried out. The sound absorption coefficient (SAC) measuring setup is depicted in Figure 1 with two microphones and an impedance tube. The transfer function method was used to evaluate the SAC where sound propagates via a tube and reflects back from the test object. The AFD 1001 measures the sound absorption coefficient according to DIN EN ISO 10534-2. Audible acoustic frequencies range from 200-1600 Hz. 200–1600 Hz for the 100-mm impedance tube. Impedance test specimens are 100 mm diameter and 20 mm thick in the frequency range 200-1600 Hz. Testing sample connected to reverse tube. Sound is directed via the impedance tube equipment and then strikes the sample to be evaluated, where it reflects. The standing wave ratio is calculated by measuring the pressure using two microphones. The reflection factor, absorption factor at normal incidence and impedance ratio will be determined by software analysis (AFD 1001) using the acoustic transfer functions of two microphone signals. The SAC is determined by analyzing the function of two microphone signals using AFD 1001. A file with the extension.cf contains the frequency band's resulting values. The values are saved in CSV format after being imported into Microsoft Excel. Graphing software is used to view the files in.csv format.

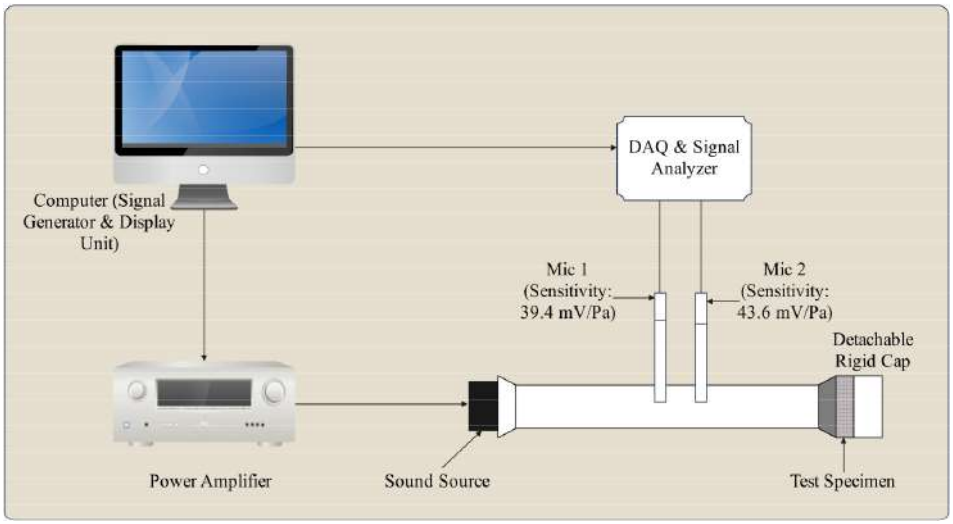


Figure 1 - Schematic diagram of impedance tube

3. Results and discussions

Sisal, banana and bamboo were used in this investigation. These combinations are used to make hand-laid materials. We received sisal, banana, bamboo and sisal-banana samples, 100 mm of diameter, 20 mm and 40 mm of thickness. Bamboo has been combined with sisal in several forms like banana and bamboo (6) and sisal and banana (7) Table 1. Comparison of Coefficient values of Sisal, Banana and Bamboo Composites with thickness

Table 1 - Experimental SAC Data of Natural Fiber Composites

S. No.	Fibers	Thickness (mm)	SAC	Density (kg/m³)
1.	Sisal	20	0.778	1032
2.	Sisal	40	0.892	1032
3	Banana	20	0.605	1049
4	Banana	40	0.81	1049
5	Bamboo	20	0.887	1232
6	Bamboo	40	0.833	1232
7	Sisal+ Banana	20	0.772	1320
8	Sisal + Banana	40	0.984	1320
9	Sisal + Bamboo	20	0.885	1132
10	Sisal + Bamboo	40	0.761	1132
11	Banana+ Bamboo	20	0.965	1259
12	Banana+ Bamboo	40	0.883	1259
13	Sisal+ Banana + Bamboo	20	0.93	1137
14	Sisal+ Banana + Bamboo	40	0.981	1137

3.1 Acoustic properties

The acoustic tests were performed on natural fibers-impregnated composites using the impedance tube method. Figure 2 shows the frequency dependence of SAC with sisal, banana and bamboo natural fiber-reinforced composites. As illustrated in Figure 2(a), the SAC of a 20 mm-thick sisal fiber-reinforced composite was at 560 Hz, and the 40 mm sample was 0.91 at 1280 Hz. In previous studies, the incorporation of banana fibers and mini-Styrofoam balls into jute-cotton fabrics enhanced the sound absorption and SAC by 0.97 [22]. From Figure 2(b), the banana fiber reinforced composite with a thickness of 20 mm has a Sound Absorption Coefficient of 0.62 at 1160 Hz, whereas the sample with a thickness of 40 mm has 0.78 at 1038 Hz. The 20 mm thick bamboo fiber reinforced composite exhibited a sound absorption coefficient of around 0.88 at 640 Hz while the 40 mm thick composite sample was 0.83 at 880 Hz, as shown in Figure 2©.

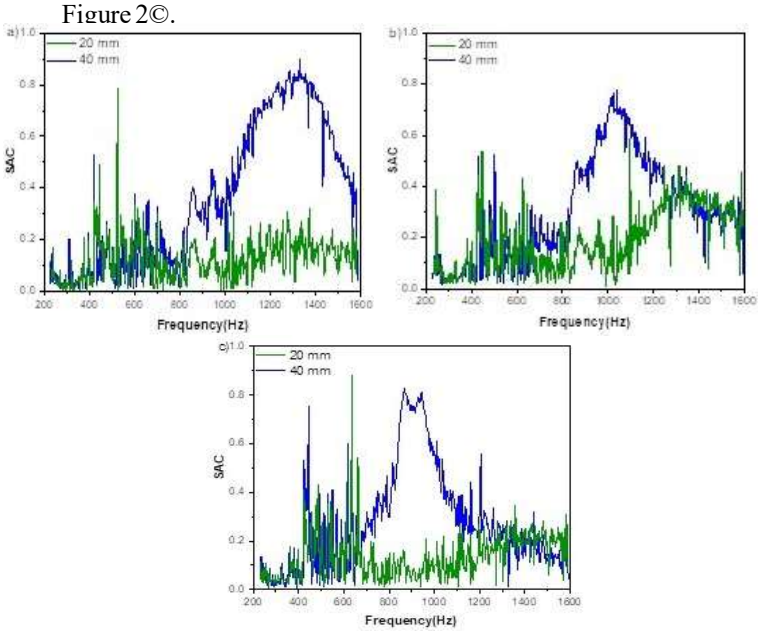


Figure 2 - Frequency Response of SAC in Natural Fiber Composites of 20 mm and 40 mm Thickness: (a) Sisal, (b) Banana, (c) Bamboo

Figure 3 shows how the SAC varies with frequency for various combinations of NFRC. According to the experimental results shown in Figure. 3 (a), the 20 mm thick sisal and banana fiber reinforced composite showed a SAC of roughly 0.28 at a frequency of 550.13 Hz, whereas the 40 mm thick composite specimen showed a huge sound absorption coefficient of roughly 0.821 at 1250.11 Hz of frequency. As illustrated in Figure. 3(b), the sisal and bamboo fiber composite sample with a 20 mm thickness has a sound absorption coefficient value of roughly 0.42 at a frequency of 650.71 Hz, whereas the sample with a 40 mm thickness has a sound absorption coefficient value of roughly 0.724 at frequency of 1050 Hz. According to the results shown in Figure. 3(c), the 20 mm thick banana and bamboo fiber reinforced composite showed a sound absorption coefficient (SAC) roughly 0.619 with frequency of 750.715 Hz, while the 40 mm thick composite sample showed SAC value of roughly 0.843 at a frequency of 1110.32 Hz. In previous study, jute fiber panels demonstrated maximum sound absorption at 30 mm thickness and 1000 kg/m³ density at 5000 Hz, while laminated panels optimized transmission loss at 1500 Hz, suitable for industrial sound insulation [23].

As demonstrated in Figure 4, the SAC fluctuates due to the natural fiber reinforced composites mixed with it. The experimental results shown in Fig. As per the test results, sisal, banana and bamboo fibre composite 20 mm thick has sound absorption coefficient (SAC) of about 0.62. On the other hand, the composite sample with a thickness of 40 mm exhibited a better standard acoustic coefficient of about 0.784 with a frequency of 1150.23 Hz. A study done earlier investigated Bamboo-based materials for railway noise barriers. They reported a sound absorption coefficient of 0.95 at a frequency of above 3500 Hz [24]. Thus, bamboo seems effective for noise reduction applications. The thickness has a considerable effect on the SAC, with thicker samples being found to produce better SAC values.

4. ANOVA-Based Optimization of Acoustic Characteristics

4.1 Sound Absorption Characteristics of NFRCs

The aim of obtaining the SAC is to promote noise reduction by maximizing the sound absorption potential of the composites. Various parameters are analysed to achieve ideal acoustic characteristics by optimizing the conditions for betterment of the SAC. The focus will thus be on improving the SAC values to make the composites more sound-absorbing.

4.1.1 Analysis of contributing factors.

Table 2 shows that the SAC values of different fiber combinations varied depending on fiber types and composite thicknesses. This means the Sisal Fiber exhibits a superior shielding and absorptive characteristics when compared to other natural fibers. The results for Banana Fiber follow a similar trend where its SAC values for thicknesses of 20 mm and 40 mm are 29.3 and 30.0, respectively. The SAC value for the Bamboo Fiber composites was found to be 29.5 and 30.6 at 20 mm and 40 mm thickness. When combined, performance improved. The SAC value of the composites of

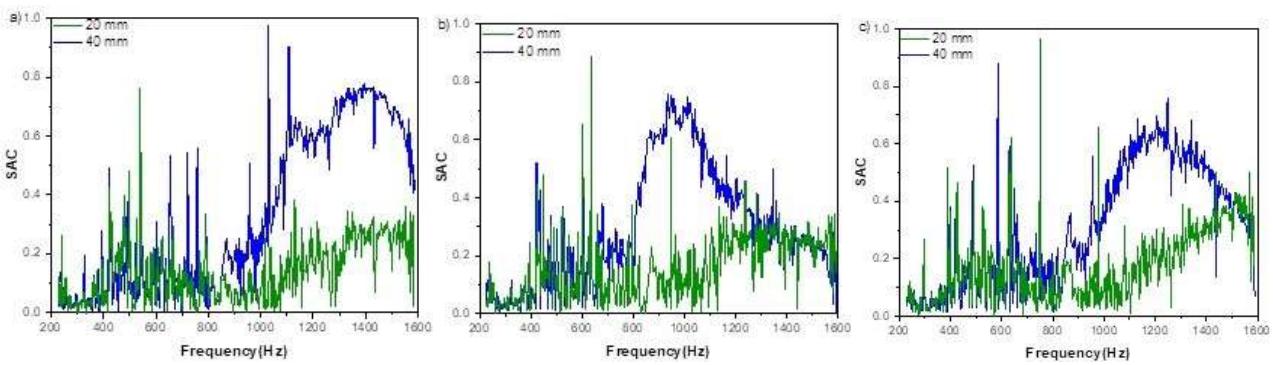


Figure 3 - Effect of Frequency on SAC of Hybrid Composites at Two Thickness Levels: (a) Sisal–Banana, (b) Sisal–Bamboo, (c) Banana–Bamboo

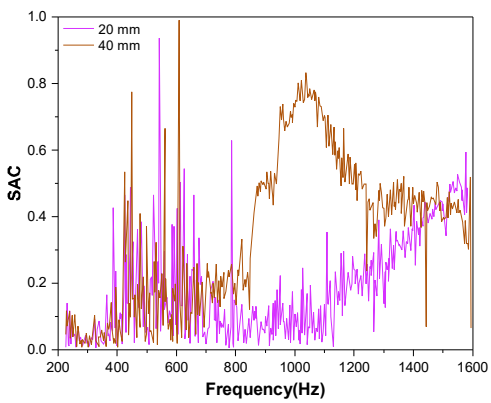


Figure 4 - Impact of Frequency on SAC in Sisal, Banana and Bamboo Fibers Composite (20 & 40 mm)

Sisal Fiber and Banana Fiber was 31.2 for 20 mm thickness and 32.1 for 40 mm thickness. Sisal Flame and Bamboo Fibre showed a SAC value of 30.8 at 20 mm thickness and 31.9 at 20 mm thickness. The SAC values of Banana Fiber and Bamboo Fiber for 20 mm and 40 mm thickness are 33.0 and 34.1, respectively. Of the fibres assessed, the combination of Sisal Fiber, Banana Fiber and Bamboo Fiber gave the highest values of SAC which were 32.5 and 34.0 at 20 mm and 40 mm thickness, respectively. Thus, proving that this hybrid fibres combination improved performance. SAC values of Bamboo Fiber + Sisal Fiber composite for thicknesses of 20 mm and 40 mm are 35.1 and 36.2 respectively, thus endorsing our view that usually fiber combinations improve the SAC values with increasing in thickness. A study indicated that sound-absorbing panels could be manufactured using eco-friendly bamboo charcoal and kaolin clay, achieving a sound absorption coefficient of 0.4 for 7 mm panels [25]. The highest tensile strength of 90 MPa and flexural strength of 143 MPa were obtained for bamboo fiber composites reinforced with 3% cellulose, whereas 5% cellulose produced the largest fracture toughness (30.29 MPa√m) and impact energy (12.5 J) [26, 27]. Developed a sustainable bamboo fiber composite reinforced with 3 vol% silane-functionalized biosilica nanoparticles with optimal mechanical properties such as tensile strength of 142 MPa, flexural strength of 165 MPa, compressive strength of 150 MPa, impact strength of 6.2 J and hardness of 90 Shore D. The tensile and flexural characteristics of sisal/carbon fibre composites are highly dependent on fibre orientations where the maximum configuration obtained 34.27% greater tensile strength and 22.76% higher flexural strength than minimum values anticipated with RSM optimization [28].

Table 2 - Measured SAC Data for Composites

S. No.	Materials	Thickness (mm)	SAC
1	Sisal Fiber	20	27.0
2	Sisal Fiber	40	28.5
3	Banana Fiber	20	29.3
4	Banana Fiber	40	30.0
5	Bamboo Fiber	20	29.5
6	Bamboo Fiber	40	30.6
7	Sisal Fiber+ Banana Fiber	20	31.2
8	Sisal Fiber+ Banana Fiber	40	32.1
9	Banana Fiber+ Bamboo Fiber	20	33.0
10	Banana Fiber+ Bamboo Fiber	40	34.1
11	Sisal Fiber + Banana Fiber+ Bamboo Fiber	20	32.5
12	Sisal Fiber + Banana Fiber+ Bamboo Fiber	40	34.0
13	Bamboo Fiber+ Sisal Fiber	20	35.1
14	Bamboo Fiber+ Sisal Fiber	40	36.2

Table 3 presents the results of the experiment about Materials and Thickness, as well as the values of each level. The values of Materials factor vary from 27.75 in level 1 to 35.65 in Level 8. The delta is 7.90 signifying materials have a substantial effect on the outcome. The material type has a large impact on performance with level 8 (35.65) having the highest value. According to the Thickness factor, from level 1 to level 6 a delta of 1.12 exists from 31.05 to 33.55. Although the impact of thickness is not as considerable as that of the materials, nevertheless thickness also gives lesser performance. Level 6 provides the highest value of 33.55. Material, based on its higher delta i.e. 7.90, has been assigned first rank (Rank 1). So Thickness which has lesser delta i.e. 1.12 has been assigned second rank (Rank 2). According to the data, Materials is the most influential factor, followed by Thickness, for performance in this experiment.

Table 3 - Response analysis about means for SAC

Level	Materials	Thickness
1	27.75	31.05
2	29.65	32.17
3	30.05	
4	31.65	
5	31.35	
6	33.55	
7	33.25	
8	35.65	

The Main Effects Plot for Means in Figure 5 illustrates the impact of two factors, materials and thickness, on the response variable. As the material number increases from 1 to 8, the average values also increase, showing that the type of material has a significant effect on the reaction. This means that various materials yield different results. Materials with a higher number yield a greater mean. The Thickness factor presents a slight increase in the response. The chart shows that when material number increases from 1 to 8, the average value also increases significantly. This indicates that material has a strong effect on the reaction. It shows that different materials have different effect of the outcome and greater numbers of materials give higher mean values. As thickness enlarges from ten to twenty, the response variable under the thickness factor exhibits a minor increase, this denotes as thickness increases the effect of thickness on response would be minimal. This paper explains the importance of the two components and their impact on the total variation in data.

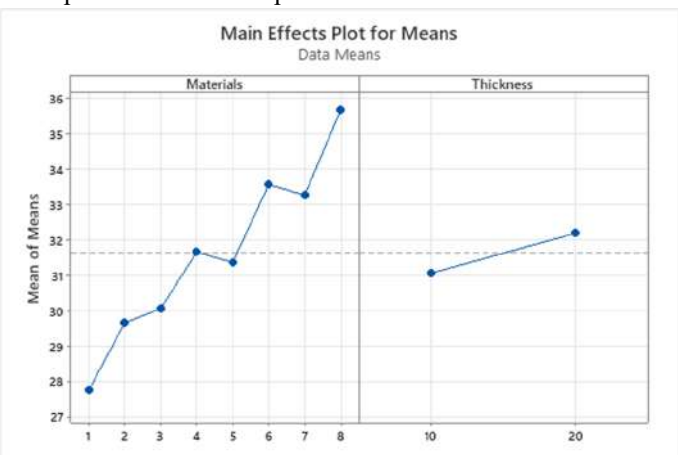


Figure 5 - Main effects plot for the Means of SAC responses

Table 4 - Analysis of variance for Means of SAC

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Materials	7	88.0375	94.30%	88.0375	12.5768	341.89	0.000
Thickness	1	5.0625	5.42%	5.0625	5.0625	137.62	0.000
Error	7	0.2575	0.28%	0.2575	0.0368		
Total	15	93.3575	100.00%				

4.1.2 ANOVA for Acoustic Properties

The response variable is significantly affected by the material and thickness factors as evidenced by ANOVA (Refer to Table 4). The material factor has the highest impact which accounts for 94.30% of variation with sum of squares of 88.0375 with F value 341.89 and P value showing significance as 0.000. The thickness component accounts for 5.42% of variations with a sum square of 5.0625, Fl value137.62 and P value 0.000 indicating that it has a major impact but a lesser impact than the materials. The error term includes only 0.28% of total variation suggested that the model captures most of the variation in the response variable. Both aspects are essential in influencing the outcome, with materials exerting a more significant impact.

5. Conclusions

The paper presents the preparation and experimental characterization of a natural fiber-reinforced composite using sisal, bamboo, and banana fibers. Natural fiber composites' sound absorption and acoustic characteristics of the impedance tube method have been estimated with the Active Format Description 1001 program have been estimated. The present paper deals with the fabrication and acoustic evaluation of natural fiber-reinforced composites (NFRC) consisting of sisal, banana, and bamboo fibre with an epoxy matrix. The impedance tube method was used for the determination of the sound absorption coefficient (SAC). The sisal fibre composites especially at the thickness of 40 mm showed highest value of SAC and it was found to be 0.91 at the frequency of 1280 Hz. The amalgamation of sisal, banana, and bamboo fibers significantly improved the sound absorption characteristics, with the composite incorporating all three fibers demonstrating commendable efficacy. Acoustic property optimization was conducted via ANOVA, revealing that material type exerted the most substantial influence on the SAC, followed by composite thickness. The results indicate that natural fiber-reinforced materials have potential for noise reduction application as an eco-friendly replacement for conventional materials.

Acknowledgement

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A Comprehensive Review of International Trade Policies and Fashion Supply Chain Resilience

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Abstract:

The global fashion industry is currently navigating a transformative era characterized by heightened geopolitical volatility, evolving trade protectionism, and a shift toward circular economic models. This review paper examines the multifaceted impact of international trade policies on the fashion sector from 2020 to 2026. It analyzes the role of Free Trade Agreements (FTAs) such as the Regional Comprehensive Economic Partnership (RCEP) and the India-EU FTA in redefining sourcing landscapes and market accessibility.

Furthermore, the paper investigates the transition from traditional tariff-based barriers to sophisticated Non-Tariff Measures (NTMs), specifically the implementation of environmental and social governance (ESG) mandates like the EU's Digital Product Passports (DPP) and carbon trading schemes. The study highlights how these policies have forced a move away from "ultra-fast fashion" toward transparent, traceable, and "near-shored" supply chains. Key findings suggest that while trade liberalization has historically lowered production costs, contemporary policies are increasingly utilized as tools for sustainability enforcement, significantly increasing compliance costs for exporters in developing nations. The paper concludes by offering strategic recommendations for brands and policymakers to align trade frameworks with global decarbonization goals while maintaining industry competitiveness.

Keywords : *Circular Economy, environmental and social governance, Free Trade Agreements, Global Value Chains, Sustainable Fashion*

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1. Introduction

The global fashion industry, valued at over $1.5 trillion, stands as one of the most complex and fragmented sectors in international commerce [1]. In recent years, the stability of this sector has been tested by unprecedented geopolitical shifts and a transition toward protectionist economic policies [2]. By 2024, protectionism emerged as a dominant organizing principle, replacing decades of liberalized trade [3]. This shift is best exemplified by the drastic expansion of tariffs, such as the reciprocal duties implemented between major trading blocs in 2025, which pushed rates on certain apparel categories above 50% [4]. Global supply chain resilience has become the primary metric for success in this volatile environment [5]. The Regional Comprehensive Economic Partnership (RCEP), which entered into force in 2022, represents a critical turning point by creating the world's largest free trade area, facilitating trade in intermediate goods across 15 Asia-Pacific nations [6, 7]. However, the industry's heavy reliance on cross-border inputs makes it particularly vulnerable to structural shocks [8]. Even as brands attempt to diversify, single-source dependencies remain high; for instance, China still controls approximately 70% of global polyester capacity [9].

Sustainability and transparency have evolved from ethical choices into regulatory requirements [10]. New mandates, such as the EU's focus on Digital Product Passports, reflect a move from traditional tariffs to non-tariff measures (NTMs) aimed at enforcing environmental standards [11, 12]. Emerging markets like India and Bangladesh are currently navigating high compliance costs and technological barriers to meet these global ESG expectations [13, 14]. While trade agreements once focused solely on cost reduction, modern frameworks now incentivize green manufacturing, such as the integration of solar power in textile zones to lower long-term operational expenses [15, 16]. Furthermore, the rise of agentic AI and e-commerce platforms has altered consumer demand patterns, requiring supply chains to be more agile than ever before [17, 18]. Resilience is no longer just about enduring shocks but about the ability to adapt to a "many-nodes, one-standard" system that prioritizes distributed production and high labor standards [19]. This review synthesizes these developments to provide a strategic roadmap for maintaining competitiveness in the 2026 fashion landscape [20].

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2. The Evolution of International Trade Frameworks

The governance of global fashion trade has transitioned from a localized, protectionist system to a highly interconnected global value chain (GVC). Historically, trade was governed by rigid quotas and high tariffs designed to shield domestic industries in the Global North. In the current 2026 landscape, the industry has entered a "Resilience Era," where frameworks have shifted once again to include broader socio-economic goals. Trade policy is no longer viewed solely through the lens of economic exchange; it is now an instrument for enforcing social chapters and environmental mandates [21, 22]. Modern research indicates that the environmental impact of "fast fashion" has catalyzed this regulatory shift, forcing a move from "efficiency at all costs" to "stability through transparency" [23, 24].

Table 1: Evolution of International Trade Frameworks in Fashion

Phase	Key Features	Policy Instruments	Industry Impact
Pre-2005 (MFA Era)	Quota-based protection	Multi Fibre Arrangement (MFA)	Distributed production in developing countries
2005–2015 (Globalization Era)	Liberalized trade	WTO agreements, FTAs	Cost optimization, outsourcing to Asia
2015–2022 (Transition Phase)	Sustainability awareness	ESG guidelines, compliance norms	Initial shift toward transparency
2022–2026 (Resilience Era)	Regionalization & regulation	RCEP, NTMs, CBAM, DPP	Near-shoring, digital traceability

2.1 From Multi-Fibre Arrangement (MFA) to Modern Free Trade Agreements (FTAs)

The transition from the Multi-Fibre Arrangement (MFA) to modern Free Trade Agreements (FTAs) represents the most significant shift in the geography of garment production. Between 1974 and 2004, the MFA utilized quotas to limit imports, which inadvertently fostered the birth of garment sectors in developing nations as manufacturers chased "unused" quotas [25]. Following the expiration of these quotas, production rapidly consolidated in scale-heavy hubs. Today, modern FTAs have replaced simple quotas with complex "Rules of Origin" (RoO), such as the "Yarn Forward Rule," which requires every stage from spinning to stitching to occur within member nations to qualify for zero-duty access [6]. Furthermore, recent studies on "Digital Product Passports" suggest that trade is becoming increasingly digitized to ensure compliance with these complex origin and sustainability rules [26].

2.2 The Role of RCEP and India-EU Partnerships in Sourcing Shifts

Regionalism has emerged as the primary successor to globalism, with the Regional Comprehensive Economic Partnership (RCEP) and potential India-EU agreements serving as primary examples. RCEP has effectively turned Asia into a "super-hub" by allowing for "Regional Accumulation" enabling a garment to utilize raw materials and labor from different member states under a single duty-free umbrella [27]. While RCEP focuses on regional consolidation, the EU's trade perspective in 2026 emphasizes "Global Sustainability in an Interconnected World," utilizing partnerships with the Global South to enforce higher labor and environmental standards [22]. For instance, India's emergence as a "China Plus One" alternative is heavily dependent on its ability to align with these new, values-based trade models [28].

2.3 Trade Liberalization vs. The New Protectionism

The current fashion climate is defined by a deep-seated tension between traditional trade liberalization and a rising "New Protectionism." While export liberalization has historically been shown to increase temporary contracts and non-standard working hours for production workers, it remains a primary driver for economic growth [29]. However, a new form of protectionism has emerged, often framed as environmentalism or national security. Tools like the Carbon Border Adjustment Mechanism (CBAM) act as "de facto" barriers that protect domestic markets by penalizing high-carbon foreign imports [21, 26]. This creates a resilience paradox: while these policies aim to build robust domestic ecosystems, they can simultaneously create global supply chain fragility by increasing compliance costs for small-scale manufacturers [24].

3. Beyond Tariffs: The Rise of Non-Tariff Measures (NTMs)

As traditional import duties have decreased through various free trade agreements, Non-Tariff Measures (NTMs) have emerged as the primary instruments for regulating international fashion trade. NTMs encompass a broad range of policy measures, other than ordinary customs tariffs, that can potentially have an economic effect on international trade in goods [21]. In the textile sector, these measures are increasingly utilized to ensure that imported goods meet the stringent safety and quality standards of developed markets. While ostensibly designed for consumer protection, NTMs often serve as technical barriers that require significant capital investment from manufacturers in emerging economies to ensure compliance [24,30]. By 2026, the complexity of these measures has outpaced traditional tariff structures, making regulatory literacy a cornerstone of supply chain resilience [31].

3.1 ESG Mandates as Modern Trade Barriers

Environmental, Social, and Governance (ESG) mandates have evolved into mandatory legal requirements. Legislative frameworks such as the EU's Corporate Sustainability Due Diligence Directive (CSDDD) require fashion brands to identify and mitigate human rights abuses and environmental harm throughout their entire tier-based supply chain [12]. The technical implementation involves:

IoT Sensors for Environmental Monitoring: Factories must deploy sensor networks to monitor water usage,

chemical discharge, and energy consumption in real-time. For dyeing and finishing operations, which consume approximately 30-50% of textile manufacturing water, IoT sensors monitor effluent treatment systems to ensure compliance with discharge standards [14, 17].

Blockchain for Immutable Record-Keeping: Distributed ledger technology (DLT) creates tamper-proof records of transactions and certifications across the supply chain. For example, blockchain platforms enable tracking of organic cotton certification from farm to garment, providing verifiable proof of sustainable sourcing [26, 31].

AI-Driven Analytics for Risk Assessment: Machine learning algorithms analyze supplier data to identify potential ESG violations. These systems scan for anomalies in labor records, environmental permits, and audit reports, flagging suppliers at risk of non-compliance [17, 18]. For garment-exporting nations like Bangladesh and Vietnam, these ESG requirements represent a significant "hidden cost" of trade, requiring a total overhaul of factory-level monitoring systems [14, 24].

3.2 Digital Product Passports (DPP) and Global Traceability Standards

The implementation of Digital Product Passports (DPP) represents a paradigm shift in global traceability standards. Under new ecodesign regulations, every garment sold in major markets must carry a digital identifier such as a QR code or RFID tag linking to a comprehensive data set regarding its material composition, repairability, and recyclability [26]. This "digital twin" of the physical product ensures transparency from the fiber origin to the point of sale. While DPPs facilitate a circular economy by assisting recyclers in identifying fabric blends, they also function as a sophisticated trade filter [22]. Suppliers who lack the technological infrastructure to maintain these data streams risk being excluded from global value chains, as traceability is now a non-negotiable prerequisite for customs clearance in high-value jurisdictions [18, 31].

3.3 The Impact of Carbon Border Adjustment Mechanisms (CBAM) on Textile Exports

The Carbon Border Adjustment Mechanism (CBAM) is perhaps the most consequential NTM introduced in the mid-2020s, designed to prevent "carbon leakage" by equalizing the price of carbon between domestic products and imports. For the textile industry, which is notoriously carbon-intensive, CBAM functions as a "green tariff" on exports from countries with less stringent environmental regulations [21, 30]. Research indicates that CBAM encourages the "decarbonization of trade," as manufacturers are forced to adopt renewable energy sources to avoid high carbon levies at the border [15, 32]. However, the mechanism also poses a risk of marginalizing small-and-medium enterprises (SMEs) in the Global South that cannot afford the transition to low-carbon technology, potentially centralizing the fashion supply chain among a few highly capitalized, "green-certified" industrial giants [8, 14].

Table 2: Key Non-Tariff Measures (NTMs) in Fashion Trade

NTM Type	Objective	Requirement	Impact
ESG Mandates	Ethical & environmental compliance	Labor and sustainability audits	Increased compliance cost
Digital Product Passport (DPP)	Traceability	Product-level digital data	Transparency, tech investment
CBAM	Carbon control	Emission-based pricing	Decarbonization pressure
Rules of Origin (RoO)	Trade qualification	Local sourcing requirements	Supply chain restructuring

4. Disruptions and Stress Tests in the Fashion Supply Chain

The fashion supply chain has historically been optimized for cost and speed, a model that has proven increasingly fragile under the weight of "polycrisis" events [8]. Stress tests in the 2024–2026 period have revealed that the industry's high level of geographical concentration and interdependency makes it uniquely susceptible to cascading failures [2]. Resilience is now defined not merely by the ability to absorb a shock, but by the "adaptive capacity" to reroute production and logistics in real-time [33]. Modern research suggests that the fashion industry must transition from "static" supply chains to "dynamic" ecosystems where trade policy compliance and risk mitigation are integrated into every sourcing decision [21].

4.1 Geopolitical Volatility and the Fragility of Just-in-Time Manufacturing

For decades, the "Just-in-Time" (JIT) manufacturing model allowed fashion brands to maintain low inventory levels and high margins. However, escalating geopolitical volatility including trade wars, regional conflicts, and shifting alliances has exposed the inherent risks of this lean approach [32]. When trade routes are closed or sanctions are applied to textile-producing regions, the lack of "safety stock" leads to immediate stockouts and financial loss. By 2026, the industry is shifting toward a "Just-in-Case" (JIC) model, which prioritizes inventory buffers and local sourcing to insulate against the unpredictability of international relations [24]. This shift is further compounded by the rise of "agentic AI" in trade, which brands use to predict geopolitical flashpoints and pre-emptively move production [18].

4.2 The "China Plus One" Strategy: Diversification vs. Dependency

As the world's largest textile exporter, China remains indispensable to the fashion industry; however, the "China Plus One" strategy has become a mandatory risk-management framework for global brands [4]. This strategy involves maintaining significant operations in China for its unmatched scale and technology while diversifying a "plus one" (or more) portion of production to hubs like Vietnam,

Figure 3 -

India, or Turkey [2, 7]. Despite these efforts, "hidden dependency" remains high, as many non-Chinese factories still rely on Chinese-manufactured yarn and fabric to function [9]. True diversification requires more than just moving garment assembly; it necessitates the development of vertical supply chains in alternative regions a process that is currently being accelerated by regional trade agreements like RCEP [6].

4.3 Logistics Bottlenecks and the Cost of Global Freight Fluctuations

Global freight has become a major variable in fashion trade policy, with fluctuations in shipping costs directly impacting the landed cost of goods. Logistics bottlenecks, exacerbated by canal disruptions and port congestion, have highlighted the vulnerability of long-haul maritime trade [30]. Between 2024 and 2026, the industry saw freight rates swing by over 300% in response to regional tensions, leading to a surge in "near-shoring" the practice of moving production closer to the end consumer (e.g., Mexico for the US, or North Africa for the EU) [8, 31]. By reducing the physical distance between the factory and the storefront, brands can mitigate the risks of global freight volatility and reduce the carbon footprint associated with long-distance transportation, aligning with new "green" trade mandates [21, 31].

Table 3: Supply Chain Disruptions (2024–2026)

Disruption Type	Cause	Impact on Fashion Industry
Geopolitical Conflicts	Trade wars, sanctions	Supply chain delays, cost rise
Pandemic Effects	COVID-19 aftermath	Production shutdowns
Logistics Bottlenecks	Port congestion, freight spikes	Increased delivery time
Raw Material Dependency	China dominance	Supply risk concentration

5. Strategic Responses: Building Resilience in a Volatile Market

In response to the "polycrisis" of the early 2020s, fashion enterprises have moved beyond reactive crisis management toward structural resilience. Building resilience in a volatile market now requires a dual approach: geographical rebalancing and technological fortification [21]. Industry leaders are increasingly adopting "resilience-by-design," where supply chains are pre-configured to absorb shocks through multi-nodal sourcing and real-time policy monitoring [33]. This strategic shift is heavily influenced by the transition from cost-centric procurement to a "value-per-unit-of-risk" model, ensuring that brands can maintain operations even during localized geopolitical or environmental disruptions [2].

5.1 The Shift Toward Near-shoring and Friend-shoring

One of the most visible strategic responses is the geographical contraction of supply chains, characterized by near-shoring and friend-shoring. Near-shoring moving production to countries in close proximity to major consumer markets (e.g., Turkey for Europe or Mexico for the United States) allows brands to drastically reduce lead times and shipping costs while responding to rapid trend cycles [8, 31]. Simultaneously, "friend-shoring" has emerged as a policy-driven strategy where production is moved to geopolitically aligned nations to avoid the risks of trade sanctions or political instability [32]. While these shifts enhance speed and security, they often come with higher labor costs, prompting a concurrent push for increased automation in these regional hubs [2].

5.2 Technological Integration: Agentic AI and Predictive Trade Analytics

The integration of Agentic AI and predictive analytics is revolutionizing how fashion brands navigate complex international trade waters. Unlike traditional software, agentic AI systems can autonomously monitor global trade policy changes, customs data, and geopolitical sentiment to provide predictive alerts on potential bottlenecks [17, 18]. These tools allow firms to simulate the impact of new tariffs or non-tariff measures before they are officially enacted, enabling proactive supply chain rerouting [33]. By 2026, predictive trade analytics have become essential for maintaining the "Digital Product Passport" (DPP) standards, as they manage the vast streams of data required for cross-border transparency and compliance [22].

5.3 Circular Economy Policies: Transforming Waste into Tradeable Value

Circular economy policies are transforming the fashion industry's waste stream into a new category of tradeable value. As major markets like the EU implement "Extended Producer Responsibility" (EPR) schemes, waste is being reclassified from a liability to a secondary raw material [23]. This shift is creating a new global trade in recycled fibers and "pre-loved" garments, supported by standardized trade classifications that facilitate the movement of textile waste for high-grade recycling [21, 26]. Modern research indicates that circularity is not just a sustainability goal but a resilience strategy, as it reduces dependency on virgin raw materials such as cotton or petroleum-based synthetics which are often subject to volatile global commodity prices [24].

Table 4: Strategic Responses by Fashion Industry

Strategy	Description	Benefit	Challenge
Near-shoring	Production closer to markets	Reduced lead time	Higher labor cost
Friend-shoring	Sourcing from allied nations	Political stability	Limited capacity
Diversification	Multi-country sourcing	Risk reduction	Complexity
Digitalization	AI, blockchain adoption	Efficiency, compliance	High investment

6. Impacts on Emerging Economies and Manufacturing Hubs

The transition toward a "resilience-first" trade model has

created a significant divide among emerging manufacturing hubs. While traditional trade liberalization provided a pathway for rapid industrialization in Southeast Asia and South Asia, the new era of "regulated trade" presents a double-edged sword [29]. For manufacturing giants like Bangladesh, Vietnam, and Ethiopia, the sudden shift in Western trade policies moving from price-driven to compliance-driven threatens to marginalize producers who cannot afford the rapid transition to green infrastructure [14, 21]. However, those hubs that successfully align with these new trade standards are seeing a surge in "friend-shoring" investments, as brands seek politically stable and environmentally compliant alternatives to traditional sourcing routes [7, 32].

6.1 Compliance Challenges for Tier 2 and Tier 3 Suppliers

A critical vulnerability in fashion supply chain resilience lies in the lower tiers of production. While Tier 1 factories (final assembly) are often under direct scrutiny, Tier 2 (fabric mills) and Tier 3 (yarn and fiber producers) face the most daunting compliance hurdles under new international mandates [24]. The EU's Digital Product Passport (DPP) and various due diligence laws require granular data from these deep-tier suppliers, many of whom operate in jurisdictions with limited digital infrastructure or regulatory oversight [22, 31]. The cost of implementing real-time traceability and carbon-monitoring systems often falls disproportionately on these smaller entities, leading to a "compliance gap" where only the most well-capitalized suppliers survive, potentially causing a bottleneck in the global supply of compliant raw materials [14, 17].

6.2 Labor Standards, Wage Growth, and Trade Preferences (GSP/EBA)

The relationship between trade preferences and labor standards has become a central pillar of 2026 fashion trade policy. Schemes like the "Everything but Arms" (EBA) and the Generalized Scheme of Preferences (GSP) are increasingly being used as diplomatic levers to enforce wage growth and collective bargaining rights [30, 33]. For many emerging economies, the "graduation" from LDC (Least Developed Country) status brings the existential threat of losing these duty-free benefits unless they can prove adherence to elevated international labor standards [2]. Recent studies show that while these policies drive social progress, they also increase the "unit cost" of garments, forcing manufacturing hubs to shift their competitive advantage from "cheap labor" to "high-efficiency, high-ethical-standard" production to maintain their position in the global value chain [23, 29].

Table 5: Impact on Emerging Economies

Factor	Positive Impact	Negative Impact
Trade Liberalization	Export growth	Labor exploitation risk
ESG Regulations	Improved standards	High compliance cost
Digital Requirements	Modernization	Tech barriers
CBAM	Green transition	SME marginalization

7. Balancing Competitiveness and Sustainability

The modern trade environment has forced a fundamental decoupling of "competitiveness" from "low-cost production." In 2026, a fashion brand's competitive edge is increasingly determined by its ability to navigate a "high-standard, high-transparency" regulatory framework [21]. This discussion examines the inherent friction between legacy business models and the mandatory transition toward a net-zero trade architecture. While liberalization previously focused on reducing border frictions, the current policy shift prioritizes "values-based trade," where market access is a reward for verified sustainability [30, 34].

7.1 The Conflict Between Ultra-Fast Fashion and Green Trade Policy

The "Ultra-Fast Fashion" model pioneered by giants like Shein and Temu faces an existential challenge from the 2025–2026 wave of trade policies. Historically, these entities utilized "de minimis" exemptions to bypass duties and labor scrutiny, but the closure of these loopholes in major markets has introduced significant friction [35, 36].

- Policy Intervention: New tariffs specifically targeting high-volume, low-durability goods have been implemented to dampen the "market bombing" strategy that encourages excessive consumer waste [36].
- Resilience Paradox: While these policies aim to protect "Mother Earth" and domestic industries, they also raise consumer prices and force ultra-fast fashion brands to pivot toward secondary markets (the "US Plus One" strategy), potentially shifting the environmental burden rather than eliminating it [24, 35].
- The Sourcing Shift: Brands are being forced to choose between the high-speed, high-waste models of the past and the slower, more resilient, and policy-compliant "Just-in-Case" models of the future [37].

7.2 Harmonizing Global Standards: A Path Toward "Many-Nodes, One-Standard"

To avoid a fragmented global market, there is a burgeoning movement toward the harmonization of international fashion standards. The "Many-Nodes, One-Standard" philosophy suggests that for a supply chain to be truly resilient, it must adhere to a single, high-level compliance baseline regardless of geographical location [21, 38].

- Standardization: Just as protocols like JSON and OpenRTB standardized digital communication, the fashion industry is adopting standardized "Bid Requests" for sustainability where a product's unique ID carries its full carbon, labor, and material history [31, 39].
- Interoperability: Harmonization reduces the "compliance theatre" often found in global sourcing, where factories maintain different records for different auditors [31,40].
- Outcome: By aligning regional trade blocs (like RCEP and the India-EU FTA) under a unified transparency protocol, the industry can reduce procedural layering and focus on actual industrial maturity rather than optics [23 , 3 & 40].

8. Conclusion

Navigating a New Era of Fashion Trade Summary of Key Policy Drivers

The global fashion landscape has moved beyond simple cost-reduction models toward a complex "Resilience Era" governed by sophisticated trade instruments. While the expiration of the Multi-Fibre Arrangement (MFA) initially led to massive production consolidation, modern Free Trade Agreements (FTAs) like the RCEP have shifted the focus toward regional "super-hubs" and strict Rules of Origin. Today, the primary drivers of trade are no longer just tariffs but Non-Tariff Measures (NTMs) and mandatory ESG mandates. Tools such as the EU's Digital Product Passports (DPP) and Carbon Border Adjustment Mechanisms (CBAM) now function as "green tariffs," requiring verifiable proof of sustainability and material traceability as a prerequisite for market access. This transition reflects a "New Protectionism" where trade policy serves as a primary tool for enforcing environmental and social governance across global value chains.

Future Outlook: The Fashion Industry in 2030

By 2030, the fashion industry is expected to operate within a "many-nodes, one-standard" system that prioritizes distributed production and high labor standards. This future landscape will see circular economy policies move from ethical goals to core resilience strategies, as brands seek to reduce dependency on volatile virgin raw materials by trading in recycled fibers. Technological fortification will be central to this evolution; the integration of Agentic AI and predictive analytics will allow supply chains to function as dynamic ecosystems capable of autonomously rerouting in response to geopolitical shocks. Furthermore, the trend toward near-shoring and "friend-shoring" is likely to stabilize, as brands seek to insulate themselves from global freight fluctuations and maritime bottlenecks by producing closer to the end consumer.

Table 6: Future Outlook of Fashion Industry (2030)

Trend	Description	Expected Outcome
Circular Economy	Recycling & reuse	Reduced raw material dependency
Digital Supply Chains	AI-driven systems	Real-time adaptability
Regionalization	Near-shoring growth	Faster delivery
ESG Dominance	Mandatory compliance	Sustainable production

Recommendations for Policymakers and Industry Stakeholders

To maintain competitiveness, stakeholders must align their strategies with these emerging decarbonization and transparency goals. Policymakers are encouraged to focus on the harmonization of global standards to reduce "compliance theatre" and procedural layering, ensuring that regional trade blocs operate under unified transparency protocols. It is also vital for governments to provide technological and financial support to Tier 2 and Tier 3 suppliers in emerging economies to prevent a "compliance gap" that could marginalize smaller producers. For industry leaders, the recommendation is to adopt "resilience-by-design" by moving toward a "value-per-unit-of-risk" procurement model. Immediate investments in digital infrastructure and low-carbon manufacturing are essential to meet mandatory traceability requirements and mitigate the rising costs of carbon-based border levies.

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Exploring the Impact of Diversity and Inclusion on Organizational Performance

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Abstract :

Workforce diversity and workplace inclusion are increasingly important to organizational performance, particularly in manufacturing environments requiring cooperation among employees with different technical, educational, professional, and demographic backgrounds. This paper explores the impact of diversity and inclusion on organizational performance, with particular reference to textile manufacturing organizations. A focused narrative literature review was used to examine scholarly contributions concerning diversity management, inclusive leadership, psychological safety, employee engagement, innovation, and organizational effectiveness. Relevant publications were identified through foundational literature and targeted searches of accessible scholarly publication records. The selected evidence was examined through qualitative thematic synthesis, distinguishing established findings from proposed applications to textile manufacturing. The review indicates that workforce diversity can broaden organizational knowledge and professional perspectives, while inclusive workplace practices may facilitate participation, communication, collaboration, and organizational learning. However, the relationship between diversity and performance is conditional rather than uniformly positive. Inclusive leadership, equitable opportunities, and psychological safety emerge as important mechanisms through which organizations may utilize workforce differences. A conceptual framework is proposed to explain these relationships and identify relevant performance dimensions. The paper concludes that textile manufacturing organizations should integrate diversity and inclusion with leadership development, technical collaboration, workforce training, and continuous improvement. Further empirical research is needed to establish the extent to which these mechanisms influence measurable manufacturing outcomes.

Keywords: *employee engagement, inclusive leadership, organizational performance, psychological safety, textile manufacturing, Workforce diversity*

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1. Introduction

Modern textile manufacturing involves interconnected activities requiring employees with different technical qualifications, occupational experiences, and professional responsibilities. Spinning, weaving, processing, garment production, quality management, engineering, merchandising, and administration depend on effective coordination among specialized personnel. These occupational differences exist alongside variations in age, gender, cultural background, educational attainment, and individual experience. Managing workforce diversity has therefore become an important organizational consideration, particularly as manufacturing enterprises respond to technological transformation, international competition, and changing production requirements.

Diversity refers to differences among organizational members, whereas inclusion emphasizes meaningful participation, equitable treatment, and recognition within the workplace. Organizational approaches to diversity significantly influence employee learning and work-group effectiveness [1]. The outcomes of workplace diversity are also shaped by contextual factors, managerial practices, and organizational conditions [2]. Inclusion encompasses employees' perceptions of belongingness and the recognition of their individual uniqueness within organizational settings [3]. Collectively, these perspectives establish diversity and inclusion as closely related but conceptually distinct dimensions of organizational functioning.

The relationship between workforce diversity and organizational performance is not inherently positive, as its outcomes depend on industry characteristics, team composition, and contextual conditions [4]. In textile manufacturing, employment practices, working conditions, and workforce management further influence diversity-related outcomes. Social sustainability challenges within textile and apparel supply chains highlight the importance of equitable employment practices, employee welfare, and responsible workforce management [5]. Gender representation and women's participation in the apparel industry also present organizational challenges that require

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attention to workplace inclusion and employment equity [6]. Furthermore, technological advancements are transforming production processes and workforce requirements, making employee adaptability and skill development increasingly important. The growing adoption of Industry 4.0 technologies in textile and apparel manufacturing underscores the need for workforce readiness, technical competencies, and organizational adaptation [7].

Although existing research offers substantial knowledge about diversity and inclusion, relatively limited evidence directly connects these practices with measurable textile manufacturing outcomes. This paper addresses that gap through a critical synthesis of organizational research and its potential applications to textile enterprises. Its contribution is to identify relevant mechanisms, differentiate performance dimensions, and propose a conceptual framework. The term impact is used to explore reported organizational relationships and theoretically plausible effects rather than to claim direct causal measurement.

2. Research Methodology

2.1 Research Design and Literature Identification

The present study employs a focused narrative literature review supported by qualitative thematic synthesis to examine diversity and inclusion in textile manufacturing. This methodological approach facilitates the integration and critical interpretation of theoretical perspectives and empirical evidence from organizational behavior, diversity management, leadership, and manufacturing research. Methodological transparency is essential in literature-based research to ensure clarity in the selection, evaluation, and synthesis of relevant scholarly contributions [8]. Accordingly, the study is explicitly positioned as a narrative review rather than a systematic review or meta-analysis. Its primary objective is to synthesize existing knowledge, identify recurring themes, and develop a conceptual understanding of how workforce diversity and inclusive organizational practices influence workplace dynamics and organizational functioning within the textile manufacturing sector.

The literature base was developed from foundational sources in the original manuscript and targeted supplementary searches of publicly accessible scholarly publisher records and bibliographic pages. Search expressions included combinations of “workforce diversity,” “organizational performance,” “inclusive leadership,” “psychological safety,” “employee engagement,” “textile manufacturing,” and “workforce inclusion.” Supplementary source checks for the revision were undertaken on 12 October 2026. The approach was purposive rather than exhaustive; it did not involve a comprehensive institutional search of subscription bibliographic databases.

2.2 Selection Criteria and Evidence Synthesis

Publications were considered relevant when they examined workforce diversity, inclusion, leadership, employee participation, organizational learning, innovation, or manufacturing-related organizational outcomes. Priority was given to peer-reviewed studies, established theoretical contributions, and scholarly reviews. Sources with insufficient relevance to the research questions were not used as substantive evidence. The literature included foundational and contemporary publications, allowing established organizational concepts to be considered alongside recent manufacturing developments.

Studies were examined according to their principal concepts, research settings, and reported relationships. The synthesis distinguished directly reported findings, evidence drawn from other industries, and the authors' proposed applications to textile manufacturing. No exhaustive screening register, independent dual screening, or formal numerical quality assessment was completed. Consequently, the paper does not claim systematic-review reproducibility or report unsupported study-selection counts.

No primary survey, experiment, statistical analysis, or meta-analysis was conducted. Quantitative findings from published studies were interpreted qualitatively because the available sources involved different populations, research designs, and performance indicators. The resulting conclusions are conceptual and evidence-informed rather than estimates of direct causal effects.

3. Review of Literature

3.1 Workforce Diversity and Organizational Effectiveness

Research on organizational diversity highlights both the potential benefits and challenges arising from differences among workforce members. Evidence suggests that workforce diversity is associated with certain indicators of business performance, indicating its potential contribution to organizational effectiveness and competitive advantage [9]. However, the strength and direction of these relationships depend on the dimensions of diversity examined, organizational characteristics, and prevailing workplace conditions. A diverse workforce can enhance access to varied knowledge, professional experiences, and alternative perspectives, thereby supporting creativity, problem-solving, and informed decision-making. At the same time, workforce differences may create additional communication and coordination challenges, emphasizing the importance of effective management practices and inclusive organizational environments.

Cultural diversity within work groups can generate both organizational advantages and interpersonal challenges, influencing collaboration, communication, and overall team effectiveness [10]. Moreover, employees' organizational experiences are shaped by the interaction of multiple social, professional, and occupational identities, which influence their workplace participation and access to opportunities [11]. These perspectives indicate that demographic representation alone is insufficient to ensure organizational effectiveness, as the benefits of diversity depend on inclusive

practices and effective workforce management. Within textile manufacturing enterprises, employees working in technical operations, production, quality control, and administrative functions contribute distinct knowledge, skills, and professional perspectives. However, the effective integration of these diverse capabilities requires clear communication, cross-functional coordination, equitable participation, and supportive managerial practices to strengthen organizational collaboration and operational performance.

3.2 Inclusion, Engagement, and Organizational Learning

Workplace inclusion concerns the extent to which employees experience respect, recognition, fairness, and opportunities for meaningful involvement. Inclusive conditions may encourage employees to communicate ideas, share information, and participate in workplace improvement activities. However, the development of such conditions requires more than formal diversity policies. Organizational practices must support equitable participation and consistent managerial behavior.

Diversity training programs differ in their approaches and outcomes, and training alone may not lead to meaningful organizational change [12]. Workplace inclusion therefore requires consistent attention to leadership practices, employee relationships, fair access to opportunities, and everyday working conditions. In textile manufacturing, these factors are particularly important because employees work across different departments and occupational levels. Involving production workers, technical staff, supervisors, and administrative employees in problem-solving and process improvement can encourage knowledge sharing and better coordination. This suggests that inclusion is more effective when it becomes part of regular workplace practices rather than remaining limited to occasional training programs.

3.3 Inclusive Leadership and Psychological Safety

Inclusive leadership can encourage employees to share their ideas and participate in workplace activities by promoting respectful communication and creating opportunities for involvement. Research conducted in a manufacturing setting found that psychological safety plays an important role in team learning, particularly when employees feel comfortable discussing concerns, asking questions, and learning from mistakes [13]. Further research in healthcare teams showed that leader inclusiveness and differences in professional status can influence employees' sense of psychological safety and their willingness to participate in improvement activities [14]. Although these studies were conducted in different organizational settings, they offer useful insights into how leadership behavior and workplace communication can support employee participation and collaborative learning.

Psychological safety plays an important role in the relationship between inclusive leadership and employees' participation in creative activities, as individuals are more likely to contribute ideas when they feel respected and supported [15]. An inclusive workplace climate can also influence how employees interact and collaborate within gender-diverse work groups [16]. In addition, inclusive leadership can strengthen employees' sense of belonging while recognizing their individual skills, experiences, and contributions [17]. These findings are relevant to textile manufacturing, where effective communication between workers, supervisors, and technical staff is essential for identifying production problems and sharing operational knowledge. Leadership practices that encourage open discussion and employee involvement may improve workplace collaboration. However, further research is needed to determine whether these practices directly contribute to measurable improvements in textile manufacturing productivity.

4. Research Gap and Conceptual Framework

4.1 Research Gap

Existing literature provides substantial evidence concerning workforce diversity, inclusive leadership, psychological safety, and employee-related outcomes. Nevertheless, much of this research originates from general organizational settings rather than textile manufacturing. The relationship between inclusion and manufacturing-specific performance indicators, including production quality, defect reduction, technical coordination, and operational adaptability, requires further investigation.

Another limitation concerns the tendency to treat organizational performance as a single outcome. Employee engagement, innovation, production efficiency, and organizational adaptability represent different dimensions that may respond differently to workplace practices. The present review addresses these limitations by identifying intermediate organizational mechanisms and distinguishing established evidence from proposed textile-specific applications.

4.2 Proposed Conceptual Framework

The proposed framework considers diversity as a source of different professional capabilities and perspectives. Inclusive leadership, equitable participation, and psychological safety are treated as organizational conditions that may influence whether these differences support communication and collaborative work. Knowledge sharing, engagement, and coordination are identified as possible intermediate processes connecting workforce composition with performance-related outcomes.

The framework recognizes that organizational culture, technology, workforce structure, and managerial systems may influence the proposed relationships. Diversity does not independently guarantee improved performance. Its potential benefits depend on whether organizational conditions allow employees to contribute relevant knowledge and coordinate effectively.

Figure 1 - Conceptual Relationship Between Diversity, Inclusion, and Organizational Performance



Source: *Authors' conceptual synthesis based on the reviewed literature. The relationships are proposed mechanisms rather than validated causal effects.*

5. Diversity, Inclusion, and Organizational Performance

5.1 Employee Engagement and Participation

Employee engagement reflects employees' involvement in and connection with their work. Inclusive practices may strengthen participation by improving perceived fairness and recognition. Employees who believe that their professional contributions receive appropriate consideration may be more willing to communicate operational concerns and participate in organizational improvement.

In textile manufacturing, production workers and technical specialists may possess practical knowledge that is not immediately visible to senior management. Inclusive communication systems can provide opportunities for this knowledge to reach relevant decision makers. Nevertheless, engagement should be measured separately from operational productivity because favorable employee perceptions do not automatically establish improved manufacturing results.

5.2 Innovation and Knowledge Sharing

Innovation frequently requires interaction among employees with different technical and professional capabilities. Textile product development may involve expertise in materials, chemistry, engineering, manufacturing, design, and market requirements. Cross-functional knowledge exchange can broaden the information available for organizational problem solving, although its effectiveness depends on technical competence and implementation resources.

The adoption of Industry 4.0 technologies varies across manufacturing companies, with differences in implementation approaches, organizational readiness, and technological capabilities [18]. These variations highlight the importance of considering organizational conditions when introducing new production technologies. In textile manufacturing, collaboration among employees with different skills and levels of experience may help connect traditional production knowledge with emerging digital technologies. Encouraging workers, technical personnel, and managers to share their expertise could support smoother technological transitions and improve coordination during operational changes. However, the potential benefits of inclusive collaboration in this context remain largely conceptual, and further empirical research is needed to establish its direct effects on manufacturing performance.

5.3 Operational and Strategic Performance

Organizational performance should be differentiated into employee-related, operational, innovative, and strategic outcomes. Operational indicators may include production quality, rework, machine downtime, and process reliability. Strategic outcomes may involve organizational adaptability, employee capability development, and responses to technological change. These dimensions are affected by multiple organizational and technical factors.

The workplace diversity climate plays an important role in shaping how workforce differences relate to organizational outcomes, particularly through employees' perceptions of fairness, acceptance, and support [19]. Research has also examined the relationship between inclusive leadership, psychological safety, and innovative performance, suggesting that employees may be more willing to contribute ideas when they feel valued and supported at work [20]. Together, these studies help explain how inclusion-related practices can influence employee behavior, collaboration, and organizational performance. In textile manufacturing, similar practices may encourage knowledge sharing and greater participation in workplace improvement activities. However, the findings cannot be treated as direct evidence of productivity gains in textile enterprises, as further industry-specific research is required to establish these relationships.

6. Evidence Synthesis and Performance Assessment

The reviewed literature suggests that diversity and inclusion may influence organizational outcomes through several interconnected mechanisms. Diversity can increase access to specialized knowledge, while inclusion-related practices may improve the conditions under which employees exchange that knowledge. Their influence is therefore better understood through organizational processes than through simple assumptions about workforce representation.

Table 1 - Diversity and Inclusion Mechanisms Relevant to Textile Manufacturing

Organizational dimension	Principal mechanism	Potential textile application	Supporting literature
Workforce diversity	Different professional perspectives	Technical problem identification	[1, 2 & 10]
Inclusive leadership	Employee participation and recognition	Shop-floor communication	[14, 17]
Psychological safety	Open information exchange	Reporting quality concerns	[13, 15]
Knowledge sharing	Cross-functional collaboration	Production improvement activities	[7, 18]
Inclusion climate	Fairness and participation	Employee engagement and development	[3, 6 & 19]

Source: *Authors' synthesis of the cited literature. Textile applications are conceptual where direct sector-specific evidence is unavailable*

Interpretation of Table 1: The table identifies mechanisms through which workforce diversity and inclusion may become relevant to textile manufacturing. The supporting studies establish relationships concerning employee participation, leadership, and organizational processes in different settings. The proposed textile applications indicate areas where these mechanisms could be investigated. They should not be interpreted as measured improvements in production performance.

A second consideration concerns how organizational performance is evaluated. Different outcomes require different indicators and research methods. Employee perceptions may be assessed through validated questionnaires, while production-related performance should be examined using appropriate operational records.

Interpretation of Table 2: The table distinguishes employee-related outcomes from measurable operational performance. Improvements in perceived inclusion or engagement cannot independently establish that production quality or productivity has improved. Research combining employee-level information with manufacturing records would provide a stronger basis for examining these relationships.

7. Inclusive Leadership and Organizational Challenges

7.1 Leadership and Employee Communication

Leadership plays an important role in determining whether workforce diversity is supported by meaningful inclusion. Manufacturing employees may hesitate to communicate concerns when organizational relationships are strongly hierarchical or when managerial responses appear inconsistent. Inclusive leaders can encourage respectful communication, clarify expectations, and provide appropriate channels for employees to contribute technical observations.

Textile enterprises can incorporate these practices into production meetings, quality circles, training programs, and interdisciplinary improvement activities. However, employee participation must be accompanied by technical accountability and suitable decision-making procedures. Effective inclusion complements operational discipline

Table 2 - Organizational Performance Dimensions and Suggested Indicators

Performance dimension	Relevant organizational process	Suggested indicator	Evidence classification
Employee engagement	Inclusion and perceived fairness	Employee engagement measures	Broader organizational evidence
Knowledge sharing	Participation and communication	Improvement activity records	Broader organizational evidence
Operational quality	Cross-functional coordination	Defect and rework rates	Proposed textile-specific relationship
Innovation	Collaborative problem solving	Implemented process improvements	Broader evidence; sectoral testing needed
Workforce adaptability	Inclusive training and learning	Skill development measures	Conceptual manufacturing application

rather than replacing established manufacturing responsibilities.

7.2 Barriers to Effective Inclusion

Differences in language, professional priorities, educational backgrounds, and organizational status may create communication difficulties. Unequal access to development opportunities and inconsistent recognition may also affect employees' perceptions of fairness. Such barriers can weaken participation even when an organization formally supports workforce diversity.

Another challenge concerns evaluation. Workforce representation is relatively straightforward to document, but meaningful inclusion requires assessment of employee experience and workplace processes. Organizations should examine communication practices, development access, participation, and managerial fairness while respecting employee confidentiality and applicable legal requirements.

8. Discussion

The reviewed literature establishes that workforce diversity and workplace inclusion are connected but analytically different. Diversity concerns the range of employee characteristics and capabilities available within an organization. Inclusion concerns the organizational conditions under which these differences can contribute to participation, knowledge exchange, and coordinated work. The literature generally supports the importance of inclusive leadership and psychological safety, but it does not establish uniformly positive relationships between diversity and every performance outcome.

Differences across research findings may arise from organizational culture, task complexity, leadership practices, diversity dimensions, and measurement methods. Some organizations may benefit from broader knowledge resources, while others may encounter communication problems or interpersonal conflict. Inclusive practices may help manage these difficulties, but technical resources, production systems, and organizational capabilities also influence outcomes. Consequently, organizational improvements cannot be attributed exclusively to workforce composition or inclusion initiatives.

Within textile manufacturing, the proposed mechanisms are relevant because production activities require collaboration among employees with specialized technical knowledge. However, evidence concerning the direct influence of diversity and inclusion on textile production efficiency remains limited. Future studies should examine whether employee participation and psychological safety are associated with operational outcomes after accounting for workforce competence, production technology, organizational size, and management practices.

9. Managerial Implications

Textile manufacturing organizations should integrate diversity and inclusion into established management processes rather than treating them as independent human-resource initiatives. Immediate priorities may include transparent communication, equitable task allocation, meaningful employee feedback, and opportunities for cross-functional problem solving. Supervisors should encourage technically relevant contributions from employees while maintaining responsibility for appropriate operational decisions.

Longer-term interventions may involve inclusive leadership development, transparent promotion procedures, equitable access to technical training, and participation during technological transformation. Organizations should evaluate these practices through suitable employee and operational indicators. Such monitoring can help distinguish improvements in workplace experience from changes in production outcomes and support more informed management decisions.

10. Limitations and Future Research

This paper is based on a focused narrative review and does not report primary survey, experimental, or textile-factory performance data. The literature-search procedure was purposive rather than exhaustive, and no formal systematic screening or statistical meta-analysis was undertaken. Furthermore, much of the reviewed evidence originates from organizational settings outside textile manufacturing. The resulting framework therefore represents an informed conceptual interpretation rather than a validated causal model.

Future empirical research should examine clearly defined samples from textile manufacturing enterprises and use appropriate measures of diversity, inclusion, leadership, and organizational performance. Comparative and longitudinal studies could assess relationships between employee participation, knowledge sharing, production quality, and technological adaptability. Such investigations would help determine the organizational conditions under which diversity and inclusion contribute to measurable textile manufacturing outcomes.

11. Conclusion

Workforce diversity and workplace inclusion are important organizational considerations, but their relationship with performance is conditional. Diversity provides access to varied employee backgrounds, expertise, and perspectives, while inclusion may influence whether these resources are effectively utilized through participation, communication, and collaborative learning. Existing research supports several underlying organizational mechanisms but does not justify assuming that workforce diversity automatically improves productivity or innovation.

For textile manufacturing enterprises, inclusive practices may contribute to employee engagement, technical knowledge exchange, cross-functional cooperation, and organizational adaptability. Their effectiveness depends on leadership behavior, organizational systems, workforce

capabilities, and production conditions. The proposed conceptual framework provides a basis for understanding these relationships while distinguishing established evidence from textile-specific interpretations.

Organizations should therefore integrate inclusion with leadership development, employee training, technical collaboration, performance management, and continuous improvement. Further empirical investigation is required to determine the extent to which these practices influence measurable manufacturing performance.

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Investigating Fabric Grain: The Influence of Grainline on Woven and Knit Fabrics

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Abstract :

The look and the shape that a fabric assumes when used in a garment depends on the grainline of the fabric. In woven fabrics grainline means the direction of the yarns which is usually in the form of with the warp that is parallel to the length of the fabric, with the weft that is perpendicular to it or at an angle to it or at right angle to it or in the bias. With knitted fabrics it is the term also called direction and it applies to the arrangement of loops of yarn in the vertical (courses) or horizontal (wales) planes. It is not very common that fabric is sold in its grained condition. Woven fabrics have three main grainlines lengthwise, crosswise, and bias. There are three types of grainlines namely; lengthwise grain or warp which is parallel to the selvedge and offers stability and is ideal for most garment pieces. The crosswise grain, or weft, is more elastic and is used where flexibility is required, for instance in pants. The bias which is cut at a 45-degree angle to both the lengthwise and crosswise grains provides the most elasticity and flow, and is ideal for body skimming outfits including dresses and skirts. In knitted fabrics, the direction should be made to stretch more in the crosswise direction (there are always exceptions here). This will lead to wrong fit and wrong garment behavior when manipulating the fabric grain or direction of the woven and fabric knitted drape, fabrics. the Grainlines fit effect of a garment on the body, the garment's durability and its appearance. In warp yarns, you have stronger and more durable yarns than in your weft; this is the structure of the fabric and the bias provides the mobility. Cutting fabric along the wrong grainline can cause garments to get warped, and the result is the garment feels uncomfortable to wear and fit strangely. Correct grainline alignment results in professional finishes, consistent seams, and true pattern matching. Through knowledge of grainline and its effects on fabric, clothing designers can produce functional, pleasing garments that also minimize fabric waste.

Keywords: *Bias Grain, Crosswise Grain, Fabric, Grainline, Lengthwise Grain, Sewing Patter*

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1. Introduction

Any garment's visual appeal is directly impacted by the properties of the fabric used to make it [1]. Fabric grain alludes to the yarn direction of woven fabric. Grain lines are a for the most part unnoticed part of the article of clothing that is until they are either utilized in the incorrect manner and cause a fit issue or utilized in fascinating manners to shape the fabric to the body [2]. Once in a while they can likewise be utilized to turn a print onto an alternate angle for fascinating special visualization [3]. The terms grain line or grainline are frequently utilized conversely. Grain can be the crosswise, lengthwise and bias [4]. Grain is significant when constructing of garment since it decides how an article of clothing will hang, fit and show up. Grain or direction appears on each fabric that is made of yarns. Actually, the term grain just alludes to woven fabric while the term direction is much of the time utilized with knitted fabrics [5]. All fabrics produced using yarns are 'grain perfect' after knitting and weaving. Sewing machines and knitting machines construct fabric in a grain immaculate way. Be that as it may, a fabric can become off-grain during the procedures of completing the process of (printing, dyeing permanent finishing, or potentially bundling, winding onto a bolt [6]. The process of cutting and sewing of garment in the manner of correct fabric grain can extend in places they ought not, have sagging hems and be awkward to wear. Grain should be kept in mind while designing a pattern with the goal that the body can exploit the measure of stretch or absence of give in the fabric [7].

There are two objectives of this study-:

i. To study about the variations in grainline.

ii. To study the impact of grainline in fabric.

2. Main Body

2.1 Woven Fabric

For woven materials, grain alludes to the direction of the warp and weft threads. The three named grains are straight, cross and the bias grain. Any grain or direction of fabric can be used to cut a paper pattern for sewing. This will affect how the fabric hangs and stretches, and ultimately how well an article of clothing fits [8]. As a rule, a paper pattern is supposed to be cut on a specific grain when the longest piece of the pattern or the principle seams of the completed piece

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are aligned with that grain. Non-woven materials, for example, felt, interfacing or leather don't have a grain [9]. The use of high-quality fabric, weft and warp yarn on the grain and at the proper angle, which create better fit, are among the functional qualities of clothing [10]. The different tensions on the yarn are influenced by the orientation of the grain. The pattern piece's orientation in relation to the warp and filler yarn determines the gravitational attraction [11]. Additional research is necessary to determine when grainline rotation is appropriate for "certain garments and textiles without adversely affecting drape" [12]. The drape of a fabric is determined by its weight, stiffness and bending rigidity, and shear resistance.

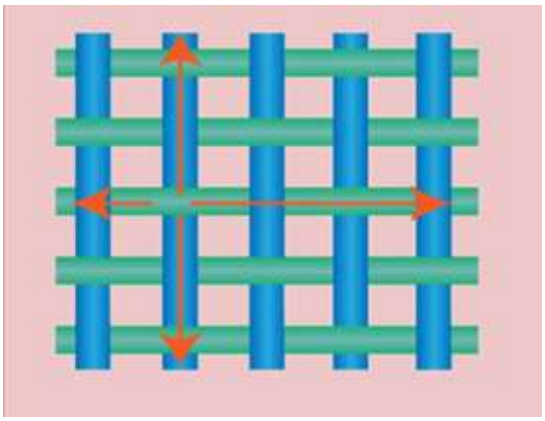


Figure 1 - Structure of Woven Fabric (https://dresspatternmaking.com/wp-content/uploads/2023/01/woven-and-knit-intro.png)

2.1.1 Lengthwise Grain

Describe the experimental procedures concisely, with appropriate references. Include instrument settings, process parameters, and sample sizes where relevant. Lengthwise grain is also known as 'warp' or 'on-grain.' The technical name for these is 'warp threads.' The lengthwise grain of the fabric is always parallel to selvage edge of the fabric. The selvage is otherwise called the warp. Selvage edges are woven firmly and tightly. It moves vertical way.

Since the warp threads will be drawn more tightly than the weft during weaving, the straight grain often has less flexibility than the cross grain [13]. Most of articles of clothing are cut on the warp in light of the fact that the fabric doesn't extend toward this direction which ensure that the hang of the piece of clothing is right. The majority of the time, the straight grain runs up the middle of the front and back of garments, as well as the middle of the sleeves and legs of pants. In circumstances where a garment is cut marginally off grain, this may cause sleeves or trouser legs to twist around the body [14].



Figure 2 - Orientation of Lengthwise Grain https://sewguide.com/wp-content/uploads/2018/08/grain-line-fabric.png

2.1.2 Crosswise Grain

Crosswise grain is also known as 'weft' or 'off-grain.' The technical name for these is 'weft threads.' The cross grain runs opposite to the selvedge and parallel to the weft threads. It moves in horizontal way. The cross grain for the most part has more stretch than the straight grain since the weft threads are commonly looser than the warp during weaving [15]. The majority of clothing, including items like shirts and pants, are cut on a straight grain, with the wearer's feet as the cross grain. This permit increasingly stretches through the width of garment, for example, in a trousers' leg which needs more circumferential than vertical stretch. Garments are in some cases cut on the cross grain, because the pieces are too wide to fit on the straight grain.

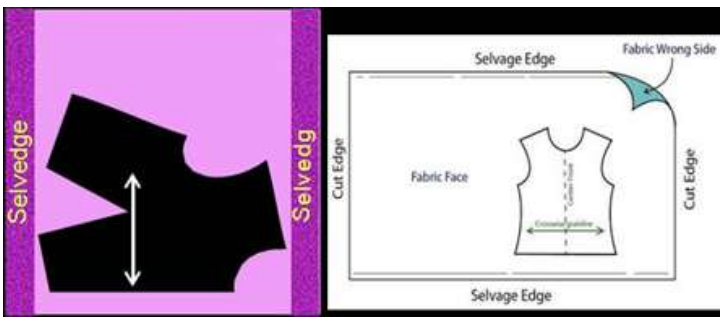


Figure 3 - Orientation of Crosswise Grain https://www.doinaalexei.com/uploads/5/7/9/5/57952549/cutting-pattern-on-crosswisegrain_orig.jpg

2.1.3 Bias Grain

Crosswise Bias grain of woven fabric, as a rule alluded to just as "the bias", is any grain that falls between the straight grain and cross grain. At the point when the grain is at 45 degrees to its warp thread and weft thread it is alluded to as "trye bias." Woven fabric has two biases, opposite to one another [16]. The garment made of woven fabric is supposed to be "cut on bias" when both of the threads of fabric are on one of the bias grains. Woven fabric has more stretch in the bias direction, contrasted with the straight and cross grains [17]. property encourages the fabric that require additional stretch ability, drapability or flexibility, for example, bias-cut skirts or common flared skirts from 1950' and dresses, neckties or bowties, piping trims and adornments, bound seams, and so on. Bias grain "is absolutely not a grain." There is airspace instead of yarn in the bias direction. The "bias cut" is a strategy utilized by designers for making the garment to utilize the more noteworthy stretch in the bias or diagonal way of the fabric, in this manner making it emphasize body lines and curves and drape softly. The authors found that the tilt angle and drape values were dependent on the fabric and had no direct relationship. As the tilt increased, the symmetry



Figure 4 - Orientation of Bias Grain https://i.ytimg.com/vi/icpqDJACXLg/hq720.jpg?sqp=-oaymwEhCK4FEIIDSFryq4qpAxMIARUAAAAAGAElAADIQj0AgKJD&rs=AOn4CLBCtyPPfo1YVJ_UEDOPGJjNhcOhBw, https://i.ytimg.com/vi/QfMFGDiFvZA/maxresdefault.jpg

of the garment changed, and the tilt had an impact on the folds that formed as the garment draped. Some garments used partial bias rather than true bias. The straight of grain would have a stabilizing effect at hemlines or necklines. The bias-cut cowl neckline, which was present in the under-review clothing, was also created by Vionnet. The garments of bias cut have progressively extended and have graceful drape. For instance, a full-skirted dress cut on the bias will hang all the more effortlessly or a narrow dress will stick to the figure. Bias- cut garments played a crucial role in the designs of Madeleine Vionnet during the 1920s and 1930s, and styles featuring bias cuts are periodically brought back into fashion. Prior to her time, bias cut was uncommon in ladies' garments and outré in garment for men. In the middle Ages, before the improvement of knitting, hose was cut on the bias so as to make them fit better [18]. The old spelling of bias was byas, or (less common) byess.

2.2 Knit Fabric

In knitted fabric, the grain is known as 'direction.' Knitted fabric comprises of a series of loops. Knowing the grain or direction of the knitted fabric is as significant as in a woven fabric(E et al., 2010). In knitting, the term direction refers to the arrangement of loops within the fabric [20]. They are arranged in a vertical or lengthwise manner (courses) and in a horizontal or transverse manner (wales), with the greatest flexibility generally found in the crosswise loop direction [21]. This arrangement is done in opposition to one another, similar to that of woven fabrics. A simple stretch test of the fabric will assist you with deciding the direction of stretch on knits [22].

i. The lengthwise loops in a knit fabric create ribs which are also known as wales. They form rows of loops and can be seen on the frontside of the fabric [23]. For the most part there is less stretch toward this direction. However, this may not always be true.

ii. The crosswise loops in a knit fabric are called courses. They form rows of loops and can be seen on the back side of the fabric [24]. For the most part there is greatest stretch toward this direction [25]. However, it is always essential to test or check the stretch in a knit before buying.

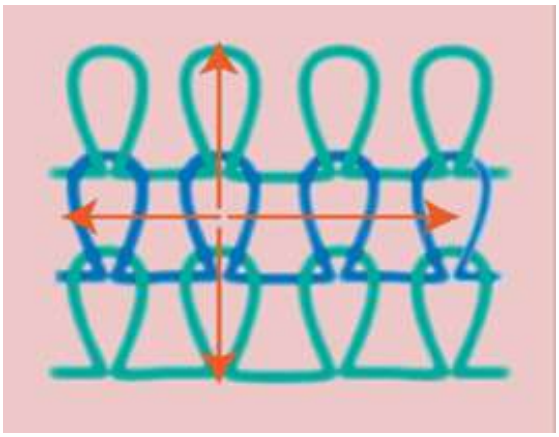


Figure 5 - Structure of Knit Fabric (https://dresspatternmaking.com/wp-

2.3 Importance of Grain in Fabric

Since fabric grainlines have a direct impact on how fabric behaves, drapes, and fits, their significance in garment production cannot be emphasized. Here is a more thorough explanation of the material with original wording and enlarged insights:

i. Warp vs. Weft Yarns

Compared to weft threads, which run across the fabric, warp yarns, which run parallel to the fabric's selvage, are usually stronger and more resilient. When clothing hangs down the body, warp yarns offer superior stability and structure because of their intrinsic strength. For increased structural integrity, this grain is typically positioned in line with clothing's vertical seams [26]. Additionally, warp threads have less flexibility than weft threads, which makes them better suited for parts of a garment that must keep their structure and shape. This quality is particularly crucial for making sure that clothes hang loosely without drooping or deforming overtime. Cutting the garment across rather than lengthwise may occasionally are a good financial decision, but you should do so fully aware that it may feel awkward or uncomfortable most of the time and may stretch and sag in places like the hems and armpits. The result is occasionally a deformed garment [27].

ii. Bias Grain Characteristics

The fabric's bias grain offers the most stretch and flexibility since it runs diagonally at a 45- degree angle to the warp and weft threads. Specifically, the genuine bias provides the most flexibility, enabling clothing to more naturally and fluidly conform to the contours of the body [28]. For some garments, like dresses or skirts, where a tight fit and fluidity of movement are preferred, this enhanced flexibility is beneficial. Because employing the bias can significantly improve the fit of the final garment, it is imperative to comprehend the grain before cutting fabric [29].

iii. Cutting Fabric Crosswise

Sometimes, especially if you are attempting to maximize your material, cutting cloth along the transverse grain (weft) instead of the lengthwise grain (warp) may prove to be more cost- effective. On the other hand, fit and durability may suffer as a result. Clothing that is cut along the transverse grain may stretch in places like the hem or underarms, which might cause drooping or discomfort when worn. This may change the garment's overall look and feel, making it less attractive and comfortable. When choosing to cut crosswise, it's critical to consider this possible trade-off, especially if money is tight.

iv. Bias Cut and Fabric Usage

Compared to cutting along the lengthwise or across grains, cutting a garment on the bias grain uses more fabric. Although the bias grain improves the drape and fits the garment more flatteringly, it also uses less fabric [30]. This additional fabric demand must be taken into consideration when designing a project, particularly if you are on a tight budget. Although bias-cut clothing tends to feel and look better, the cost of the materials is greater, so you'll need to balance the functional and aesthetic advantages against your financial constraints [31].

v. Fabric Shrinkage

The fact that longitudinal strands often shrink more than transverse yarns is a crucial consideration. This implies that after washing, cloth may behave differently, especially if the garment was cut along the longitudinal grain [32]. In order to account for any shrinkage and guarantee that the finished garment maintains its intended form and size after laundering, pre-washing fabric before cutting and stitching is a typical technique [33].

vi. Grainline Accuracy

It's crucial to remember that little variations from the ideal grainline could not have a significant impact on a project. Significant misalignment, however, may result in issues like uneven seams, mismatched pattern pieces, or undesired stretch regions [34]. For instance, seams may stretch or bunch when sewed if the grainline of a fabric is too far away, particularly if they are close to the bias. The cloth won't hang or fit as intended, which might be uncomfortable and distort the image. Maintaining grainline accuracy is essential to making sure clothing looks good and holds up over time [35].

vii. Positioning Pattern Pieces

To get the desired result, pattern pieces must be placed precisely. The majority of sewing designs come with a grainline mark, which is a double-headed arrow that indicates the pattern's proper placement on the cloth. Generally, this grainline mark should be positioned parallel to the selvage of the fabric, unless the pattern instructions specify otherwise. When the garment is built, adhering to these indications guarantees that the cloth will perform as intended. For example, using the bias grain improves drape and mobility, while positioning the longitudinal grain at the center of the body or sleeves provides rigidity [36].

2.4 Impact of Grainline in Sewing Pattern

In the context of sewing patterns, the grainline refers to the lines printed on the pattern pieces that guide you on how to place the fabric. This marking ensures the fabric is cut in the most appropriate direction for the design. Generally, patterns specify that the lengthwise grain should be aligned along the center front and back of a garment, down the sleeves, or along the pant legs. This positioning ensures the garment maintains its structure and stability. However, depending on the design, the bias grain or crosswise grain may be used to achieve a different effect, such as added stretch or a flowing drape. The grainline mark helps ensure that the fabric is positioned correctly before cutting, resulting in a well-constructed garment.

2.5 Matching Panels and Seams:

When constructing a garment, aligning fabric grainlines is especially important for matching panels and seams. If the grainline is off, the pieces of fabric may not fit together properly, leading to issues such as uneven seams or misaligned patterns. This can also cause areas of the garment to stretch or bunch, affecting both comfort and appearance. Ensuring the grainline is accurately followed prevents these issues, allowing for a polished, professional result.

3. Methodology

In order to investigate the idea of fabric grainlines and their significance in the creation of textiles and clothing, the suggested study employs a descriptive approach. Since this study aims to offer in-depth observations and insights rather than verify a theory, descriptive research is implemented. Through the analysis of secondary data and current information, this study aims to get comprehensive understanding on grainlines and their varied features.

Using a qualitative approach and gathering secondary data-

Since the focus of this research is on comprehending concepts, relationships, and approaches rather than quantifying data, a qualitative approach has been used. For a topic like fabric grain lines, which entails analyzing fabric behavior and how various grain lines affect garment

fabrication, this method works well. This study's secondary data was gathered from books, scholarly publications in high indexed journal i.e., Scopus, web of science and project reports. These resources include a variety of professional viewpoints on graininess, which serves as a strong basis for the topic's examination.

4. Results and Discussion – Impact of Grainline

A key component in clothing pattern development, the grain line has a big impact on the final product's fit, look, and durability. Making sure that the cloth is cut according to the proper grain line guarantees that the garment will function as intended and helps the material behave as intended. The following are the main advantages of following the grain line while creating patterns and sewing:

- **Better Fit and Stability**

For clothing to fit well and hold its shape, the grain line is essential. The longitudinal grain, which runs parallel to the selvage, gives your garment support and aids in maintaining its form. The garment fits more consistently and provides the structure required for fitted items like skirts, pants, or jackets when patterns are properly aligned with this grain. This method helps maintain the fabric's original fit by preventing it from drooping or stretching unevenly over time. Cutting on the bias grain, at a 45-degree angle, provides the fabric a drapery aspect that enables it to embrace the body's contours for designs that require a more flexible, body- hugging finish. Most frequently, bias cutting is applied to flowing clothing, such dresses or skirts, where a pleasing fit and movement are essential. But compared to straight cuts, this technique might use more fabric and demands accuracy [37].

- **Improved Drape and Flow**

The way a cloth falls on the body is influenced by the grain line. For structured clothing, patterns that line up with the longitudinal grain are favored because they provide a more stable and straighter drape [38]. On the other hand, bias grain enhances the fabric's flow, giving it a more intricate, rippling movement. This method is widely used to create clothing that has to seem incredibly soft and flowing. To prevent distortion, you should handle bias-cut cloth gently since it has greater drape and may stretch more readily.

- **Enhanced Durability**

Placement of grain lines improves a garment's durability. Clothes cut on-grain have a higher resistance to normal wear and tear because the warp threads, or longitudinal grain, are often stronger than the weft threads, or across grain. This is particularly true for regions that experience greater strain, such as the shoulders, waist, or hems [39]. The garment won't stretch or lose its shape because the grainline runs with the fabric's strongest threads. Bias and off-grain cuts will typically stretch more and need to be constructed with more care to maintain their shape. However, bias-cut components can still provide a long-lasting, robust finish if they are properly maintained.

- **Stronger Seams**

Grainline placement is crucial for quality seams. When fabric is cut along the lengthwise grain, seams will stretch or warp less frequently during stitching and wear [40]. Since seams that are in accordance with the grainline are more stable, this is significant for the integrity of the garment's overall structure [41]. Following the grainline can help avoid issues like skirt drag or an uneven fabric bunch in high-stress locations like the shoulder or side seams. Off-grain or bias-cut garments are more likely to stretch along the seams, necessitating the use of reinforcement techniques like interfacing or stay-stitching to avoid distortion [42].

- **Consistent Fabric Behavior**

This is where the grainline comes into play; by adhering to it, the cloth will behave uniformly throughout your garment. Each cloth has a unique grain, and patterns are created to reflect this. When cloth is cut on-grain, it drapes, stretches, and wears like the designer intended. Therefore, no, even while you can deviate from the grainline, doing so may result in unintended stretch or topsy-turvy seams. Sewists can guarantee constant fabric behavior by adhering to the grainline, which facilitates stitching and increases the finished garment's dependability in terms of fit and functionality.

- **Efficient Fabric Use**

This is where the grainline comes into play; by adhering to it, the cloth will behave uniformly throughout your garment. Each cloth has a unique grain, and patterns are created to reflect this. When cloth is cut on-grain, it drapes, stretches, and wears like the designer intended. Therefore, no, even while you can deviate from the grainline, doing so may result in unintended stretch or topsy-turvy seams. Sewists can guarantee constant fabric behavior by adhering to the grainline, which facilitates stitching and increases the finished garment's dependability in terms of fit and functionality.

- **Accurate Pattern Matching**

When attempting to match fabric patterns like plaid, stripes, or checks, the grainline is very crucial. When done correctly, grainline enables specific pattern insignias to line up between seams, creating a polished, businesslike appearance. An uneven or scrappy appearance can result from mismatched designs at seams caused by a misaligned grainline. To guarantee that the overall construction of clothing with prints or woven-in motifs is completed without interruption, it is crucial to respect the grainline during sewing.

- **Control Over Stretch and Elasticity**

The stretchiness of your fabric is also determined by the grainline. It is also possible to stretch across a cloth, although this happens more across the bias and transverse grains than the lengthwise ones. For clothing that needs a secure fit, such as structured dresses or pants, cutting along the lengthwise grain is the best option since it prevents stretching and helps

the clothes maintain their shape [43]. On the other hand, clothing that needs more stretch think sportswear often uses the bias or across grain to take advantage of the fabric's inherent give.

- **Polished, Professional Finish**

A neat, polished finish is one of the many advantages of sewing along the grainline. The hang may be impacted if the grainline is not correctly aligned since edges and seams might not line up. Therefore, even little departures from the grainline could result in obvious issues like twisted sleeves or uneven hems. For a more polished and expert appearance, adhere to the grainline.

- **Design Versatility**

Designers can increase their creative process's flexibility and control by learning about grainline. Cutting cloth on the bias, for instance, can provide intriguing visual effects with stripes or prints, providing a variety of artistic options. Grainline expertise allows designers to purposefully alter fabric behavior, guaranteeing that their clothing is both practical and aesthetically pleasing.

5. Conclusions

Direction of grain plays a significant role in sewing pattern. Ignoring the direction of the woven threads can affect the lay and stretch of the garment because of the way in which the various grainlines act. The preferred way to cut main project pieces is with the lengthwise grain as the fabric will generally not stretch or become misshapen during stitching. Before cutting out any pattern pieces, be sure to understand the importance of the grainline. Cutting without considering the grainline could mean fabric waste as well as less than desirable results after sewing the project.

6. Acknowledgements

On a very outset of this research, I would like to extend my sincere and heartfelt obligation towards all the personages who helped me in this endeavor. Without their assistance, guidance, cooperation and encouragement this research could not have been possible. Their contributions are sincerely appreciated and gratefully acknowledged. Author Contribution

Table 1 - Difference Between Impact of Grainline on Woven and Knit Fabrics

S. No	Woven Fabric	Knit Fabric
1.	By designating the direction of the warp, weft, and bi as threads, Grainline regulates the behavior of the fab ric as it is cut and sewn into garments.	The configuration of loops in wales and courses deter mines grainline, or direction, in knitted materials.
2.	The lengthwise grain (warp), which helps clothes ma intain its original shape over time, provides maximu m strength and dimensional stability.	When compared to woven fabrics, the lengthwise dire ction (wales) often has less stretch and offers modest vertical stability but less rigidity.
3.	The across grain (weft) allows for controlled stretch, which improves comfort and convenience, especially in areas that require widthwise flexibility.	The fit, comfort, and mobility of clothing are greatly i mpacted by the crosswise orientation (courses), which provides the most stretch.
4.	The bias grain, which is cut at a 45degree angle and gives tremendous elasticity and flowing drape, allow s clothing to closely follow body forms	Although diagonal stretch is present in knitted textiles , woven bias cuts result in a more controlled drape. Knitted textiles lack real bias grain.
5.	Proper grainline alignment guarantees even hems, a balanced drape, and consistent seam behavior across the garment.	In order to avoid discomfort and distortion, proper dir ectional alignment guarantees that the required stretch corresponds with body movement.
6.	Incorrect grainline alignment can cause uneven or wa rped seams, sagging hems, and twisting garment pan els.	Incorrect orientation can lead to rippling seams, exces sive stretching, poor recovery, and loss of garment sha pe during wear.
7.	By affecting how the garment falls on the body, Grai nline instantly modifies the garment's silhouette and visual appeal.	The appearance of a garment is more affected by loop elasticity and recovery than by precise directional alig nment.
8.	Seams that are sewn along the correct grainline rema in stable and avoid deformation during sewing and w ear.	Seams may easily stretch or wave if the primary stretc h direction is not considered while sewing.
9.	Woven fabrics shrink differently depending on the or ientation of the grain; lengthwise yarns usually shrin k more than transverse yarns	The primary elements affecting shrinkage in knitted fa brics include not only direction but also fiber type, stit ch density, and finishing.
10.	Accurate grainline placement is essential for durabili ty, a polished appearance, and reliable garment perfo rmance.	Accurate direction placement is essential for achievin g practical garment performance, comfort, and stretch efficiency.

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Development of Graphite–Polypyrrole Conductive Textile Coatings and their Electromagnetic Characterization

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Abstract:

This study examines graphite–polypyrrole (G–PPy) as a conductive finish for woven cotton and polyester. The fabrics were coated by using padding mangle, followed by drying. Surface morphology was examined by SEM and electrical behaviour was assessed from surface resistivity. A laboratory SignalVu-PC DPX arrangement was also used to observe changes in the received signal at 2.43 GHz. The coated fabrics showed a noticeable change in received electromagnetic signal compared with the untreated fabrics. The coated cotton showed 1.67 × 10^7 Ω/sq., whereas the coated polyester showed 3.42 × 10^8 Ω/sq. The SEM images indicated a more continuous deposit on cotton, and the cotton sample also gave the larger change in received signal. The electromagnetic response was evaluated by comparing the received signal levels of untreated and coated fabrics at 2.43 GHz using a laboratory SignalVu-PC DPX arrangement.

Keywords: *Conductive textiles, Electromagnetic interference, Graphite, Polypyrrole, Surface resistivity*

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1. Introduction

Conductive finishes can give a textile fabric useful electrical behaviour while retaining the basic character of the fabric. This is attractive for applications in which the material has to remain flexible and textile-like [1–3]. Earlier studies investigated PPy-modified cotton and reported electromagnetic behaviour using a standardized approach [2]. Their material and measurement method were different, but the work supports the usefulness of conductive pathways in functional cotton fabrics. The response of a textile to electromagnetic radiation depends on several factors, including its electrical properties, construction, thickness, frequency and the nature of the applied finish [4, 5]. A coating that creates conductive paths can therefore change the way the fabric interacts with an electromagnetic signal. Different routes have been used to make textiles conductive. These include conductive polymers, metallic materials, conductive yarns and carbon-based fillers [6]. Applying such materials as a textile finish is of practical interest because the treatment can be carried out with equipment already used in wet processing. Graphite was selected in this work because it is a carbon material and it can provide electrical conduction without adding any large metallic component. Carbon-based textile systems have also been investigated for electromagnetic applications [4, 7 & 11].

Polypyrrole (PPy) is another useful material for conductive textiles. Previous studies have combined PPy with carbon-based materials and have reported improvements in electrical or functional behaviour [8, 10]. Its use with graphite provides the basis for the coating studied here. The final result is not controlled only by the formulation. The substrate can affect how the coating wets, spreads and remains on the fibres. These factors can change the continuity of the conductive layer and, consequently, the measured electrical response [5–9]. Textile coatings using conductive materials such as graphite and polypyrrole can find wide application areas in functional and smart textiles where electrical conductivity and electromagnetic properties are necessary. Such coated fabrics can be considered for the protection of electronic devices against electromagnetic interference, for the development of wearable electronic textiles, and for conductive textiles and other applications where conductive textiles with textile substrates are needed. The textile finishing technique makes it possible to introduce conductivity into textile products with only slight modifications of their textile character. The objectives of the present study were to prepare a conductive graphite-polypyrrole coating on textile fabrics and then to test the effectiveness of the same on 100% cotton and 100% polyester fabrics. In the present study, the conductive coating was evaluated by SEM, surface resistivity testing, and an electromagnetic signal response test under the laboratory conditions. Also, the objective of the study was to determine the possibility of the reduction in the electromagnetic signal received due to the conductive coating in laboratory test conditions.

2. Materials and Methods

2.1 Materials

Three woven fabrics, namely 100% cotton, 100% polyester and 50:50 cotton/polyester (P/C) blend, were used in the study. The cotton fabric had a GSM of 125 g/m², plain weave (1/1), 40s Ne yarn count, a thread density of 220 ends × picks per square inch and a thickness of 1.0 mm. The polyester fabric had a GSM of 110 g/m², plain weave (1/1), 85 denier yarn, a thread density of 230 ends × picks per square inch and a thickness of 0.8 mm. The P/C blend fabric contained 50:50

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cotton/polyester, with a GSM of 120 g/m², plain weave (1/1), a thread density of 225 ends × picks per square inch and a thickness of 1.0 mm. All fabrics were procured from Om-Sidhi Garment Pvt. Ltd., Shirpur, Maharashtra, India. For the detailed electrical and electromagnetic characterization reported in this manuscript, the analysis was restricted to the 100% cotton and 100% polyester fabrics. The P/C blend was not included in the reported surface-resistivity and electromagnetic-response results. Isopropyl alcohol (IPA, 99.7% pure, Purenso Select) was used as the liquid medium for preparation of the graphite–polypyrrole dispersion. The material was supplied by Purenso Global, India. Polypyrrole (PPy) powder (Aldrich, Product No. 530573; bulk conductivity 30 S/cm) was used as the conductive polymer. Dodecylbenzenesulfonic acid (DBSA, 90.3% purity, laboratory grade) was used as the dispersing agent and was supplied by Jinendra Scientific Pvt. Ltd., Jalgaon, Maharashtra, India. Polypyrrole (PPy) was used as the conductive polymer.

Before coating, both fabrics were desized, scoured and dried. Graphite powder and polypyrrole (PPy) formed the conductive part of the finish. DBSA was used to disperse the conductive materials and IPA served as the liquid medium. The chemicals were used without further purification. The experiments were conducted at the Centre for Textile Functions, Mukesh Patel School of Technology Management & Engineering (MPSTME), SVKM's NMIMS, Shirpur Campus, Dhule, Maharashtra, India; month and year of experimentation: February 2026.

2.2 Methodology

2.2.1 Preparation of graphite–polypyrrole conductive dispersion

Parameters for coating process: The graphite-polypyrrole suspension was subjected to stirring by magnetic stirrer at 600-800 rpm for 4 hours to achieve a well-dispersed suspension. The cloth materials were passed through this suspension and then through a laboratory mangle kept at 3 kg/cm² padding pressure and fabric speed of 3 m/min. The wet pick-up was maintained at about 70%. The padded cloth material was dried at 95°C in an oven for 15 minutes. Post drying, the coated cloth materials were conditioned for 24 hours in a desiccator. The formulation used for the coating is given in Table 1.

Table 1: Composition of graphite–polypyrrole conductive dispersion

Component	Quantity
Graphite powder	10 g
Isopropyl alcohol	35 g
Dodecylbenzene sulfonic acid (DBSA)	20 g
Polypyrrole	2.5 gm

The dispersion was kept under stirring during preparation and application so that the conductive ingredients remained reasonably distributed.

2.2.2 Application of conductive coating

Each fabric was passed through the prepared dispersion and then through a laboratory padding mangle at a constant pressure. Excess liquor was removed by padding. The coated samples were dried in a hot-air oven and conditioned before testing. The same procedure was used for both fabrics so that the effect of the substrate could be compared under identical coating conditions. Using one coating procedure for both materials allowed the difference in the final electrical response to be considered mainly in relation to the fabric substrate.

2.2.3 Scanning electron microscopy

SEM examination was carried out on untreated and coated specimens. Samples were mounted on aluminium holders with conductive carbon tape and gold sputtered before imaging. The selected magnifications were used to examine how the coating covered the fibre surfaces.

2.2.4 Surface resistivity measurement

A calibrated surface-resistivity meter was used under laboratory conditions. Four positions were selected on each coated specimen and one reading was taken at each position. The four readings were averaged to obtain the value used for comparison. A lower value was considered to represent easier electrical conduction across the coated surface.

Cotton fabric: 1.67×10^7 Ω/sq

Polyester fabric: 3.42×10^8 Ω/sq

2.2.5 Electromagnetic signal response measurement

The electromagnetic test was carried out near 2.43 GHz. A continuous signal was directed toward the fabric and the received level was observed first without the specimen and then with the coated fabric placed between the source and receiver. SignalVu-PC DPX was used to display the received spectrum and to observe the change in signal level. The same arrangement was maintained for the untreated and treated specimens.

For each fabric, the untreated sample served as the reference. The treated response was compared with that reference to determine the change in received signal.

2.2.6 Statistical analysis

Four readings were used for the electrical measurements. Mean and standard deviation were calculated in Microsoft Excel. The replicate values were also checked for consistency before comparing the two fabric types. The electrical results were considered together with the SEM observations and electromagnetic response rather than being interpreted as separate findings.

3. Results and Discussion

3.1 Surface morphology of conductive coated fabrics

Scanning electron microscopy was carried out to compare the distribution of the deposited material and to examine the continuity of the coating on cotton and polyester fabrics.

Images at different magnifications were considered to study the deposited layers. At 120× magnification, the deposit appeared broader and more connected on cotton, whereas some regions of the polyester fabric showed thinner and less uniform coverage. With increasing magnification, the cotton fabric showed a more connected layer, while the polyester fabric surface appeared smoother with less coverage. Large separate graphite clusters were not prominent in the examined areas. Therefore, uniform coating is important during application. The deposited material appeared to form comparatively more continuous conductive paths, which was associated with the lower surface resistivity measured for cotton. Cotton had a surface resistivity of 1.67×10^7 Ω/sq. The corresponding value for polyester was 3.42×10^8 Ω/sq. Thus, the cotton sample was considerably more conductive after coating. The lower surface resistivity measured for cotton was consistent with the comparatively more continuous coating observed in the SEM images. Because surface resistivity directly influences a material's Electromagnetic Interference Shielding Effectiveness (EMI SE) by modulating how much radiation is reflected or absorbed, managing the unique moisture absorption profiles of a P/C blend is critical. In other words, the visual and electrical measurements point to the same difference between the two substrates. Although both fabrics received the same finish, their responses were not the same. Under the conditions used here, cotton provided the more favourable surface for forming the conductive layer.

3.2 Electromagnetic signal response

The electromagnetic signal response of the untreated and coated fabrics was evaluated at approximately 2.43 GHz using SignalVu-PC DPX. The coated fabrics showed a measurable change in the received electromagnetic signal compared with the corresponding untreated fabrics. The change was more pronounced for the coated cotton fabric than for the coated polyester fabric under the laboratory test configuration used in this study. Figure 1 shows the spectra recorded for the untreated and coated cotton and polyester samples. After coating, both fabrics showed a lower received signal than their untreated references. The change was more noticeable for cotton. This sample also had the lower surface resistivity and the more continuous coating seen by SEM. Polyester also responded to the coating, but the higher resistivity indicates that its conductive paths were less effective than those formed on cotton. The SEM analysis, surface resistivity measurements, and electrical signal tests showed consistent trends in the electromagnetic response of the fabrics. The treated cotton fabric exhibited better coating coverage than the treated polyester fabric. The electromagnetic response of the fabrics was evaluated from the received signal levels. The changes in signal response were expressed in decibels (dB), and the coated fabrics showed a noticeable change compared with the untreated fabrics. Comparison of the treated and untreated samples showed a measurable change in the received electromagnetic signal after application of the graphite–polypyrrole coating.

3.3 Comparison with published literature

Other conductive-polymer and graphite-containing textile systems have likewise shown that the substrate and coating structure affect the final response. The difference between cotton and polyester in the present experiment supports this point. The SEM images in the present work provide a possible explanation: cotton showed a more connected deposit than polyester. A more connected deposit can provide easier paths for electrical current. Previous research has reported PPy/RGO-coated cotton fabric with an electromagnetic shielding effectiveness of about 31 dB at 8.4 GHz [12]. Again, this value cannot be directly compared with the attenuation measured in the present work. Published studies show that conductive textile systems can give measurable electromagnetic shielding, but their numerical results cannot be compared directly with the present experiment because the materials, frequencies and test procedures are different. For example, previous studies reported 16–59 dB for Ni–W–P coated polyethylene /polyester textiles, and 26.4 dB for PPy-coated cotton [13, 14]. Earlier work also indicates that the base fabric can influence the electrical behaviour of a conductive coating [5, 8]. The lower resistivity measured for cotton in this study is consistent with that observation. Systems containing silver, carbon nanotubes or magnetic components can reach higher shielding values because they introduce additional conductive, interfacial or magnetic-loss effects as suggested [15, 16]. Those additional components were not used in the present formulation.

Earlier work on conductive cotton composite fabrics against electromagnetic waves, further supporting the relevance of conductive cotton structures for electromagnetic shielding applications [17]. The main limitation of the literature comparison is therefore the measurement method. The present study compares the two fabrics within one laboratory setup using received-signal change, whereas most published studies report standardized shielding effectiveness. Previous research has reported about 34 dB for SWCNT-coated polyester in the 8–12 GHz range [18]. Because the coating, frequency range and test method differ from those used here, the value is included only as background information. Similarly, an EMI shielding effectiveness of 31 dB at 8.4 GHz was reported for a conductive cotton-based fabric containing reduced graphene oxide and polypyrrole [19]. Their material and test conditions differed from those used in the present study, so the result is considered as supporting literature rather than a direct comparison.

Earlier research has also reported that a cotton fabric incorporating Ag/CNT conductive networks and an Fe_3O_4/chitosan-modified polyurethane layer, achieving an EMI shielding effectiveness above 73.77 dB in the X-band [20]. Their multilayer material system and measurement conditions differed from those used in the present study, so the result is considered supporting literature rather than a direct comparison. Overall, the published work supports the importance of conductive paths, while the present

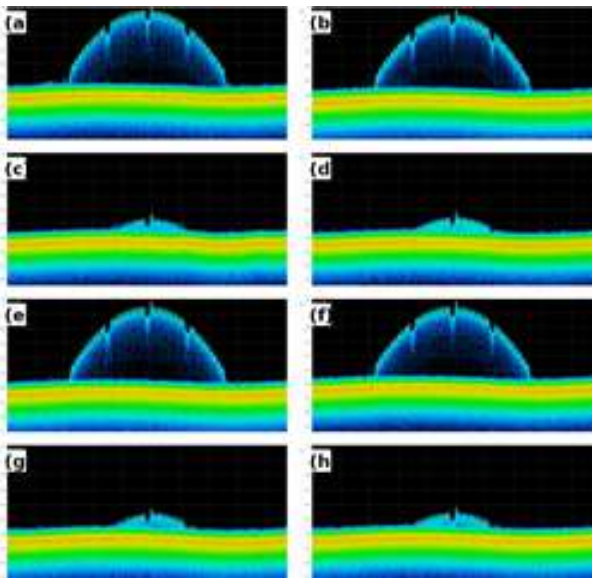


Figure 1: Signal Vu-PC DPX spectra for untreated and coated cotton and polyester at 2.4325–2.4375 GHz

Table 2: Replicate surface resistivity of treated cotton and polyester fabrics

Sample No.	Fabric	Replicate 1	Replicate 2	Replicate 3	Replicate 4	Mean ± SD (Ω/sq)
2603310-1(A)	Cotton	2.0 × 107	1.2 × 107	1.4 × 107	2.1 × 107	1.675 × 107± 4.43 × 106
2603310-2 (B)	Polyester	4.2 × 108	3.8 × 108	2.8 × 108	2.9 × 108	3.425 × 108± 6.85 × 107

**ND—Not detectable. Surface resistivity exceeded the measurable range of the instrument because the untreated fabrics were electrically non-conductive.*

experiment shows that the same G–PPy finish can behave differently on cotton and polyester. The combination of SEM and surface resistivity helps explain the difference.

The surface resistivity of the coated cotton fabric was $1.675 \times 10^7 \pm 4.43 \times 10^6$ Ω/sq, whereas the coated polyester fabric showed a higher surface resistivity of $3.425 \times 10^8 \pm 6.85 \times 10^7$ Ω/sq as shown in table 2. The lower resistivity of the cotton fabric indicates comparatively better conductive behaviour of the coating on the cotton substrate

Importance of moisture content: The surface resistivity of the textile fibres can be affected by moisture content, since the absorbed moisture might enhance the ionic conductivity on the fibre surface and charge transportation. The extent to which this happens depends on the nature of the fibre and environmental factors. In the current study, it has been noted that the surface resistivity of the coated cotton is lower compared to that of the coated polyester. This could be attributed to the high moisture absorption capability of cotton apart from the continuous graphite-polypyrrole coating as seen using SEM. As the moisture content has not been independently evaluated in the current study, this can only be a speculated conclusion.

According to the results from SEM observations, the graphite-polypyrrole coating had relatively more continuity in the cotton fabric compared to the polyester fabric, where the coating had a relatively lower degree of uniformity. The coated cotton fabric had a relatively low surface resistivity when compared to the coated polyester fabric. The relatively continuous coating observed on the cotton fabric was associated with its lower surface resistivity.

4. Conclusions

Cotton showed the lower surface resistivity (1.67×10^7 Ω/sq) and a more connected coating in the SEM images. It also produced the larger change in received electromagnetic signal. Polyester improved after coating, but its surface resistivity remained higher at 3.42×10^8 Ω/sq. The graphite–polypyrrole dispersion was applied by padding followed by drying, and both fabrics showed improved electrical behaviour. The results indicate that the substrate influenced the performance of the conductive finish. Under the laboratory test configuration used in this study, the coated fabrics showed a measurable change in the received electromagnetic signal.

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Performance Evaluation of Warp-Knitted Spacer Fabrics for Athletic Shoe Uppers

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Abstract:
This study evaluates the structural, mechanical and comfort-related performance of warp-knitted spacer fabrics intended for athletic shoe uppers. Five spacer-fabric samples (SA–SE) were evaluated for thickness, fabric weight, wale and course density, tear strength, tensile strength, elongation, water-vapor permeability, hole density and compression behaviour using specified standard test methods. The results indicate that the tested fabrics exhibited thicknesses of 2.52–3.00 mm and fabric weights of 272–285 g/m². Compression showed a very strong relationship with thickness (R^2 = 0.9603) and a strong relationship with hole density (R^2 = 0.8592), while water-vapour permeability showed a strong relationship with thickness (R^2 = 0.830). Sample SE exhibited the highest measured elongation, water-vapor permeability, hole density and compression among the five samples. The findings indicate that spacer-fabric architecture influences the mechanical and moisture-management characteristics relevant to athletic footwear. The study provides a preliminary basis for evaluating spacer-fabric structures for applications requiring a combination of cushioning, flexibility, ventilation and structural stability

Keywords: *Athletic footwear, Breathability, Compression behavior, Spacer fabrics, Water vapor permeability, Warp-knitting,*

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1. Introduction

1.1 Athletic footwear and requirements of shoe-upper materials

Advancements in sports science and material engineering have significantly influenced athletic footwear design, where upper materials play a vital role in determining comfort, fit, breathability, and performance. This is particularly critical for adolescent athletes engaged in high-intensity racquet sports, which demand materials capable of withstanding dynamic movements and repetitive impact. Warp-knitted spacer fabrics have emerged as promising upper materials due to their 3D porous structure, which integrates cushioning, ventilation, and mechanical stability. The interconnected spacer yarns facilitate airflow and moisture transfer, supporting thermal regulation and impact absorption.

1.2 Structure and properties of spacer fabrics

Spacer fabrics are advanced functional textiles widely used in applications requiring cushioning, breathability, and ergonomic performance. Manufactured through warp-knitting, they form a 3D sandwich structure with two outer layers connected by monofilament spacer yarns, enabling mechanical stability, moisture management, and flexibility [1]. The defining feature of spacer fabrics is their engineered 3D architecture, which creates an internal air gap that enhances ventilation and thermal regulation. This structure allows for efficient air circulation and moisture dissipation, contributing to improved thermos-physiological comfort during prolonged physical activity [2]. Additionally, the warp-knitting process allows variation in surface texture, density, and aesthetic design, enabling designers to integrate both functional and visual attributes within athletic footwear [3].

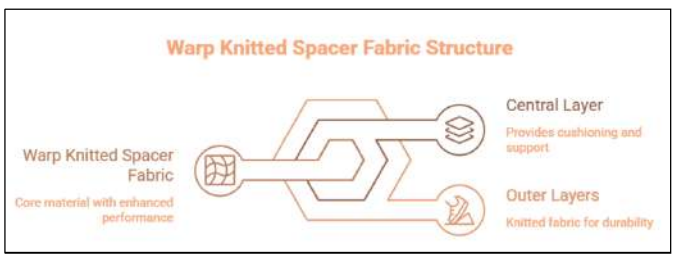


Figure 1 - Spacer Fabric structure showing different layers

1.3 Previous research

Spacer fabrics exhibit compressive elasticity and recovery, enabling effective shock absorption and pressure distribution [4]. Thickness improves strength and impact resistance, while porosity governs breathability and moisture transport [5]. The open-pore structure further supports heat dissipation and microbial resistance, improving hygiene and long-term usability [6]. These Spacer fabrics provide excellent water vapor transmission and moisture-wicking, maintaining a dry in-shoe microclimate. The air gap supports heat dissipation and faster drying [6]. Additionally, their design adaptability

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and durability enhance product appeal and lifecycle [7].

Spacer fabrics improve cushioning, flexibility, and pressure distribution, reducing impact forces and skin abrasion during dynamic movements [8]. Their use in key shoe zones helps minimize plantar pressure and injury risks, while ensuring durability under repeated stress [9]. These fabrics address issues such as heat buildup, sweating, and limited flexibility, enhancing overall performance and comfort. Their lightweight and recyclable nature aligns with sustainable design trends. Overall, spacer fabrics represent a paradigm shift in athletic footwear, integrating performance, comfort, and aesthetics [10, 11].

1.4 Research gap

Existing studies highlight that thickness enhances strength and cushioning, while porosity governs breathability and moisture management. However, optimizing these parameters remains challenging, as excessive thickness reduces flexibility, whereas high porosity may compromise structural stability. Despite their growing application, there is limited research systematically linking structural parameters with functional performance using standardized evaluation methods. This study investigates the relationship between fabric structure and performance, aiming to identify an optimal balance for improved comfort, durability, and biomechanical efficiency in athletic shoe uppers.

1.5 Research Objectives

The objective of this study was to evaluate the structural, mechanical and moisture-management characteristics of warp-knitted spacer fabrics intended for athletic shoe uppers and to investigate the relationships between thickness, hole density, compression behaviour and water-vapor permeability.

2. Methodology

2.1 Material

Five spacer fabric samples (SA–SE) were procured from three international athletic footwear manufacturers for experimental evaluation. The samples were systematically deconstructed to analyse their layer-wise fibre composition in accordance with ASTM D629, and the corresponding results are presented in Table 1.

A comprehensive assessment of key physical and functional properties including fabric mass per unit area, thickness, water vapor permeability, tear strength, and elongation was conducted using standardized testing protocols, as detailed in Table 2. These parameters were selected to evaluate the suitability of the fabrics for application in athletic shoe uppers, with emphasis on comfort, durability, and performance efficiency.

Table 1 - Sample Structure and its composition

S. No.	Sample Structure	Composition			
		Sample	First Layer	Second Layer	Third Layer
1		SA	100 % Polyester	100 % Polyester	100 % Polyester
2		SB	100 % Polyester	100 % Polyester	100 % Polyester
3		SC	100 % Polyester	100 % Polyester	100 % Polyester
4		SD	100 % Polyester	100 % Polyester	100 % Polyester
5		SE	98 % Polyester +2% Elastane	98 % Polyester +2% Elastane	98 % Polyester +2% Elastane

Table 2 - Test standards and minimum requirements for spacer fabrics in shoe upper and orthotic use [8]

Sr. No.	Test Name	Test Method	Requirement
1	Thickness of Fabrics	GE 05	1-3 (mm)
2	Spacer Fabric Weight	GE 07	200-400(GSM)
3	WPI ((Wales Per Inch)	ASTM D3887	= 12–18
4	CPI (Courses Per Inch)	ASTM D3887	= 10–16
5	Spacer Fabric Tear Strength A	ST 02	0.03 kN (min)
6	Spacer Fabric Tear Strength B	ST 02	0.03 kN (min)
7	Spacer Fabric Tensile Strength A	ST 03	0.600 kN/0.05m (min)
8	Spacer Fabric Tensile Strength B	ST 03	0.400 kN/0.05m (min)
9	Spacer Fabric Elongation A	ST 03	40 percent (min)
10	Spacer Fabric Elongation B	ST 03	60 percent (min)
11	Spacer Fabric Water Vapour Permeability	IS 15298 Part 2: 2016	0.0008 g/cm2h
12	Spacer Fabric Water Vapour Coefficie nt	IS 15298 Part 2: 2016	0.150 g/cm2
13	Hole Density (no/unit area)	ASTM D3887	= 150–200
14	Compression (%)	ASTM D6571	20–30%

The fabric properties such as fabric weight, thickness, water vapor permeability, tensile strength, tear strength, extension, abrasion resistance, structural parameters, and compression behaviour were evaluated using standardized test methods, as presented in Table 2. Fabric weight and thickness are fundamental parameters influencing density, flexibility, thermal behaviour, and cushioning performance. These properties are interrelated, as increased thickness generally enhances stiffness and insulation, while also affecting overall comfort. All measurements were conducted under controlled conditions to ensure accuracy and reproducibility.

Tensile and tear strength are critical for athletic footwear, as they determine the fabric's load-bearing capacity and resistance to damage under stress. Tensile strength reflects the material's ability to withstand axial forces, whereas tear strength indicates resistance to tear propagation during repeated flexing. Extension and modulus further define flexibility and stiffness, with lower modulus indicating softer and more adaptable materials suitable for upper applications. Abrasion resistance evaluates the fabric's surface durability and wear performance, which is essential for maintaining structural integrity under continuous movement and friction.

Water vapor permeability is a key parameter governing breathability and moisture management, allowing sweat to escape and maintaining a dry in-shoe environment. This property is typically expressed as the rate of moisture transfer per unit area over time, indicating the material's efficiency in regulating microclimate conditions. Structural characteristics, particularly hole density, were analysed to represent fabric porosity and airflow behaviour, while compression testing assessed cushioning, deformation, and recovery properties. These parameters collectively determine the suitability of spacer fabrics for providing comfort, durability, and performance in athletic footwear

3. Results and Discussions

The performance and comfort characteristics of fabrics are shown in Table 3. It can be observed that all the samples have a similar fabric weight per unit and are composed of the same fibre, apart from sample SE.

The analysis, as shown in the graphs, revealed that within the five spacer-fabric samples investigated, thickness and hole density showed strong linear associations with compression behaviour. Among the evaluated properties, compression exhibited a very strong correlation with thickness (R^2 = 0.9603) and a strong correlation with hole density (R^2 = 0.8592), indicating that structural parameters play a dominant role in cushioning and deformation behaviour. Similarly, water vapour permeability (WVP) demonstrated a strong positive correlation with thickness (R^2 = 0.83), while its relationship with compression remained moderate (R^2 = 0.5887), suggesting that different structural mechanisms govern moisture management and mechanical properties. These findings indicate that increased thickness enhances compression resistance, while within the investigated samples, higher measured hole density was associated with higher compression values

Furthermore, samples with higher hole density showed greater compression, with sample SE exhibiting superior cushioning and structural adaptability. These characteristics are critical for ensuring comfort, breathability, and impact absorption, making such fabrics highly suitable for athletic shoes, particularly for adolescent athletes engaged in high-intensity activities. The fabric samples were evaluated across various properties using a scale of 1 to 5, as depicted in Figure 4.8. Sample SE, despite being thicker yet lighter and containing elastane, demonstrated superior performance and comfort. Differences in performance between SE and the other samples may arise from both structural differences and the presence of elastane.

Table 3 - Performance and Comfort Characteristics of Fabrics for Shoe Upper

S. No.	Fabric Characteristics	Test Method	Sample No.				
			SA	SB	SC	SD	SE
1	Thickness of Fabrics (mm)	GE 05	2.54	2.82	2.54	2.85	3.00
2	Fabric Weight (g/m2)	GE 07	274	284	272	285	282
3	WPI ((Wales Per Inch)	ASTM D3887	23	30	24	35	25
4	CPI (Courses Per Inch)	ASTM D3887	72	40	92	45	25
5	Tear Strength (N) lengthwise	ST 02	84.3	82.3	80.2	84.6	82.8
6	Tear Strength (N) cross-grain	ST 02	69.3	68.3	67.3	69.6	68.2
7	Tensile Strength (N) Lengthwise	ST 03	1105	1102	1100	1108	1104
8	Tensile Strength (N) cross-grain	ST 03	418	420	412	421	423
9	Elongation % Lengthwise	ST 03	61	64	62	63	74
10	Elongation % cross-grain	ST 03	85	83	82	84	93
11	Spacer Fabric Water Vapor Permeability (g/cm2h)	IS 15298 Part 2: 2016	0.0755	0.0782	0.0759	0.0842	0.0891
12	Spacer Fabric Water Vapor Coefficient (g/cm2)	IS 15298 Part 2: 2016	0.5615	0.7437	0.5276	0.8474	0.9843
13	Hole Density (no/unit area)	ASTM D3887	147	241	68	219	247
14	Compression (%)	ASTM D6571	23.11	31.04	21.75	29.47	33.00

Table 3 .1 - Adidas test-method designations

Code	Full designation	Organization	Method
GE 05	Adidas PHM-FW0205 (GE-05)	Adidas	Material Dimensions
GE 07	Adidas PHM-FW0207 (GE-07)	Adidas	Material Weight
ST 02	Adidas PHM-FW0302 (ST-02)	Adidas	Trousers Tear Strength and Split Tear
ST 03	Adidas PHM-FW0303 (ST-03)	Adidas	Tensile Strength

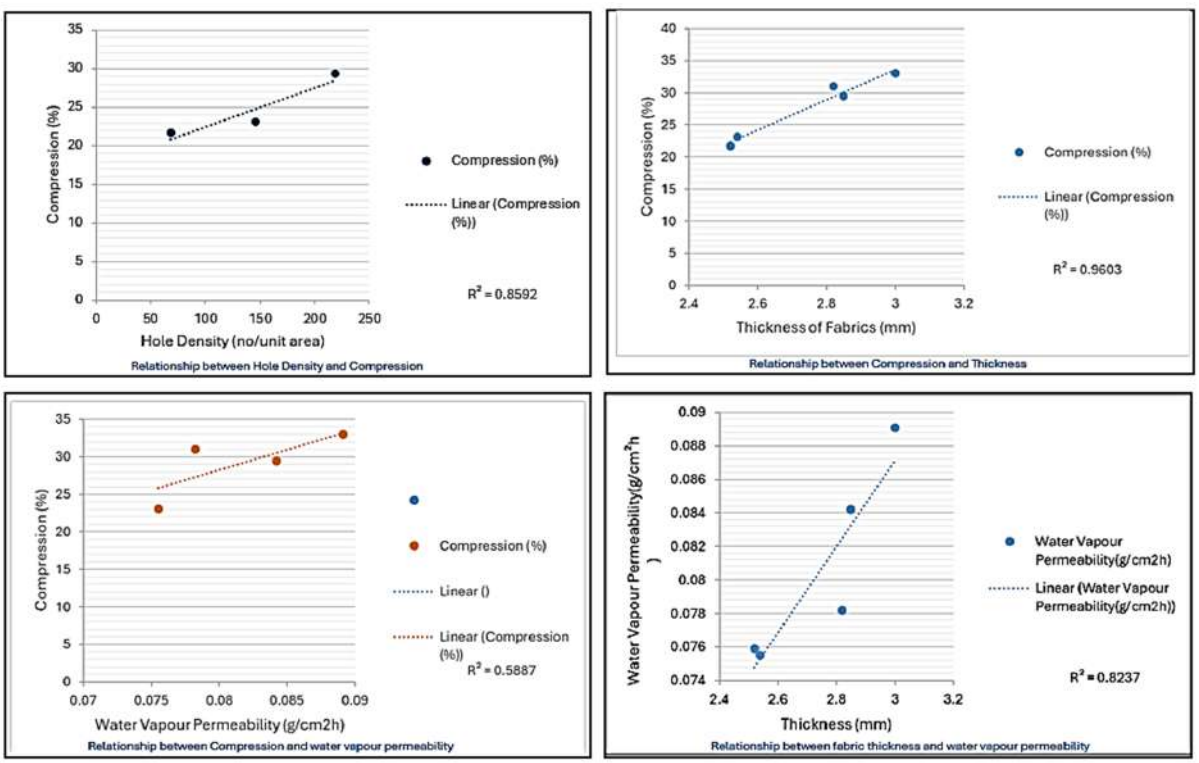


Figure 2 - The scatter plot showing different physical properties correlation

Table 4 - Correlation Analysis of Selected Physical and Functional Properties of Spacer Fabrics

Relationship	R^2
Compression vs. thickness	0.9603
Compression vs. hole density	0.8592
Compression vs. WVP	0.5887
WVP vs. thickness	0.8300

Table 5 - Property-specific rubrics

Property	*1 – Very Poor*	*2 – Poor*	*3 – Fair*	*4 – Good*	*5 – Excellent*
Fabric Thickness	Unsuitable thickness; poor cushioning/structural support	Less suitable	Acceptable	Suitable	Optimum thickness for intended shoe-upper function
Fabric Weight	Excessively heavy or otherwise unsuitable	Relatively heavy	Moderate/acceptable	Lightweight and suitable	Very lightweight while retaining required performance
Tensile Strength	Very low; likely failure during use	Low	Moderate	High	Very high; excellent resistance to tensile loading
Elongation	Excessive or insufficient; poor dimensional behaviour	Less suitable	Acceptable stretch	Good controlled stretch	Optimum controlled elongation for fit and movement
Water Vapour Permeability	Very poor breathability	Poor breathability	Moderate breathability	Good breathability	Excellent breathability/moisture transmission
Hole Density / Porosity	Very low/unsuitable pore structure	Low/less suitable	Moderate	Good	Optimum pore structure for air/moisture movement and shoe-upper function
Compression	Very poor cushioning/compression behaviour	Poor	Moderate		

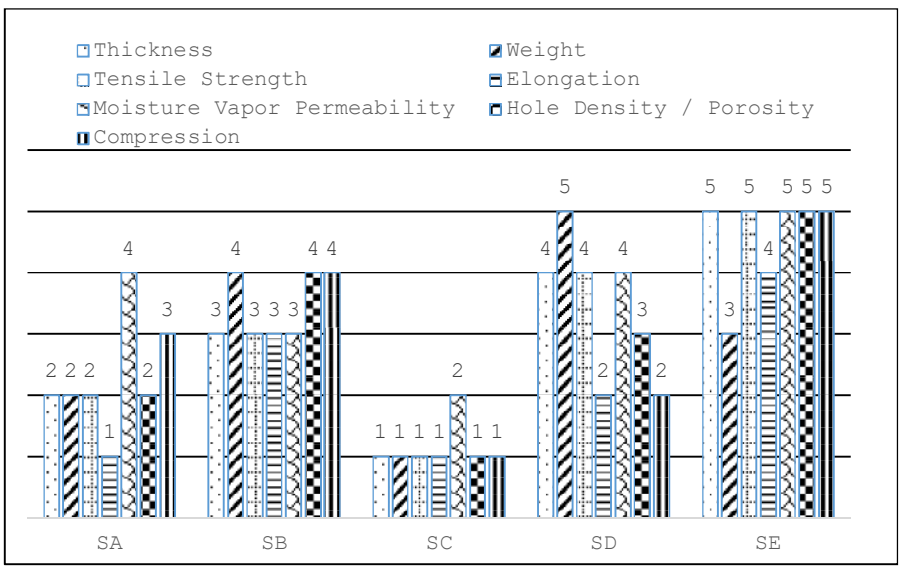


Figure 3 - Various properties of samples using a scale of 1 to 5

Table 6 - Various Properties of Samples Using a Scale of 1 to 5

			SA	SB	SC	SD	SE
1	Fabric Thickness	GE 05	2	3	1	4	**5**
2	Fabric Weight	GE 07	2	4	1	5	**3**
3	Fabric Tensile Strength	ST 03	2	3	1	4	**5**
4	Fabric Elongation	ST 03	1	3	1	2	**4**
5	Fabric moisture vapour permeability	IS 15298 Part 2: 2016	1	3	2	4	**5**
6	Hole Density/ Porosity	ASTM D3887	2	4	1	3	**5**
7	Compression	ASTM D6571	3	4	1	2	**5**

4. Conclusion

This study demonstrates that the performance of warp-knitted spacer fabrics for athletic shoe uppers is primarily governed by structural parameters, particularly thickness and porosity. Thickness enhances strength, cushioning, and durability, while porosity significantly improves breathability, moisture management, and compressibility. Fabrics with a balanced combination of these parameters exhibited superior overall performance, ensuring comfort, flexibility, ventilation, and structural stability required for athletic applications. Among the five samples investigated, SE exhibited the highest measured values for elongation, water-vapour permeability, hole density and compression, while maintaining a comparable fabric weight. Its performance may be associated with its structural characteristics and the inclusion of 2% elastane; therefore, the relative contributions of fibre composition and fabric architecture require further investigation. The findings highlight the importance of optimizing fabric architecture to achieve enhanced comfort and biomechanical efficiency. This study provides a practical, evidence-based framework for material selection, supporting the design of high-performance athletic footwear. This study provides a systematic basis for material selection in athletic shoe uppers and orthotics by integrating key physical and functional properties, enabling optimized comfort, durability, breathability, and performance.

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Biomechanics-Informed Textile Selection Framework for Functional Apparel Design

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Abstract:

Background

Functional apparel performance depends on the interaction between textile mechanical properties and human movement. Conventional textile selection commonly considers strength, elasticity, comfort, and appearance, but may not explicitly relate these properties to movement-related deformation. Garment–body interaction and textile behaviour during activity are therefore relevant considerations in functional apparel design [1, 2].

Methods

A laboratory study was described involving 36 healthy adults (18 males and 18 females; 22–35 years) performing treadmill trials at 10 km/h under three textile conditions: polyester woven (F1), polyester–elastane knit (F2), and engineered multidirectional knit (F3). The reported methods include motion capture, surface electromyography (EMG), force-related assessment, and textile mechanical characterization. The available manuscript does not include the original statistical output needed to verify inferential tests or the predictive model; these are therefore not presented as confirmed findings.

Results

The reported mean quadriceps muscle activation values were 48.2% MVC for F1, 43.6% MVC for F2, and 41.8% MVC for F3. Based on these reported means, F3 was approximately 13.3% lower than F1: (48.2 − 41.8) / 48.2 × 100. This is a descriptive comparison and should not be interpreted as statistically significant without verified analysis.

The Biomechanics-Informed Textile Selection Framework (BTSF) is proposed as a structured way to consider textile mechanical properties alongside movement-related measurements in functional apparel design. The reported descriptive values suggest that the engineered multidirectional knit had the lowest mean quadriceps activation among the three tested conditions. The framework and Textile Biomechanical Compatibility Index (TBCI) require transparent, reproducible calculations and independent validation before predictive or causal claims can be made.

Keywords: *Biomechanics, Functional apparel, Garment biomechanics, Motion analysis, Sportswear engineering, Textile biomechanics*

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1. Introduction

Functional garments used in sportswear, protective clothing, and performance apparel are required to provide structural stability, elasticity, thermal comfort, and durability while accommodating dynamic human movement. During activities such as running, walking, and jumping, garments undergo repeated tensile deformation, shear displacement, and multidirectional strain across major anatomical regions, including the knee, hip, and shoulder joints. These garment–body interactions significantly influence wearer comfort, movement efficiency, and overall garment performance [1, 2].

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Human locomotion generates localized strain patterns that vary with joint articulation, muscular contraction, and movement velocity. If textile materials fail to accommodate these dynamic strain patterns, increased muscular activation, higher energy expenditure, localized fabric stress, seam failure, and reduced ergonomic comfort may occur. Therefore, the mechanical compatibility between textile materials and biomechanical movement is an important consideration in functional apparel design [3, 4].

Recent advances in stretch fabrics, engineered knit structures, and high-performance textiles have improved garment flexibility and adaptability. However, textile selection in apparel engineering remains largely based on conventional material properties, such as tensile strength,

elasticity, comfort, and aesthetics, with limited consideration of quantitative biomechanical movement patterns. Consequently, the relationship between textile mechanical behaviour and biomechanical strain distribution remains insufficiently integrated into apparel design methodologies, limiting the ability of designers and textile engineers to select materials that effectively support dynamic body motion [5, 6].

To address this limitation, the present study proposes a Biomechanics-Informed Textile Selection Framework (BTSF) that integrates biomechanical motion analysis with textile mechanical characterization to evaluate the compatibility between fabric behaviour and human movement. By combining motion capture, physiological response measurement, and textile mechanical testing, the framework establishes a Textile Biomechanical Compatibility Index (TBCI) to support evidence-based textile selection for functional apparel engineering [7].

2. Literature Review

Recent advances in textile engineering have increasingly integrated biomechanics, material science, and wearable technologies to improve the performance of functional apparel. Traditional textile selection has primarily focused on mechanical properties such as tensile strength, elasticity, durability, and comfort, whereas the interaction between textile materials and dynamic human movement has received comparatively less attention. Previous studies have demonstrated that garment–body interaction, textile elasticity, shear rigidity, and multidirectional stretch significantly influence wearer comfort, movement efficiency, and overall garment performance during physical activity [2, 5 & 8].

The development of engineered knit structures, smart textiles, and wearable sensing technologies has further enhanced sportswear functionality by enabling continuous monitoring of physiological and biomechanical parameters. In addition, digital garment simulation and virtual prototyping have improved the evaluation of garment fit, strain distribution, and fabric behaviour before physical production [9, 11].

Despite these advances, most studies investigate textile mechanical properties, biomechanical movement, or wearable technologies independently. Limited research has integrated biomechanical strain patterns with textile mechanical characteristics to support systematic textile selection for functional apparel. To address this gap, the present study proposes a Biomechanics-Informed Textile Selection Framework (BTSF) and introduces the Textile Biomechanical Compatibility Index (TBCI) to evaluate the relationship between textile mechanical properties, biomechanical efficiency, and garment performance during human movement [10, 12].

2.1 Research gap and contribution

Prior research has examined textile mechanical properties, garment fit, clothing comfort, skin-surface deformation, compression garments, and wearable sensing [2, 5, 6, 8, 11 & 12]. The design problem addressed here is how to organize material characterization and movement-related measurements within one textile-selection process. BTSF proposes this integration, while TBCI is presented as a candidate quantitative measure. The novelty claim is limited to this proposed organization and its application to the textile systems described here; it does not claim to invent textile testing or garment biomechanics. Reproducibility and predictive validity depend on clearly defined inputs and validation using the underlying experimental data.

Previous research has examined garment–body interaction, textile mechanical properties, skin-surface deformation, compression garments, and wearable sensing technologies. These studies provide foundations for understanding garment fit, movement-related deformation, and functional textile performance [2, 5, 6, 8, 11 & 12]. The proposed contribution of this study is to organize textile mechanical characterization and movement-related measurements within a common textile-selection framework. BTSF links measured textile properties with biomechanical requirements, while TBCI is intended to provide a quantitative compatibility measure. The novelty claim is therefore the proposed integration and operationalization of these components, rather than the invention of textile testing or garment biomechanics. The framework's predictive validity depends on transparent index calculations and statistical validation using the underlying experimental data.

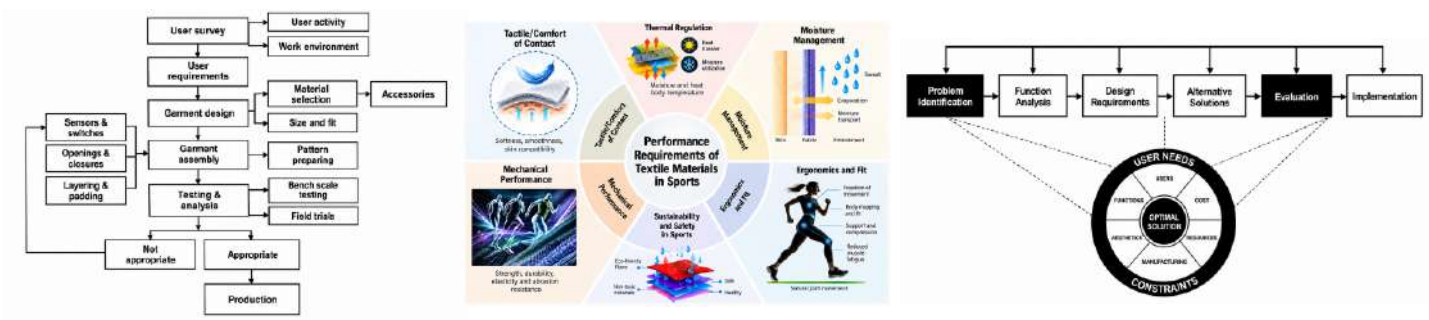


Figure 1 - Conceptual structure of the biomechanics-informed textile selection framework integrating biomechanical motion analysis, textile mechanical testing, and compatibility modeling

3. Research Objectives

Despite recent advancements in textile engineering and wearable biomechanics, the integration of biomechanical strain mapping with textile mechanical characteristics for fabric selection in functional apparel remains limited. Most existing studies evaluate textile properties or biomechanical movement independently, which restricts the development of predictive models for optimizing garment performance during dynamic human motion.
The primary aim of this study is to develop and evaluate a biomechanics-informed framework for textile selection in functional apparel design.

To achieve this aim, the study addresses the following objectives:

a. To quantify joint-induced strain patterns occurring during running locomotion using motion capture analysis.

b. To characterize the mechanical behavior of selected textile systems, including tensile strength, elongation, Young's modulus, shear rigidity, air permeability, and moisture vapor transmission rate.

c. To develop a Textile Biomechanical Compatibility Index (TBCI) that quantifies the compatibility between textile mechanical properties and biomechanical movement requirements.

d. To examine the relationship between textile biomechanical compatibility and muscular activation during running performance.

4. Hypotheses

Based on the research objectives, the following hypotheses were formulated:

H_0 (Null Hypothesis):
Textile mechanical properties do not significantly influence biomechanical efficiency during running locomotion.

H_1 (Alternative Hypothesis):
Textile systems whose mechanical properties align with biomechanical strain demands significantly reduce muscular activation and improve movement efficiency during running.

5. Materials and Methods

5.1 Participants

Thirty-six healthy adults participated in the experiment. The participant group consisted of 18 male and 18 female individuals. The mean age of participants was 27.4 years (SD = 3.2). The mean body mass index (BMI) was 22.1 (SD = 1.8). All participants reported no musculoskeletal injuries within the previous six months.

5.2 Ethical Considerations

Participants were informed about the study purpose, procedures, and potential risks and provided informed consent.

5.3 Sample Size Estimation

Statistical power analysis was conducted using G*Power software to determine the appropriate sample size for the experiment. The analysis used an effect size (f) of 0.40, a significance level (α) of 0.05, and statistical power of 0.80. The required sample size was calculated as 30 participants. To improve statistical reliability, a total sample of 36 participants was recruited.

5.4 Experimental Design

A within-subject design was described in which each participant completed trials under three textile conditions. The supplied manuscript identifies running speed (10 km/h), footwear type, and ambient temperature (22°C) as controlled conditions.

5.4.1 Independent Variable

Textile system

F1 – Polyester woven

F2 – Polyester–elastane knit

F3 – Engineered multidirectional knit

Dependent Variables

- Quadriceps muscle activation (%MVC)
- Peak strain (%)
- Energy expenditure (VO_2 proxy)
- Fabric shear displacement
- Controlled Variables
- Running speed (10 km/h)
- Footwear type
- Ambient temperature (22°C)

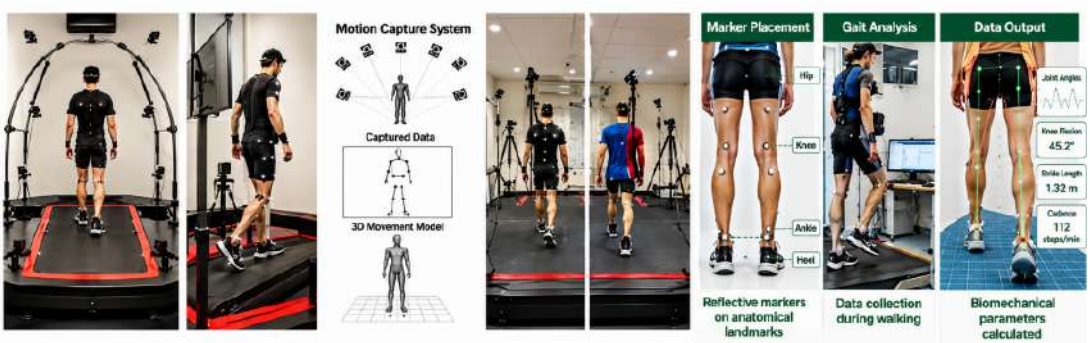


Figure 2 - Participant performing running trials with biomechanical sensors for muscle activation and movement analysis

5.5 Textile Mechanical Characterization

Table 1 presents the measured mechanical properties of the three textile systems evaluated in the study.

Table 1 - Mechanical properties of textile systems

Property	F1	F2	F3
Tensile Strength (N)	820	940	910
Elongation (%)	18	28	35
Young's Modulus (MPa)	420	310	250
Shear Rigidity (N/m)	0.85	0.62	0.48
Air Permeability (mm/s)	110	125	140
MVTR (g/m²/day)	7500	8800	9600

Tensile strength and air permeability were associated in the draft with ASTM D5034 and ASTM D737, respectively. To make the methods reproducible, the authors should ensure that the actual editions, specimen preparation, replicate counts, test directions, equipment, deviations, and methods for elongation, Young's modulus, shear rigidity, and moisture-vapour transmission rate (MVTR) are accurately documented from laboratory records. These details have not been inferred or added.

5.6 Mathematical Modeling

a. Stress–Strain Relationship

The mechanical behavior of textile materials was evaluated using classical stress–strain relationships.

(1) $\sigma = F / A$

(2) $\varepsilon = \Delta L / L_0$

Young's modulus was calculated as:

(3) $E = \sigma / \varepsilon$

Where σ represents stress, ε represents strain, F represents applied force, a represents cross-sectional area, ΔL represents extension length, and L_0 represents the original length.

b. Textile Biomechanical Compatibility Index (TBCI)

To quantify compatibility between textile mechanical behavior and biomechanical movement demands, a Textile Biomechanical Compatibility Index (TBCI) was developed.

(4) Proposed index equation: $TBCI = 0.35(Eopt/E) + 0.45(\varepsilon/\varepsilon req) + 0.20(MVTR/MVTRopt)$.

Where:

For independent reproduction, Eopt, εreq, and MVTRopt must each be defined with units and a documented source or derivation. The strain value used for each textile, the rationale for the weights, and the index normalization and interpretation must also be specified. The original records supplied with this manuscript do not establish these inputs sufficiently to independently reproduce the previously reported TBCI scores; those scores are therefore not treated as verified results in this revision.

In the proposed equation, Eopt denotes the selected reference modulus, εreq the required movement-related strain, and MVTRopt the selected reference moisture-vapour transmission rate. Their numerical values and derivation must be documented before the index is used for quantitative comparison.

F1 = 0.52

F2 = 0.78

F3 = 0.91

Table 2 - Stress–strain test data

Strain	F1	F2	F3
5	20	18	15
10	40	32	28
20	80	60	50
30	120	85	70

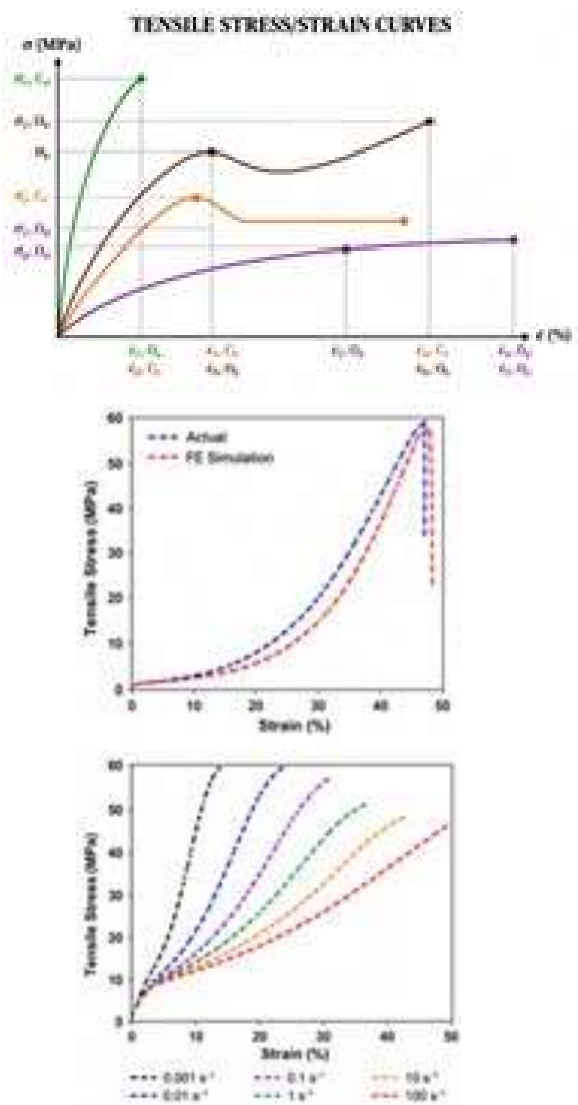


Figure 3 - Stress–strain curves of the tested textile systems (verify plotted values and units against the original test data)

5.7 Experimental Procedure

The experimental protocol followed a structured testing sequence.

i. Participant calibration for motion capture system

ii. Surface EMG electrode placement on quadriceps muscles

iii. Reflective marker placement on lower body joints

iv. Baseline standing data recording

v. Ten-minute treadmill running trial at 10 km/h

vi. Data acquisition (100 Hz motion capture, 1000 Hz EMG)

vii. Ten-minute recovery interval

viii. Repeated testing for each textile condition

5.8 Statistical Analysis

The available manuscript reports that the study used a within-subject comparison of quadriceps muscle activation across three textile conditions. The original statistical output and analysis details were not supplied with the manuscript file, so the model specification, usable sample count, assumption checks, degrees of freedom, post-hoc procedure, effect size, confidence intervals, and regression analysis cannot be independently verified. No unverified inferential statistic is presented as confirmed in this revision.

The draft previously reported a repeated-measures ANOVA result of $F(2,105) = 14.32$, $p < 0.001$. This result is not retained as a confirmed finding because the original output was not supplied. For a conventional uncorrected univariate repeated-measures ANOVA with 36 complete participants and three conditions, the expected degrees of freedom would ordinarily be (2,70); the correct model and degrees of freedom must be taken from the actual analysis output.

The three reported means are presented descriptively in Table 3. The percentage difference between F1 and F3 is approximately 13.3% relative to F1, calculated from the supplied means. This calculation does not establish statistical significance.

Mean quadriceps activation values are presented in Table 3.

The draft previously reported Cohen's $d = 1.12$ for F1 versus F3. This effect size is omitted because the calculation and its definition for the repeated-measures design could not be checked against participant-level data.

The draft previously reported $R^2 = 0.74$ and $p < 0.001$ for a regression involving TBCI and biomechanical efficiency. This result is omitted as an unverified claim because the outcome variable, predictors, observation count, model specification, handling of repeated observations, and original regression output were not available.

Table 3 - Mean quadriceps muscle activation

Textile System	Muscle Activation (%MVC)
F1 – Polyester woven	48.2
F2 – Polyester–elastane knit	43.6
F3 – Engineered multi directional knit	41.8

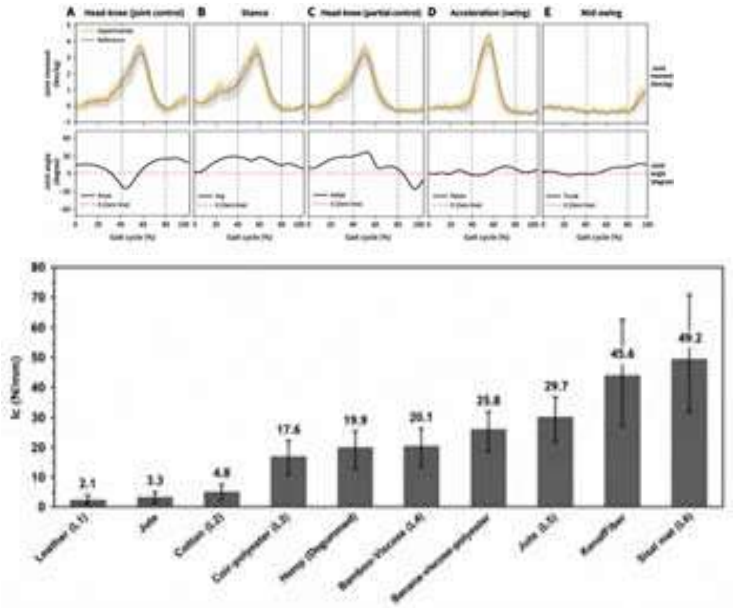


Figure 4 - Muscle-activation chart

6. Results and Discussion

Among the three textile systems, F3 had the lowest reported mean quadriceps activation (41.8% MVC), followed by F2 (43.6% MVC) and F1 (48.2% MVC). The reported F3 mean was 13.3% lower than F1 when calculated relative to F1. These are descriptive comparisons only; without the original participant-level data and verified statistical output, no claim of statistical significance can be made. The textile measurements in Table 1 show that F3 had the greatest reported elongation (35%), lowest Young's modulus (250 MPa), lowest shear rigidity (0.48 N/m), highest air permeability (140 mm/s), and highest MVTR (9600 g/m²/day). These properties may be relevant to movement-related deformation and moisture management, but this study file alone does not establish that they caused the observed activation differences.

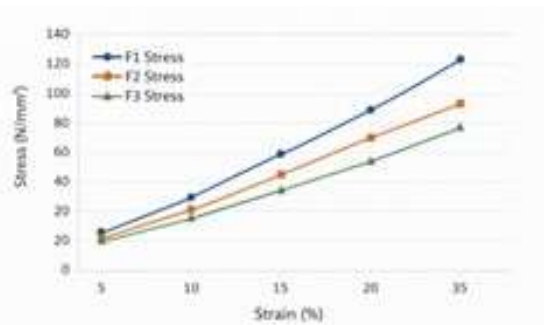


Figure 5 - The figure currently shown appears to depict stress–strain behaviour rather than muscle activation

If this is the intended data, relabel it "Comparison of stress–strain behaviour of the three textile systems" and verify its plotted values against Table 2. If a muscle-activation figure is intended, replace it with the correct graph generated from the underlying data, with units and textile conditions clearly labelled.

The results can be considered alongside literature on garment–body interaction, skin deformation, and compression textiles [2, 5, 6, 8]. However, the available results do not establish that textile compatibility itself caused reduced muscular activation or improved whole-body movement efficiency. The current contribution is best framed as a proposed integration of textile characterization and biomechanical measurement, requiring transparent calculations and stronger validation.

BTSF organizes textile mechanical characterization and movement-related measurements within a common selection process. TBCI may be useful as a candidate index, but its reference values, weighting rationale, normalization, and calculations need to be fully specified before numerical scores or predictive performance can be relied upon. The previously reported regression statistic is not included as a confirmed finding because its supporting output was unavailable.

The descriptive results indicate that F3 combined the greatest reported elongation with the lowest reported mean quadriceps activation in the tested conditions. This pattern may justify further investigation, but the study does not establish a general rule that lower-stiffness or multidirectional-stretch textiles are superior for all functional apparel. Such conclusions require replication across materials, garment constructions, activities, and participant groups.

7. Practical Implications

The proposed framework may inform apparel product development through potential applications including:

- Biomechanical garment zoning
- CAD-based strain mapping
- Sportswear performance optimization
- Reduction of seam stress concentration
- Improved ergonomic comfort in functional garments

8. Limitations and Future Research

The study is limited to three textile systems, a short-duration treadmill protocol at one reported speed, and the measurements documented in the supplied manuscript. The results may not generalize to other activities, garment constructions, body types, or environmental conditions. The TBCI cannot yet be considered independently reproducible from the information available, and the inferential statistics and regression claims require verification against original records. Future work should include larger and more diverse samples, additional textile structures and movement tasks, repeated testing, transparent index specification, test–retest assessment, and validation on independent observations.

Future research should evaluate BTSF across a broader range of textiles, garment constructions, body regions, activities, and environmental conditions. Researchers should predefine TBCI reference values and weighting, publish the calculation procedure, assess measurement reliability, and test any predictive model on independent data. Integration with finite-element garment simulation or digital strain mapping may be explored, but should be evaluated empirically rather than assumed to improve performance.
Future investigations may expand this framework through integration with artificial intelligence-based textile optimization, finite-element garment simulation, smart adaptive textile systems, and long-term fatigue testing of high-performance fabrics. Further work should also predefine TBCI reference values and weighting, test the index across a wider range of textiles and activities, assess test–retest reliability, and validate any predictive model on independent observations. These steps would help establish whether the framework generalizes beyond the specific laboratory conditions examined here.

9. Acknowledgements

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A Review on Evolution of Cyperus Fibres: From Craft Traditions to Textile Innovation

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Abstract:

Global interest in plant-based fibres as alternatives to synthetic ones has increased owing to growing environmental concerns and the demand for sustainable materials. Bast fibres are one of the various sources that plants have made available, and they have been gaining popularity because of their excellent mechanical properties, biodegradability, and usability in both textile and composite applications. An example of such a plant source is the Cyperus genus, which consists of approximately 5000 genus and is highly likely to be a source of natural fibres. Among the widespread taxonomy of the Cyperus genus, the genus known as Cyperus pangorei, C. esculentus, C. articulatus, and C. rotundus stand out as they have advantageous morphological characteristics and high cellulose content, thus making them suitable for fibre extraction and value-added product development. In the past, Cyperus plants were primarily used in handicrafts, such as making baskets and mats. However, they have started drawing research attention for their use in eco-friendly fabrics, reinforcement materials, and high-tech bio-composites. Moreover, recent studies suggest that Cyperus fibres have been demonstrating intrinsic antimicrobial and antioxidant properties, which have opened up their applications in biomedical textiles and functional material development. This study offers the material potential of consolidated Cyperus fibres and highlights the functionalization of fibres, performance enhancement, and wider industrial deployment as areas of opportunity. The results point out the necessity of considering the underutilized botanical resources that will eventually lead to the support of circularity, the decrease in environmental impact, and the increase in the variety of sustainable textile-grade fibres.

Keywords: *bast fibres, bio-based materials, cyperus pangorei fibres, eco-friendly textiles, fibre functionalization, sustainable textiles*

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1. Introduction

In recent years, sustainable materials have gained importance in the environment. Due to the impacts of climate change, resource depletion and ecological degradation, the use of sustainable materials is being sought to replace conventional materials to reduce harm to the environment. Whereas, the conventional materials produce waste and pollution that lead to a carbon footprint [1]. One quarter of the world's industrial water consumption is from the textile sector. To address this, multiple innovations are carried out to save the environment. As the textile industry is growing, the consumption of fibre materials needs better performance, cost-effectiveness and biodegradability, as shown in Figure 1. Nowadays, most fibres depend on petrochemicals, which have more advantages like good mechanical properties, but this is coupled with high-emission production methods [2].

Natural fibres are sourced from plants, animals and minerals, and the fibres are extracted from stems, bark, seeds, and fruits. These fibres are recognised for their cost-effective extraction, wide applicability, easy process methods, and material quality. And for effective extraction, it is essential to be aware of the appropriate stage of plant maturity and how to employ the techniques to a specific fibre type (water retting, enzymatic treatment, or chemical processing). In natural fibres, cellulose molecules consist of glucose units arranged in parallel configurations to form microfibrils, which determine their mechanical strength, flexibility, and resilience. Due to its abundance, renewability, and versatility, cellulose has emerged as a key material for the development of innovative biomaterials [3]. The primary components of plant fibre are cellulose, which is marked by its chemical stability, biodegradability, and sustainability. Due to their unwavering properties, these fibres are used in the processing of functional textiles like anti-microbial,

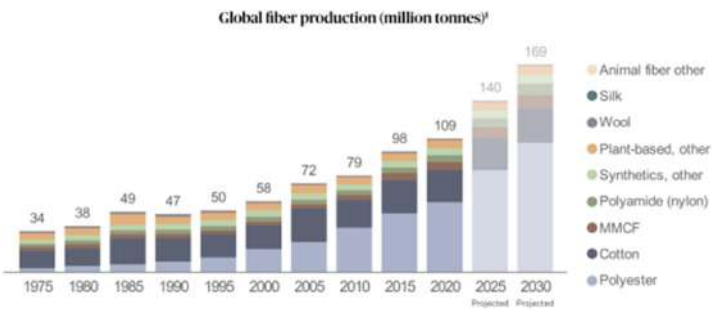


Figure 1: Source - Textile Exchange, Materials Market Report 2025

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flame-retardant, UV-protective, and moisture-absorbent. On the other hand, animal fibres are made up of protein structures, which make them suitable for biomedical applications[4], as shown in Figure 2. Bast fibres are preferred for their wide properties like breathability, high-tensile strength, and good moisture absorption. The major component present in bast fibre is cellulose, and other non-cellulosic compounds include pectin and lignin [5]. Due to its various characteristics and applications, an attempt was made to extract a fibre from the culm of C. pangorei. It has also been proven that it has good qualities for textile applications; it contains 82.2% holocellulose and 13.28%lignin [6]. This study explores the obstacles that prevent plant-based fibres like Ficus carica bark and Cyperus pangorei from being transformed into textile products and specifically speaks about the underutilized potential of the Cyperus genus for developing sustainable products.

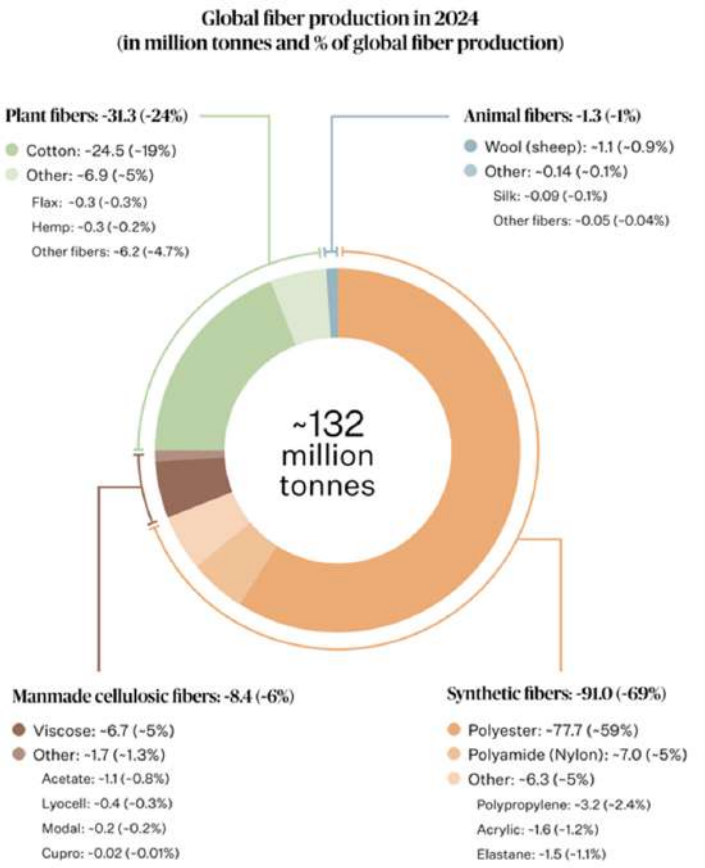


Figure 2: Textile Exchange, Materials Market Report 2025

1.1 Cyperaceae



Figure 3: Classification of Cyperus

The Cyperaceae family is the largest monocotyledonous plants has 5000 genus and 120 genera. There is no restrictions on genera within its subfamilies [12]. This is the largest genus spread around the world, of which 80 genus are found in India, as shown in Figure 3. This family consists of perennial genus with some grass-like plants that grow in wetlands. It possesses significant economic and ecological importance. Some of these are used as food, fodder, fuel, medicines, for construction, weaving, mat-making, and perfumery [13]. Numerous civilizations have used Cyperus plants as traditional treatments for a variety of human illnesses, such as diuretics, digestants, lacto depurants, and the therapy of bowel and stomach issues. Furthermore, the extracts of these plants have been used to treat a variety of inflammatory diseases, bronchitis, blood problems, irregular menstruation, amenorrhea, diarrhea, and dysentery. These three taxa- Cyperus rotundus L.(purple nutsedge), Cyperus esculentus L.(yellow nutsedge), and Cyperus papyrus are well-known [14]. The rhizomes of C.esculentus are traditionally consumed as a food source and for medicines, as mentioned in Table 1. C. castaneus, C. elatus, C. haspan, C. iria, and C.pilosus are used as fodder. Some genera in this family are used as ornamental flowers. In ancient times, the Egyptians utilized pith of C. papyrus for papermaking and in construction works. In earlier times, the philosophers noted that Africans and Asian people have used sedges for basketry and mat weaving [15], as shown in Figure 4.

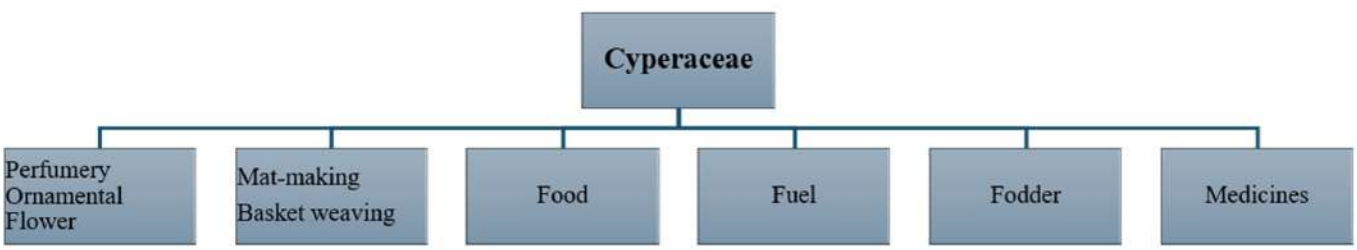


Figure 4: Potential end uses of Cyperus

Table 1: Species, geographic distribution, fibre characteristics, chemical composition, and potential textile applications

Species	Geographic distribution	Fibre characteristics	Chemical composition	Potential textile applications	Reference
C.rotundus	Tropics, subtropics	Rhizome-rich in bioactives	Cellulose- 65%, lignin – 10%	Biofunctional finishing textiles	[7, 8]
C.esculentus	Europe, Africa, Asia	Tuber rich in starch/oil	Starch 20-30%,oil 25-35%	Biopolymer coatings, binder	[9]
C.articulatus	Africa, South America, Asia	Stem fibrous, aromatic	Cellulose 73%, lignin 7.5%	Paper textiles, non-wovens	[10]
C.pangorei	India, Sri Lanka, Nepal	Stem fibrovascular bundles	Holocellulose 82.2%, lignin 13.2%	Mats, composites, eco-textiles	[11]

1.2 Phylogeny of Cyperaceae

Cyperaceae is an herbaceous plant that looks like grass with thin leaves with parallel veining and solid, non-jointed stems. Its tiny strands give fruits that resemble nuts. Their morphology and development of spikelets have provided the foundation for most evolutionary ideas about this family. When it comes to clade age, diversification rates, geographic distribution and ecological niches, the Cyperaceae family provides a useful framework for researching diversification and biodiversity management [16].

1.3 Origin and diversification

The name was first described by De Jussieu in 1789, derived from the Greek word kupeiros, which means sedges. Though the Cyperaceae family has global diversification has not yet been fully explored. In accordance with records that says, family is likely to be found in the South America region [16].

1.4 Habitat specificity of Cyperaceae

The family is most diverse in humid climates, and they thrive in a variety of habitats, particularly in wetlands. These genus evolved around swamps, cliffs, and high altitudes. Many genus are becoming rare and endangered because they are less competitive and confined to sensitive habitats [13].

1.5 Cyperus rotundus

Cyperus rotundus, commonly known as Nutgrass, is also referred to as "the world's worst weed" globally. It is broadly distributed over tropical and subtropical regions. Appearance-wise, this is smooth, grass-like, fibrous-rooted, and grows up to a length of 15- 60 cm. A key factor of this is the underground rhizomes and tubers. It has been traditionally utilized in Ayurvedic, Chinese, and Siddha medicine for treating fever, gastrointestinal disorders, dysmenorrhea, inflammation, and wounds. It's rich in phytochemicals and is notable for antioxidant, antimicrobial, anti-inflammatory, and anticancer properties [12, 13], as shown in Figure 5.



Figure 5: Cyperus rotundus and its uses [19]

1.6 Cyperus Esculentus

Cyperus esculentus, which is also known as "underground walnut", is commonly known as tigernut, as shown in Figure 6 It has 40-50% carbohydrates,20-30% fats, 7-9% proteins, and 8- 10% dietary fibre. It is used in making oil due to its hypocholesterolemic properties. It is widely cultivated in Southern Europe, the Middle East, and some parts of Asia and America. It is consumed as food and medicine in various parts of the world. In various places, it has different names: aya in Hausa, Ofio in Yoruba, and Akiausa in Igbo. The roasted tigernut, known as sweetmeat in Egypt, is high in nutrients. In Spain and Africa, it is a speciality crop with an annual production of over 9000 tons. These tubers are also used as hog feed and extracted juice for making beverages. This beverage is called Horchata de Chufa or Tigernut milk, which is consumed by the people of Spain and Africa [14, 15].



A



B

Figure 6: A- Fields of Cyperus esculentus; B- Tigernut [22]

1.7 Cyperus articulatus

Cyperus articulatus, commonly called joined flat sedge, is a perennial rhizomatous sedge. It grows widely in tropical and subtropical zones and in wetlands, riverbanks across Africa, South America, and South Asia. This is characterized by its distinct jointed culms, bladeless leaves, and aromatic rhizomes, which also serve as bioactive phytoconstituents. The essential oil obtained from this is known as priprioca oil, which is used in perfumery and aromatherapy for its fixative properties in Brazil. Nowadays, this is encapsulated and used in biomedical and food preservation. It is used in chitosan nanoparticles loaded with oil. Though it has good medicinal and spice properties, it also stands out for its fibrous structure and cellulose content of these rhizomes, possesses for sustainable textile applications, leading the way to green technology [16, 17] as shown in Figure 7.

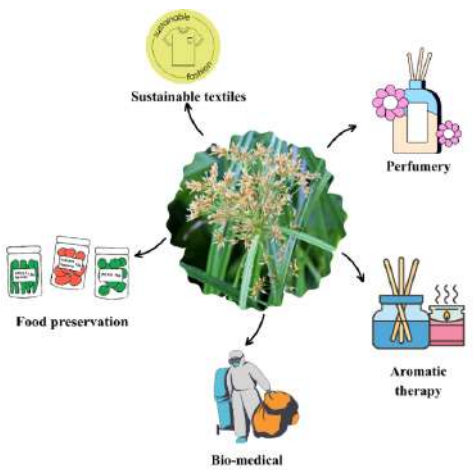


Figure 7: Cyperus articulatus and its uses

1.8 Cyperus pangorei

Cyperus pangorei is used in the making of silk mats of Pathamadai. These crops are available in India, Sri Lanka, Nepal, and Myanmar (Burma). It streams across tropical and various temperature regions. Normally in India, C.Pangorei is used for mat-making in West Bengal, Kerala, Tamil Nadu, and Andhra Pradesh. In Tamil Nadu, across districts like Vandavasi, Karur, Thanjavur, and Tirunelveli, people are pursuing as their primary occupation. This fibre has inherent stability and fibrovascular bundles, which stand for its durability in mat industries. With these, they also make products like handbags, baskets, table mats, window curtains, wall hangings, and hand fans. This plant grows in slow-moving water bodies, paddy fields with over 3 to 6 feet long and 0.5 m depth. There is an issue with this plant because it occupies a larger area, which also alters the natural flow of water as shown in Figure 8(A) and extraction process of CP is shown in Figure 8(B-D). It has 13.28% lignin and 82.2% holocellulose, which highlights its properties for the textile industry, as recently demonstrated [6].

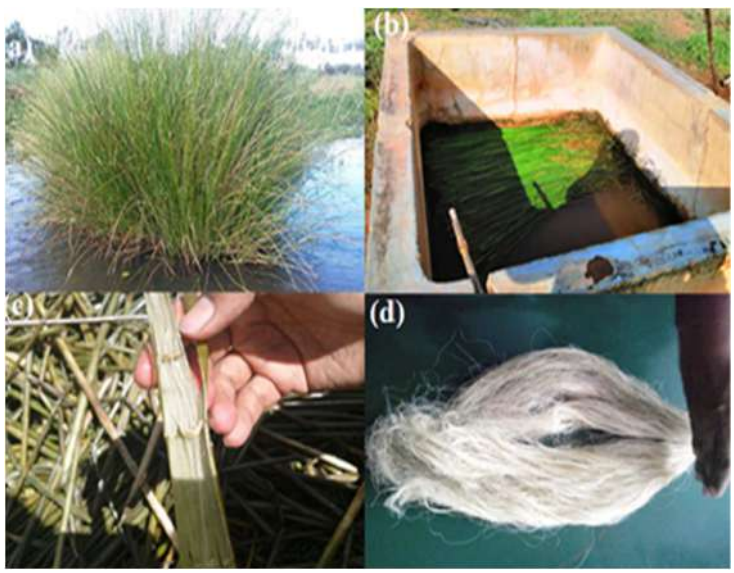


Figure 8: Cyperus pangorei [11]
A-CP plant; B-Water retting; C- fibres inside the stem; D-extracted fibre

2. Structural characteristics and fibre properties

In Table 2, the Cyperus genus has been compared and analysed, and its distinct roles in textile applications have been identified. Cyperus rotundus is mostly studied for its bioactive compounds, which exhibit antimicrobial and antidiabetic properties [8]. Cyperus Pangorei and Cyperus articulatus are good for pulp processing, fibre extraction, and structural textile applications like nonwovens and composites [19, 21 & 22]. Cyperus esculentus has a starch-rich tuber, and it is used as a biopolymer binder or coating material in textiles [25]. This comparison suggests that the Cyperus genus has multifunctional textile properties and is a sustainable, high-performance textile material.

Table 2: Cyperus Genus - Structural Characteristics, Extraction Methods and its End-uses

Cyperus Genus	Structural Characteristics	Extraction Method	End-uses	Reference
Cyperus rotundus	Rhizome -rich inbioactive compounds	Solvent extraction	For a biofunctional finishing agent	[8]
Cyperus articulatus	Stem-based-Cellulose-73.2% Ligin-7.5%	Fibre extraction strength testing	Paper textiles, non-woven materials	[10]
Cyperus esculentus	Tuber rich in Starch 20-30% Oil -25-35%	Starch extraction	Biopolymer coating, binder	[25]
Cyperus pangorei	Stem based-holocellulose-82.2% Lignin-13.2%	Fibre extractions	Composites	[26]

3. Extraction Methods

Table 3: Cyperus Genus - Plant Organ, Extraction Methods, and its Purpose

Cyperus Genus	Plant Organ	Extraction Method	Purpose	Reference
Cyperus rotundus	Rhizome	Hydro distillation, Pressurised extraction (PLE), Supercritical Fluid Extraction (SFE)	Essential extraction oil	[7]
Cyperus esculentus	Tuber	Mechanical+ Solvent/Microwave extraction/wetmilling + Starch extraction	Fibre	[24, 25]
Cyperus articulates	Stem	Alkali (NaOH) pulping	Fibre	[10]
Cyperus Pangorei	Stem	Water retting	Fibre	[11]

In the above Table 3, the plant part being used and the extraction methods of the Cyperus genus are listed. Cyperus rotundus is known for its phytochemical components present in fibre, to extract the oil from the tuber, various methods have been carried out like Pressurized liquid extraction (PLE), Hydrodistillation and Supercritical fluid extraction(SFE). By these extraction methods, the medical components present are being extracted by high-pressure heat [7]. Cyperus esculentus focuses on fibre to chemicals, which is rich in bioactive compounds, by mechanical grinding with solvent/microwave assisted methods, the starch from tubers are extracted by wet milling and fibres are used for valorisation [24, 25]. Whereas Cyperus articulatus and Cyperus pangorei have high cellulose and lignin, which can be treated with alkali and water retting processes to extract fibre [19, 22].

Table 4: Comparative evaluation of Cyperus fibre extraction/processing

Species	Extraction Methods	Advantages	Limitations	Environmental impacts	Fibre quality outcomes	Reference
C.Pangorei	Water retting	Low-cost, traditional, widely practised; durable fibres	Time-consuming	Use fewer chemicals; but may degrade water quality	Holocellulose 82.2%, lignin 13.2%; good tensile strength but hydrophilic	[6]
C.articulatus	Alkali pulping	Efficient fibre separation; reduces non-cellulosic compounds	Requires NaOH: chemical effluents; may weaken fibres	Chemical disposal challenges; higher energy demand	Cellulose 73.2%, lignin 7.5%; fine fibres, suitable for nonwovens/paper textiles	[16]
C.esculentus	Mechanical+ solvent extraction	Dual value streams(starch/oil + fibre)	Energy-intensive; lower fibre yield	Valorises food waste; solvent use may impact sustainability	Starch 20–30%, oil 25–35%; fibres used for biopolymer coatings/binders	[10]

Table 4(cont.): Comparative evaluation of Cyperus fibre extraction/processing

Species	Extraction Methods	Advantages	Limitations	Environmental impacts	Fibre quality outcomes	Reference
C.rotundus	Bioactive extraction	Provides antimicrobial/ antioxidant properties	Limited scalability for structural fibres	Low chemical footprint compared to synthetics	Cellulose ~65%, lignin ~10%; fibres weak but biofunctional	[8]
Jute	Water retting, mechanical decortication	Abundant, low-cost, biodegradable	Coarse texture; high moisture absorption	Low carbon footprint; retting water pollution	Cellulose 59–71%, lignin 11–13%; moderate tensile strength	[28]
Flax	Water retting, enzymatic retting	Fine fibres, high tensile strength	Labour-intensive; retting requires controlled conditions	Biodegradable: retting water management needed	Cellulose 65–71%, lignin 2–3%; superior fibre fineness	
Hemp	Water retting, alkali pulping	Strong fibres, versatile applications	Woody core complicates processing	Biodegradable; retting effluent concerns	Cellulose 70–76%, lignin 4–19%; high tensile strength	[29]
Banana	Mechanical extraction from pseudo stem	High elongation, flexible fibres	Seasonal availability; Bulk waste handling	Utilises agricultural waste; eco-friendly	Cellulose 60–65%, lignin 5–10%; high elongation	[28]
Sisal	Mechanical decortication, water washing	Stiff, durable fibres; widely cultivated	Brittle; limited flexibility	Biodegradable; low chemical input	Cellulose 60–64%, lignin 10–12%; strong but coarse fibres	[29]

In table 4, Cyperus fibres, notably C. pangorei and C. articulatus, have competitive cellulose content (73-82%), equivalent to bast fibres like flax (65-71%) and hemp (70-76%). Cyperus is a viable option for eco-textiles and composites due to its high holocellulose proportion. In contrast to flax and hemp, which are renowned for their exceptional tensile strength and fineness, Cyperus fibres are more hydrophilic, which restricts dimensional stability. Jute and sisal, due to their coarse texture, are less suitable for fine apparel because they have high lignin content (10-13%). These fibres are used to produce matting, ropes, and composite applications. Whereas banana fibres extracted from the pseudo stem are unique for their elongation, seasonality, waste reduction, and flexibility. These fibres are biodegradable, eco-friendly, and renewable. Cyperus fibres are a low-cost, chemical free method, but they require proper maintenance. However, they possess good cellulose content like flax and hemp. The improvement in processing is essential to achieve comparable mechanical properties and their versatility for making ropes, matting, and bifunctional textile applications.

4. Textiles and non-textile use

Cyperus fibres (C.pangorei, C.articulatus) have diverse applications for textiles like yarn spinning, fashion, and technical textiles (filtration fabrics, geotextiles, home textiles). The high cellulose content present in the fibres supports strength and durability although it has a hydrophilic nature the limits dimensional stability. Blending with cotton or polyester improves mechanical performance and usability for common textile applications. Cyperus fibres are being investigated more in biocomposites (furniture, car panels), biomedical textiles (antibacterial fabrics, scaffolds, wound dressings), and eco-packaging (biodegradable films, fibre-based packaging). They are positioned as a flexible and sustainable material in both the textile and non-textile industries due to their innate antioxidant and antibacterial qualities.

5. Future Trends

Cyperus fibres have significant value in both textiles and non-textiles. In textiles, they can be used in ropes, apparel and home furnishings, and technical textiles like filtration and geotextiles. Whereas in non-textiles like bio composites and construction materials, biomedical textiles for wound healing, antimicrobial fabrics, and eco-packaging aligning with sustainability. Their performance is further improved by blending techniques: Cyperus/polyester composites have higher tensile strength than pure Cyperus, similar to jute/polyester. Despite these benefits hydrophilicity and processing issues such chemical pulping and retting effluents. Emerging research avenues such as hydrophobic coatings for increased durability. Furthermore, Cyperus fibres are positioned for innovation in biomedical textiles,

functional fabrics with thermal insulation and wound healing due to their antibacterial and antioxidant qualities. Cyperus fibres are a sustainable resource that may lead to a balance between durability, comfort, and environmental responsibilities.

6. Rural entrepreneurship and livelihood opportunities

The value-adding of Cyperus fibres offers a great deal of promise for promoting sustainable resource use and stimulating rural communities. In later years, species like C.pangorai are woven into mats, handicrafts, empowering women crafters and generating additional income to their lives. Now, Cyperus's story goes beyond traditional crafts; where the plant grows widely, they are used in biomedical materials, eco-friendly home textile products, and bio-composites. These products promote organised entrepreneurship, family income, improve skills in fibre extraction, encourage a circular economy, and create local value.

7. Policy and Support Needs

To promote the fibre business, there is a need for technical skills, institutional assessment, and market cooperation. This may lead to thriving opportunities. This paves the way for resilience, independence, and an eco-friendly approach to build these kinds of activities. It needs strong government support and policy frameworks, and training programs to have a significant impact in rural communities; it may promote their livelihood and gender equality.

8. Conclusion

Cyperus fibre has viable properties for incorporation into textile and non-textile applications. Traditionally, it is used in making ropes, mats, and other products. These fibres are explored in technical textiles like filtration fabrics, geotextiles and composites. Their cellulose content highlights its structural strength it also has good moisture absorption and thermal stability. These fibres are rich in antimicrobial and antibacterial properties; however, these application in biomedical products, including wound dressing and scaffolds. The renewable nature of the fibre offers an opportunity to support sustainable material development. Nevertheless, their wider industrial use may be limited by the availability of raw materials and extraction methods; further research is focusing on extraction methods and surface modification. Cyperus-derived materials could find wider application in sustainable textile innovation.

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Digital Skilling for Inclusive Less-Literate Workers in the Textile and Apparel Industry

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Abstract:

Background: *Digitalisation is transforming textile and apparel job-work environments through mobile training and skill-development platforms. However, less-literate workers in stitching, knitting, embroidery, finishing, rectification, and quality checking often struggle to use smartphone-based skilling applications independently. This study investigates the usability of digital skilling platforms among less-literate textile and apparel workers and proposes inclusive interface design strategies.*

Methods: *Field observations and semi-structured interviews were conducted with 27 participants, including 23 less-literate users and 4 domain experts. Participants attempted course discovery and enrolment on the Skill India Digital Hub (SIDH). Usability barriers informed a prototype redesign guided by Dillman's Visual Interaction Cues Framework, adapted for textile job-work contexts. The redesigned interface was evaluated through usability testing, with outcome measures including task completion, help requests, navigation errors, enrolment success, hesitation, and user confidence.*

Results: *The original interface presented substantial usability barriers: no participants completed enrolment independently and only one participant was able to locate the course pathway partially. However, the redesigned prototype allowed 19 out of 27 participants (70.4%) to complete the task successfully. The number of help requests decreased from 22 to 2 and navigation errors decreased from 58 to 17. Participants demonstrated greater confidence and reduced hesitation when interacting with the redesigned screens.*

Conclusion: *Digital skilling platforms for textile and apparel workers should be designed around task complexity, work context, and the needs of less-literate users. Task-linked visual guidance can improve course discovery, reduce assistance needs, and support more independent interaction with digital skilling platforms in job-work environments.*

Keywords: *Digital Skilling, Inclusive Interface Design, Less-Literate Workers, Skill India, Textile and Apparel Job Work, Visual Guidance*

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1. Introduction

India's textile and apparel sector is one of the country's largest employment generators, employing about 45 million people directly and supporting over 100 million indirectly [1]. The industry is gradually shifting from traditional production processes to digitally enabled workflows [2]. Digital tools are now embedded across garment factories, job-work units, tailoring clusters, embroidery centres, finishing units, artisan workshops, and training environments [3, 4]. Smartphones and mobile apps have become an integral part of everyday work, supporting productivity, transparency, quality control, payments and market connectivity [5].

Government and sectoral initiatives increasingly support technology-enabled vocational training and workforce skilling in textile and apparel production [6, 10, 11 & 24]. These programmes aim to enhance employability and strengthen production-related skills. However, effective use of digital systems depends not only on access to technology and training but also on workers' ability to interact with these systems independently. Many artisans and textile job-workers have low literacy and rely primarily on practical skills. As a result, they often struggle with technology usage that requires reading instructions, interpreting icons, navigating multiple screens, or completing procedural tasks without assistance.

Such usability barriers may increase dependence on supervisors and discourage independent use of digital tools. This creates a gap between national skill development initiatives and the practical usability of digital platforms at the worker level. Selected screens of the Skill India application were redesigned using the Visual Affordance Framework to bridge this gap. The redesign included

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familiar visual cues, shorter steps of interaction, and task-based guidance related to real textile and apparel work practices. The prototype was subsequently evaluated with less-literate users to examine whether task-linked visual guidance could support course discovery, enrolment, and more independent interaction with the digital skilling platform.

2. Review of Literature

This section reviews the literature on textile and apparel digitalisation, digital skilling platforms, challenges to less literate users, task complexity, and inclusive interface design. It highlights how digital skilling intersects with textile production and job-work practices in apparel sector, drawing on government initiatives, sector skill council structures, and human–computer interaction (HCI) research.

2.1 Textile and Apparel Digitalization

Digitalization in textiles is no longer confined to large-scale automation or enterprise software. It is increasingly entering everyday production, training, quality control, communication, and job-work practices. In India, the textile and apparel sector remains highly labour-intensive and includes organised factories, de-centralised job-work units, tailoring clusters, embroidery centres, finishing units, handloom and handicraft activities, and informal production networks. This makes digitalisation a complex process because technology must work not only for managers, engineers, and supervisors, but also for less-literate workers who perform practical and repetitive production tasks [7].

Recent literature on textile digitalisation discusses Industry 4.0, Industry 5.0, smart manufacturing, and digital technologies for improving production efficiency, transparency, traceability, and responsiveness [5, 8 & 9]. In textile processes, digital tools may support machine monitoring, fabric inspection, production planning, yarn and fabric testing, and process optimisation. However, most studies focus on technological capability rather than usability for workers.

For textile work environments, digitalisation appears in more practical forms: smartphones used for instructions, training videos, supervisor communication, product uploads, and defect reporting. The challenge is not technology availability but whether less-literate users can independently operate these tools. Many tasks require interpretation and decision-making, such as identifying faults or correcting stitches. Industry 5.0 reinforces this human-centred perspective, stressing worker inclusion, confidence, and independent task performance [9].

2.2 Digital Skilling Platforms in Textile, Garment, Made-Ups and Home Furnishing Sectors

India's skilling ecosystem has expanded through national skilling initiatives, digital skilling architecture, and sector skill councils [6, 10, 11 & 24]. These connect training to industry-defined job roles and occupational standards. The Textile Sector Skill Council develops qualifications for spinning, weaving, knitting, and fabric inspection [10], while the Apparel, Made-Ups and Home Furnishing Council focuses on garmenting, stitching, finishing, and embroidery [11].

The Skill India Digital Hub consolidates courses, programmes, and digital learning resources within an online and mobile-accessible skilling platform [25]. This structure is useful as it brings skilling resources into one accessible digital space. However, users must search by keyword, identify sectors, interpret icons, and navigate multiple screens before reaching content. Thus, the issue is not content availability but usable access. For less-literate workers, especially those who rely more on practical knowledge than formal reading, the platform itself may become a barrier. Therefore, digital skilling in the textile and apparel sector should not be studied only as a question of training content. It must also be studied as a question of interface design, task flow, and user comprehension.

2.3 Less-Literate Workers and Barriers

Low-literate individuals have been defined as those educated between Standard Four and Standard Eight in the Indian education system [12]. These individuals often recognize and understand basic numerals (0–9) but face difficulties in reading textual content and have limited or no experience with personal computing. Illiterate individuals have been distinguished from low-literate individuals, with the latter experiencing difficulties in reading and comprehension despite some basic literacy skills [13]. For this study, "less-literate" refers to participants with limited formal education and functional reading ability who could recognise familiar words, numbers and everyday visual symbols but experienced difficulty interpreting text-intensive instructions, formal terminology and multi-step digital interfaces independently. The term does not imply lack of occupational skill; participants possessed practical experience or familiarity with textile and apparel activities. Research in human-computer interaction has shown that low-literacy users can experience difficulty with text-heavy interfaces, typed input, and unfamiliar symbols [14, 15 & 19]. Medhi, Sagar, and Toyama demonstrated that contextual cue and visual feedback improve access, but images must be carefully tested since interpretation varies [14]. Later studies confirmed that mobile access alone does not solve usability problems; interfaces must reduce memory load, minimise text dependence, and provide clear feedback [15].

In textile contexts, barriers are sector-specific. A worker may recognise a stitch defect but fail to locate the "Sewing Machine Operator – Knits" course. A trainee may operate a machine but struggle to enrol in particular course online. Quality-control staff may identify faults visually but face difficulty uploading evidence or interpreting navigation error messages. These are not only literacy barriers but also challenges of terminology, interpretation, timely response and navigation. Less-literate users depend on trainers, supervisors, family members, or peers to complete digital tasks. This dependency reduces opportunities for independent interaction with digital skilling platforms and may limit their effective use.

2.4 Task Complexity in Interfaces

Task complexity strongly influences usability, particularly for users with limited literacy and digital experience [16, 17]. Drawing on this task-complexity literature and the usability requirements of the present study, tasks were operationalised at three levels: Level 1 (Recognition), Level 2 (Interpretation), and Level 3 (Procedural). Visual complexity can also influence how users explore and interpret interactive visual information [18]. For low-literacy and novice users, increasing memory demands and poorly communicated interaction states can further create usability difficulties [15, 19]. In textiles, many production tasks are procedural, making alignment between digital flows and work routines essential.

2.5 Visual Interaction Cues and Inclusive Design

Inclusive design is critical in textile skilling because the sector is visual and practice-based. Workers learn by observing, repeating, and correcting. Affordance theory describes how objects signal what can be done [20]. Visual cues and signifiers can help users recognise possible actions and navigate digital interfaces [21]. For digital interfaces, cues (icons, highlights, arrows, progress bars) indicate possible action. According to Norman's design theory [22] perceived affordances and signifiers are important especially for less-literate users. Interfaces should therefore emphasise visual recognition, contextual understanding, and step-by-step guidance rather than text-heavy structures. The Visual Interaction Cues Framework provides a structure for analysing visual cues [23]. In this study, the framework was adapted to classify visual-cue requirements across three levels of task complexity.

2.6 Research Gap

Recent Industry 5.0 research emphasises a human-centric approach to industrial digitalisation, where technological transformation, productivity improvement, and workforce training should be aligned with workers' abilities and interaction with digital systems [5, 9]. However, limited research has examined how this human-centric perspective can be applied to less-literate textile and apparel workers using digital skilling platforms. Challenges include recognising course content, interpreting job role information, navigating multi-step flows, and understanding feedback. This study fills this gap by using field observations, interviews, task complexity analysis and prototype validation to suggest inclusive design directions for the Skill India Digital Hub.

3. Methodology

3.1 Research Design

This study used an exploratory prototype-based usability research design combining qualitative field observations and semi-structured interviews with descriptive quantitative performance measures. The study examined how less-literate users interacted with the Skill India Digital Hub while performing course-discovery and enrolment tasks related to textile and apparel skilling. Qualitative observations were used to identify interaction difficulties, behavioural patterns, hesitation and comprehension barriers, while descriptive measures including task completion, help requests, navigation errors and enrolment success were used to compare interaction with the existing interface and the redesigned prototype.

3.2 Participants and Recruitment

Purposive sampling was used to recruit 27 participants, comprising 23 less-literate users and four domain experts. The less-literate participants represented two occupational pathways: Self-Employed Tailor (n = 13) and Sewing Machine Operator–Knits/textile job-work (n = 10). The four domain experts provided contextual insights regarding work practices, training requirements, and usability expectations. Participant characteristics and recruitment details are presented in Table 1. Participant identities were anonymised throughout the study. For participant recruitment, less-literate users were operationally defined as individuals educated between Standard IV and VIII who had functional recognition of familiar words, numbers and everyday visual symbols but experienced difficulty independently interpreting text-intensive or multi-step digital interfaces. Informed consent was obtained from all participants prior to participation.

Table 1: Participant Characteristics and Usability-Testing Context

Characteristic	Details
Less-literate participants	23
Domain experts	4
Education range	Standard IV–VIII; limited formal education and functional literacy
Age range	25–55 years
Gender distribution	Female: 20 (87.0%); Male: 3 (13.0%)
Languages used	Hindi and Marathi
Smartphone experience	Existing smartphone users with varying levels of digital experience; usability testing was conducted on participants' own smartphones
Occupational status	Less-literate trainees and workers with practical experience or familiarity with textile and apparel activities, including self-employed tailoring and textile job-work
Recruitment location	DejaVeu Skill Learning and Training Centre, Koparkhairane, Navi Mumbai, Maharashtra
Occupational pathway	Self-Employed Tailor (n = 13); Sewing Machine Operator–Knits/textile job-work (n = 10)

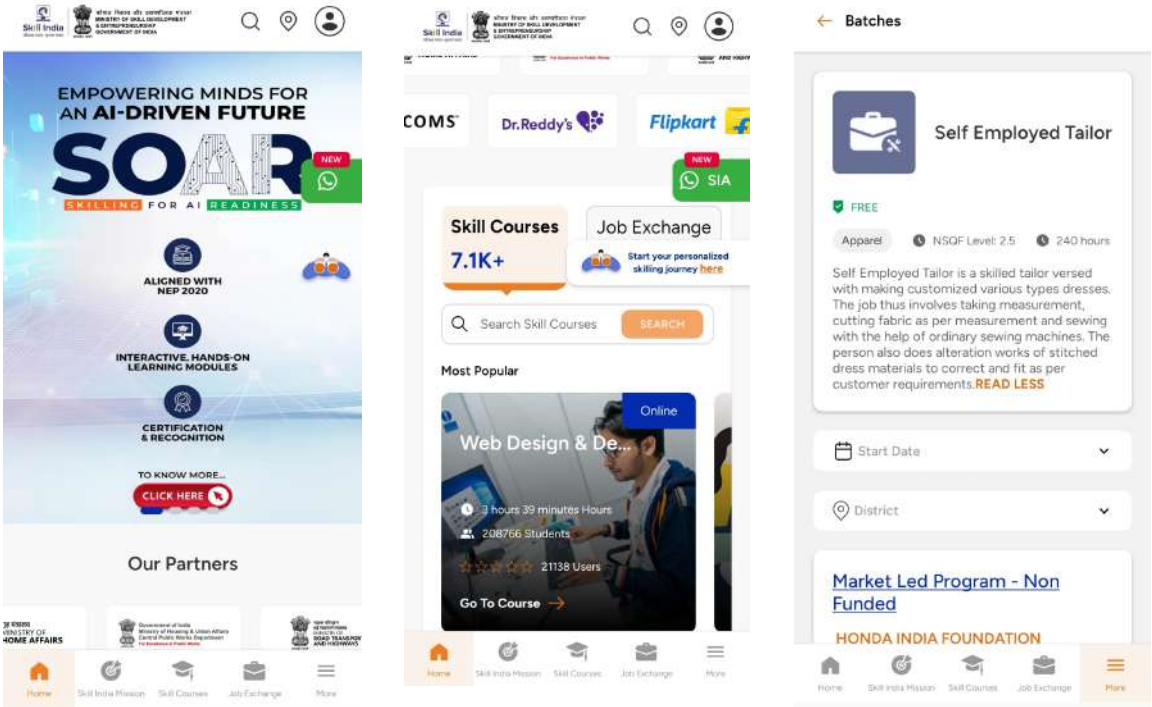


Figure 1: Existing Skill India Digital Hub interface screens. Source: Skill India Digital Hub [25]

3.3 Study Procedure

The study was conducted in two usability-testing phases. In Phase 1, participants interacted with the existing Skill India Digital Hub and performed three tasks of progressively increasing complexity. Level 1 involved recognition of relevant textile or apparel information; Level 2 required interpretation and selection of the appropriate occupational/course pathway; and Level 3 required completion of the multi-step enrolment process. Researchers observed participant behaviour, navigation patterns, requests for assistance, hesitation and errors during task performance.

Observations from Phase 1 were used to redesign selected screens using the Visual Affordance Framework. The prototype was developed in Axure RP 10 and subjected to pilot testing and two rounds of user evaluation. In Phase 2, the same participant group completed equivalent recognition, interpretation and procedural tasks using the redesigned interface. Performance on the existing and redesigned interfaces was then compared using descriptive usability measures. Each session lasted approximately 45 minutes. Testing was conducted using participants' own smartphones. Task instructions were provided verbally in Hindi or Marathi according to each participant's preferred language. Researchers did not intervene during independent task performance; assistance was provided only when a participant explicitly requested help, and each such instance was recorded as a help request.

3.4 Usability Measures

Task completion: Successful completion of the predefined task endpoint without the researcher performing or directing the required navigation step.

Navigation error: A user action that moved away from the intended task pathway, including selecting an incorrect category or course, opening an irrelevant section, choosing an incorrect navigation option, or returning/restarting because of an incorrect previous selection.

Help request: An explicit verbal or gestural request for assistance regarding what to select, where to navigate or how to proceed with the task.

Hesitation: Observable uncertainty before performing an action, indicated by prolonged scanning, repeated movement between options, pausing before selection, or verbal expressions of uncertainty.

User confidence: Observable certainty during task performance, reflected in participants' willingness to proceed without assistance, reduced repeated checking, and fewer verbal expressions of uncertainty. Confidence was treated as a qualitative observational measure rather than a numerical score.

3.5 Data Analysis

Qualitative observation notes and semi-structured interview responses were reviewed to identify recurring usability barriers, including difficulties related to text-heavy content, unfamiliar terminology, search-based navigation, unclear visual cues, uncertainty regarding the next action and insufficient system feedback. These observations were grouped according to the three task-complexity levels: recognition, interpretation and procedural interaction.

Descriptive quantitative measures were used to summarise

usability performance across the existing and redesigned interfaces. These included successful task completion, number of help requests and number of navigation errors. Hesitation and user confidence were interpreted qualitatively from observational records and participant behaviour during task performance. As the study was exploratory and involved a small purposively selected sample, inferential statistical testing was not used. The quantitative measures were used descriptively to support interpretation of the usability observations.

4. Results and Visual Affordance-Based Redesign

4.1 Usability of the Existing Skill India Interface

Participants experienced substantial difficulty completing the required tasks using the existing Skill India interface. None of the 23 less-literate participants independently located the complete required course pathway. Participants frequently scrolled without identifying the appropriate next action, and elements such as the Course tab, formal course titles and enrolment section were rarely recognised. Among the four domain experts, only one partially located the relevant course section but continued to experience uncertainty regarding the appropriate navigation pathway. Observation identified five recurring usability barriers: text-heavy screens, dependence on search-based navigation, formal occupational terminology, insufficient visual guidance and limited feedback regarding the next action.

4.2. Visual Affordance-Based Redesign

The study proposes a redesigned Skill India Digital Hub prototype tailored for less-literate textile and apparel workers. The solution improves course discovery, comprehension, and enrolment by embedding task-linked visual guidance, reducing reliance on text-heavy screens, search-based navigation, and formal terminology. The redesign is based on the insight that workers relate more easily to familiar practical categories than to formal qualification names. The interface therefore organises entry points around recognisable work domains such as stitching, knitting, embroidery, finishing, checking, repair, alteration, touch-up, machine operation, and self-tailoring. This approach eliminates the need to search for formal course titles like Sewing Machine Operator. Knits or Self-Employed Tailor at the outset. The redesign was informed by the Visual Interaction Cues Framework [23], which was adapted in the present study to map progressively stronger forms of visual guidance across three levels of task complexity, as shown in Table 2.

Overall, the framework links task complexity with the intensity and type of visual guidance required. As task complexity increases from recognition to procedural interaction, the interface provides progressively stronger contextual, integrated, and overlaid guidance. This design approach aims to support course discovery, interpretation, and multi-step enrolment among less-literate users.

Table 2: Task-Complexity and Visual-Cue Mapping Framework

Task Level	Task Type	User Challenge	Recommended Visual Guidance	Intended Support
Level 1	Recognition	Identifying familiar icons, work categories, or course cards	**Subtle cues (M1):** light outlines, spacing, minimal contrast; **Emphasised cues (M2):** colour contrast, increased size or visual weight	Supports recognition and directs attention to relevant options
Level 2	Interpretation	Understanding options, distinguishing between choices, and identifying the next action	**Emphasised cues (M2):** highlighted buttons or enlarged imagery; **Contextual cues (M3):** task-state information; **Integrated cues (M4):** embedded guidance connecting related elements	Supports interpretation, comparison, decision-making, and confirmation of choices
Level 3	Procedural	Completing multi-step enrolment, maintaining sequence, and recovering from errors	**Contextual cues (M3):** current-task or active-step indicators; **Integrated cues (M4):** linked steps and next-action guidance; **Overlaid cues (M5):** instructional prompts, progress indicators, or step trackers	Supports sequencing and progression while reducing memory demand and assistance needs

Note: *M1 = Subtle; M2 = Emphasised; M3 = Contextual; M4 = Integrated; M5 = Overlaid.*



(a) Level 1—Recognition *(b) Level 2—Interpretation* *© Level 3—Procedural*

Figure 2: Redesigned Digital Skill India prototype screens: (a) Level 1—Recognition, (b) Level 2—Interpretation, and (c) Level 3—Procedural.

Overall, the framework links task complexity with the intensity and type of visual guidance required. As task complexity increases from recognition to procedural interaction, the interface provides progressively stronger contextual, integrated, and overlaid guidance. This design approach aims to support course discovery, interpretation, and multi-step enrolment among less-literate users.

4.3 Comparative Usability Performance

The redesigned prototype showed a clear improvement in usability performance compared with the existing interface. Successful task completion increased to 19 out of 27 participants (70.4%). At the same time, the number of help requests decreased from 22 to 2, while navigation errors were reduced from 58 to 17. These results indicate that the redesigned interface supported more independent task completion and reduced the need for assistance during interaction.

*One participant partially located the required course pathway but did not complete enrolment independently.

Note: Task completion, help requests, and navigation errors were recorded as descriptive quantitative measures. Hesitation and user confidence were assessed qualitatively through behavioural observations during task performance.

5. Discussion

The findings indicate that the major barriers experienced by less-literate participants were associated with interface demands rather than the availability of digital training content. The existing platform required participants to search for formal course names, interpret textual information and maintain orientation across multiple screens. These difficulties are consistent with previous HCI research showing that text-heavy navigation, unfamiliar terminology and increased cognitive demands can create usability barriers for low-literacy users [14, 15 & 19].

The redesigned prototype produced better immediate usability outcomes. Successful task completion increased to 19 out of 27 participants (70.4%), while help requests

Table 3: Comparative Usability Performance of the Existing Interface and Redesigned Prototype

Usability Measure	Existing Interface	Redesigned Prototype	Observed Change
Successful completion	0 independent enrolments*	19/27 (70.4%)	Substantial improvement
Help requests	22	2	- 90.9%
Navigation errors	58	17	- 70.7%
Hesitation (observed)	Frequently observed	Less frequently observed	Reduced
User confidence (observed)	Lower	Higher	Increased

decreased from 22 to 2 and navigation errors decreased from 58 to 17. These findings suggest that task-linked visual guidance supported more independent interaction with the platform and reduced assistance needs during the usability tasks.

The findings further support the relationship between task complexity and the intensity of visual guidance. Recognition tasks were supported through subtle and emphasised cues, while interpretation required contextual and integrated guidance. Procedural tasks required more persistent and explicit cues to support sequencing and progression. This interpretation is consistent with principles of perceived affordances and signifiers [20] and extends the Visual Interaction Cues Framework [23] to a textile and apparel digital-skilling context.

However, the observed improvements represent **interface usability and immediate task performance**, rather than evidence of sustained digital skill acquisition or learning. Longitudinal evaluation is therefore required to determine whether improved interface accessibility translates into sustained independent use of digital skilling platforms.

6. Limitations and Future Research

The study has several limitations. First, the relatively small, purposively selected sample limits the generalisability of the findings across the diverse textile and apparel workforce. Second, the usability evaluation focused on selected course-discovery and enrolment tasks and therefore does not measure long-term learning, retention or sustained digital skill acquisition. Third, the same participants interacted with the existing interface and the redesigned prototype; therefore, familiarity with the tasks during the second evaluation may have contributed to some improvement in performance. Fourth, the study focused on selected occupational pathways within textile and apparel skilling, and the findings may not apply equally to other job roles, regions, languages or levels of digital experience. Future studies should validate the framework using larger samples across diverse textile clusters and undertake longitudinal evaluation to determine whether improved interface usability results in sustained independent platform use and learning outcomes.

7. Conclusion

The study demonstrates that interface accessibility can substantially improve task performance and support more independent interaction with digital skilling platforms among less-literate textile and apparel workers. Replacing search-based navigation with familiar work-category entry points and task-linked visual cues increased successful enrolment, reduced assistance needs, and supported more independent navigation and task completion.

The findings further indicate that the intensity and type of visual guidance should correspond to task complexity. Recognition tasks can be supported through subtle and emphasised cues, interpretation tasks through contextual and integrated cues, and procedural multi-step tasks through more persistent and overlaid guidance. This task-complexity-based mapping represents the study's principal design contribution and extends the Visual Interaction Cues Framework to the context of inclusive digital skilling for textile and apparel workers.

Designing interfaces around familiar occupational categories such as stitching, tailoring, embroidery, repair, and machine operation, together with local-language and visual guidance, can reduce dependence on text-heavy navigation and support more independent interaction with digital skilling platforms. The proposed framework therefore provides a practical direction for designing more accessible digital skilling interfaces for workers with limited literacy and digital experience.

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Seminar on "COMPOSITES: DRIVING THE RISE OF TECHNICAL TEXTILES"

Rajasthan Unit

The Textile Association (India), Rajasthan Unit organized a seminar on "Composites: Driving the Rise of Technical Textiles" on 26 September 2026 at Hotel Ranbanka, Bhilwara, in association with MLV Textile & Engineering College (MLVTEC), Bhilwara, Mewar Chamber of Commerce & Industries (MCCI), Bhilwara Textile Trade Federation (BTTF), Thriving Engineers Association of MLVTEC (TEAM) and ATIRA, Ahmedabad.

The programme was organized as an important initiative of the The Textile Association India, Rajasthan Unit to create awareness among textile entrepreneurs, industry professionals, faculty members, students and other stakeholders about the rapidly emerging opportunities in composites and technical textiles. It also provided a platform for interaction between the textile industry, academia, technology institutions and professional and trade organizations.

Programme and Participation

The programme commenced with registration and welcome, followed by Saraswati Vandana and lamp lighting.

Dr. Dhirendra Sharma, Hon'ble Secretary, The Textile Association India, Rajasthan Unit, gave an overview of the programme and highlighted the objectives and relevance of organizing the seminar after a formal welcome of the guests and delegates by Prof. Arvind Vashishtha, Principal, MLV Textile & Engineering College, Bhilwara,



The programme was graced by Hon'ble Shri Damodarji Agrawal, Member of Parliament, as the Chief Guest. Shri S. N. Modani, Vice Chairman, Sangam Group, was the Special Guest. Other distinguished participants included Dr. Kameshwar Rao, Assistant Director, ATIRA, Ahmedabad. The programme was attended by Shri Prem Swaroop Garg, Secretary, Bhilwara Textile Trade Federation (BTTF) and Shri R. K. Jain, Secretary, Mewar Chamber of Commerce & Industries, along with representatives of various industrial and professional organizations.The programme was attended by around 100 participants, including textile entrepreneurs, industrialists, technical professionals, faculty members, students and representatives of various industrial, trade and professional organizations.

Technical Session

The technical session comprised three detailed presentations by experts from the Centre of Excellence for Composites, ATIRA, Ahmedabad.

The first presentation, "Composites: Technology to Application," was delivered by Dr. Ankush Sharma, Senior Scientific Officer, COE-Composites, ATIRA. He covered the fundamentals of composite materials, recent advances, their diverse industrial applications and the facilities offered by ATIRA.

The second presentation, "Market Landscape & Business Opportunities for MSMEs," was delivered by Dr. Kameswara Rao P. V., Assistant Director, COE-Composites, ATIRA. His presentation focused on the Indian composite market landscape, emerging sectors, product opportunities for MSMEs and relevant government initiatives.

The third technical presentation, "Composite Manufacturing Technologies: Investment, Capacity & ROI," was delivered by Mr. Bhushan Choudhary, Head – BD, NPD & Operations, COE-Composites, ATIRA. The presentation covered composite manufacturing processes, application-based studies, plant and machinery requirements, investment models, indicative capacity, cost economics, break-even considerations and return on investment.

The technical sessions were followed by an Open Forum on Industry Interaction & Discussion, during which participants raised questions relating to industry opportunities, technological challenges, investment considerations and potential areas of collaboration.

The formal programme concluded with a Vote of Thanks by Dr. Harshvardan Saraswat, followed by a networking dinner, which provided an opportunity for informal interaction and one-to-one discussions among industry representatives, technical experts, entrepreneurs, faculty members and students.

Role of The Textile Association India, Rajasthan Unit
The seminar was primarily conceived and organized as an activity of The Textile Association India, Rajasthan Unit, with the objective of bringing emerging technological developments in technical textiles and composites closer to the textile industry and professional community of Rajasthan.

The Rajasthan Unit has been continuously working towards promoting technical knowledge, professional interaction, industry–academia linkages and awareness of emerging opportunities among textile professionals and entrepreneurs. The present programme was another significant step in this direction.
The collaboration with MLV Textile & Engineering College, Bhilwara, further strengthened the academic and technical dimension of the programme. The College is developing facilities and capabilities in the area of composites, and its faculty members and students are undertaking research and project work in this emerging field.

Industry Opportunities and Future Initiatives
The seminar highlighted the potential of composites as an important component of technical textiles, with applications in automotive and transportation, infrastructure and construction, aerospace and defence, renewable energy, electrical and electronics, sports and industrial equipment, among other sectors.

Particular emphasis was placed on the opportunities available to MSMEs, startups and existing textile industries for diversification into composites and other technical textile products. The discussions also covered technology availability, manufacturing requirements, investment possibilities, market opportunities and government support.

A significant outcome of the programme was the interest expressed by members of The Textile Association India, Rajasthan Unit and other participating organizations in visiting ATIRA, Ahmedabad, to understand its facilities and activities relating to composites and technical textiles. The proposed visit will be worked out and finalized in consultation with interested members and Dr. Kameswara Rao P. V., ATIRA, with the date and number of participants to be finalized subsequently.

The programme was a meaningful contribution towards the objectives of The Textile Association India and its continuing efforts to support the growth and technological advancement of the Indian textile sector.

Mr. R. K. Vij attends various Textile forums meetings

Mr. R. K. Vij, President, The Textile Association (India) and Mr. Madhav Bhageria, MD, Filatex India, Mr. Debdatt, CEO Garden Silk Mill attended PM Mitra Park meeting with Hon'ble Giriraj Singh ji, Centre Textile Minister, Govt. of India, Add. Textile Secretary Mrs. Aarti Kanwar in Surat on 10/10/2026 with other industry leaders from Gujrat and Maharashtra.






He attended FICCI Conference, Office of the Ministry of the Textiles, Govt. of India.

Seminar and Workshop : Khadi & Upcycling 2026

The "Khadi & Upcycling 2026 – Seminar and Workshop" was organised by Alumni Association of College of Home Science Nirmala Niketan & Anveshanam oundation on 26th September 2026 at the Marie Adelaide de Cice College Hall, College of Home Science Nirmoala Niketan, Churchgate. The programme brought together participants interested in Khadi, upcycling, micro-enterprises, handmade products, natural personal care and traditional hand-spinning techniques.

The event was attended by more than 75 participants, including staff, students, aspiring entrepreneurs, professionals, media partners and individuals interested in developing skills into sustainable livelihood opportunities.





The other dignitaries were Ms Noella Dias, Prescilla Pinto, Minal Savla, Sharvari Kalantre, Shreedevi Poduval. The photography and videography was covered by Niyati Mota.

The organizing partners of the event were NIF Global, Ghatkopar, Mumbai, Gnanajyoti Community College, Karajgaon and Raj Institute of Fashion Designing. The media partners were Textile Jagat, Journal of the Textile Association and Textile Value Chain.

Seminar: Khadi and MSME – Micro Enterprises

The seminar session was conducted by Dr Ela Dedhia, Director, Anveshanam Foundation and Managing Trustee, AACHSNN.

The session covered several practical aspects of converting skills and ideas into viable micro-enterprises. The key topics included:

- Emerging trends in Khadi,
- Understanding micro-enterprises,
- Identifying a viable business idea,
- MSME registration – its importance and the registration process,
- Government schemes and support available for entrepreneurs,
- Basic business planning and marketing,
- Product costing and pricing,
- The journey from skill → product → market → income

The session particularly highlighted how traditional skills, sustainable practices and innovative product ideas can be developed into small-scale entrepreneurial opportunities.

Demo & Hands-on Workshop on Handmade Fabric Jewelry making was conducted by Rabia Banu and her team of 4 women and Aburkani Mohommad, associated with the Self Help Group of Anveshanam Foundation, and Dhara Padia, Founder, Mitti N Metal. The kit was provided to the participants.

Participants were introduced to creative ways of using pre consumer waste fabric and other materials to develop attractive jewellery products. The session demonstrated how waste and leftover materials can be transformed into value-added lifestyle products with potential for sale and income generation.

The activity also connected the concept of upcycling with entrepreneurship, showing participants how simple skills can be developed into marketable products and sold nationally and internationally.

Hand Spinning – Demonstration & Hands-on Session was conducted by Usha Trikmaniji and Rajashri Chocheji. Participants were introduced to the traditional process of hand spinning on Takli and hand charkha. All participants had an opportunity to understand and experience the hand technique.

The session helped create awareness about the significance of hand spinning in the Khadi tradition and its continuing relevance in the context of sustainable and handmade textiles.

Display and Sale of sustainable Upcycled products made by women Self Help Group of Anveshanam Foundation, the differently abled benefiaries and care takers of SVRR and Vaitarna at the event. Thus display and promotion of handmade, sustainable products added a practical marketplace dimension to the seminar.

This component also complemented the central theme of the programme by connecting skills and creativity with product development, presentation and potential market opportunities.





Key Highlights

The programme successfully brought together knowledge sharing, demonstrations, hands-on learning and entrepreneurship awareness under one platform.

Some of the major highlights were:

- Participation of 75+ attendees
- Awareness about current Khadi trends,
- Practical introduction to micro-enterprise development and MSME registration,
- Information on government support and schemes for entrepreneurs,
- Hands-on exposure to fabric jewellery making,
- Demonstration and hands-on experience of traditional hand spinning.
- Stalls for product display,
- Focus on upcycling, sustainability and livelihood generation,
- Interaction between participants, trainers and emerging entrepreneurs.

Conclusion

Khadi & Upcycling 2026 – Seminar and Workshop provided a meaningful platform for participants to explore the connection between traditional textile practices, sustainability, creativity and entrepreneurship. The programme emphasised that skills can be transformed into viable products and enterprises when combined with appropriate planning, costing, marketing and market access.

The event also reinforced the importance of upcycling and sustainable product development as avenues for creativity, responsible consumption and livelihood generation. The participation of more than 75 individuals reflected the interest in practical hands on learning and new opportunities in the fields of Khadi, handmade products and micro-enterprises.

Change of Leadership at Rieter

Thomas Oetterli has decided to step down from his function as CEO, effective October 31, 2026, and hand over the Chairmanship of the Board of Directors. "After the successful implementation of the Next Level performance program, the structural measures initiated to consolidate the sites and the acquisition of Barmag, the time has come to hand over responsibility to new hands," explains Thomas Oetterli.

The eventual separation of the functions of CEO and Chairman of the Board of Directors was planned since Thomas Oetterli took office.

The Board of Directors thanks Thomas Oetterli for his great commitment and his important contributions to the strategic and operational development of Rieter. It is convinced that the measures initiated will strengthen the competitiveness of the Group and create a solid foundation to benefit from a future market recovery.

Daniel Lippuner will take over as CEO of Rieter on November 1, 2026. He combines broad international leadership experience with in-depth knowledge of the textile machinery and components industry. As former CEO of the Saurer Group and previously as Head of Oerlikon Textile Components, he led businesses along the value chain of spinning machines, yarn processing and textile components. As Chairman of the Board and co-owner of Heberlein Technology, he also remained closely connected to the chemical fiber industry. His experience in transformation, technology and quality management, operational leadership and Asian markets is particularly relevant for Rieter with its established short-staple fiber business and the newly acquired man-made fiber business.

Carl Illi will assume the role of Chairman of the Board until the next Annual General Meeting on April 14, 2027. Carl Illi has been a member of the Rieter Board of Directors since 2017 and is a recognized textile industry expert.

With the acquisition of Barmag in February 2026, Rieter has expanded its traditional business focused on short-staple fibers to include the attractive man-made fibers segment. The transaction strengthens the focus on the technology leadership of the Rieter Group, opens up additional growth opportunities and creates a broader basis for digital solutions in the textile industry.

Forthcoming dates

Investor Update 2026 October 28, 2026
Results press conference 2027 February 24, 2027
Deadline for proposals regarding the agenda of the Annual General Meeting March 3, 2027
Annual General Meeting 2027 April 14, 2027
Semi-Annual Report 2027 July 20, 2027
Investor Update 2027 October 27, 2027

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KARL MAYER Product Show in Changzhou 2026

KARL MAYER Product Show in Changzhou 2026: Three Highlights, One Event

Exclusive machine premieres, textile innovations, and expert discussions during ITMA ASIA 2026

During ITMA ASIA 2026, KARL MAYER will not only welcome visitors to its exhibition booths in Shanghai but will also showcase additional innovations in the fields of WARP KNIT, WARP PREP, and TECHNICAL TEXTILES at a product show held at its Changzhou location from 19 to 21 November and on 23 November 2026. Visitors will experience exclusive new machines live in action and discover how the Textile Innovation Center (TIC) is driving the development of new textiles with high market potential. They will also have the opportunity to discuss current challenges with experts in individual workshops and consultation sessions.

With this format, KARL MAYER is once again underscoring its close ties to the Asian markets. The Product Show demonstrates how the company translates market requirements into innovative machine and textile solutions, delivering measurable customer benefits and tapping into new business potential.

Experience World Premieres under Production Conditions

Several machines are in operation in Changzhou; these are being unveiled for the first time in Asia and can be seen exclusively in Changzhou. Visitors can observe the entire manufacturing process under real production conditions, directly assess machine performance, and form their own impression of productivity, process stability, and product quality.

Innovative Warp Knitting Machines for Lingerie, Sportswear, and Athleisure

KARL MAYER presents a range of innovative machine solutions for manufacturers of functional lingerie, high-quality performance sportswear, and sophisticated athleisure products.

These include the HKS 4-S EL in 290", which is setting new standards for speed and flexibility in the market for four-bar short-stroke warp knitting machines. With its E 36 gauge, it is the finest KARL MAYER warp knitting machine with four guide bars. The fabrics it produces stand out for their premium look and feel.

Another highlight is the RASCHELTRONIC® RJ 4/2 EL in E 32. Its combination of high efficiency and versatile patterning makes it particularly appealing to brands and manufacturers prioritising functionality in lingerie and athletic performance and aesthetics in sportswear. The E 32 fabrics in particular, with their elegant, clean appearance and cool touch, give customers a genuine edge in the market. In addition, KARL MAYER is introducing a TM WEFT with targeted enhancements for the fashion industry. A finer gauge, an EL pattern drive, and intelligent yarn tension control improve fabric quality and expand the range of applications for this established warp knitting machine with weft-insertion.

New Prospects for the Footwear Industry

The footwear industry will be particularly interested in several public world premieres of machines in the field of double-raschel technology. With its three Jacquard bars, the new RDJ 7/3 opens up completely new possibilities for patterning. It enables nearly perfectly round and larger openings in hole designs, precisely differentiated functional zones, creative multicolour designs, and surfaces with multidimensionality and embossed effects. Also making its debut is an RDJ 6/2 in the new E 32 gauge. The machine produces spacer fabrics with an exceptionally soft handle, incredibly fine structures, and particularly smooth surfaces. The fabric's homogeneous look and a delicate design are certain to impress.

New Efficiency for Composite Applications

Manufacturers of technical textiles will also benefit from the innovations in Changzhou. Highlights include a new high-performance composite machine for the production of biaxial non-crimp fabrics. The design is specifically tailored to the needs of Asian producers, particularly in the wind energy sector. Its strengths include exceptionally high productivity, smooth running, and an intelligent operating concept that boosts efficiency in day-to-day production.

Textile Innovation Center: Inspiration for New Business Opportunities

The Textile Innovation Center (TIC) helps customers discover new business opportunities and turn innovative textile ideas into market-ready solutions. In addition to the latest machinery developments, it is another highlight of the Product Show.

Across approximately 480 m², KARL MAYER presents an exclusive selection of current textile innovations and trend themes. The exhibition demonstrates how new ideas can be translated into marketable products – and the potential that modern textiles hold for a wide range pf markets.
The TIC focuses on:

- woven-like knits
- athleisure innovations
- functional sports textiles
- stylish shoe uppers
- items made from natural fibres

In addition, visitors will gain insights into current developments in the fields of fashion & apparel, lace, home textiles, and technical textiles.

Solutions for Today's Challenges

The Product Show is not just a platform for innovation, but a place to collaborate on solutions for current challenges in production and the market, including:

- expanding production capacity
- manufacturing small batch sizes cost-effectively
- developing differentiated materials and textiles
- increasing cost efficiency
- implementing sustainable production concepts.

Specialists in machinery, processes, textiles, and end-use applications will be on hand to provide guests with in-depth technical discussions, workshops, and technical consultations on these topics.

Plenty to Discover in Shanghai, Too!

KARL MAYER's presentation at ITMA ASIA in Shanghai will also feature exclusive world premieres and practical innovations. New products for WARP PREP will be on display in Hall 3, Booth A24. The company will present additional machine innovations and textile developments for WARP KNIT in Hall 4.1, Booth C18. By combining its trade show presence with a product show, KARL MAYER is offering the Asian textile industry a unique opportunity to see how new technologies can translate into tangible business success.

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LIVA's Tag Check Kiya Kya campaign

LIVA's 'Tag Check Kiya Kya?' campaign urges consumers to check the fabric tag before they buy.

The campaign highlights the importance of checking fabric labels to make informed fashion choices, reinforcing LIVA's focus on transparency, fabric authenticity and conscious consumer awareness.

Liva, a premium fluid and natural fabric offering from the house of Birla Cellulose, has launched 'Tag Check Kiya Kya?' their latest campaign. The unique concept encourages consumers to look beyond the garment's appearance and check fabric labels before making a purchase, empowering them to make more informed and safe choices about the clothes they wear.

As a pioneer in Fabric innovation, Liva continues to shape the fashion landscape by championing a more discerning approach to fashion choices. Through a distinctive new campaign, brought to life by a compelling Ad film, the brand places the spotlight on an often-overlooked yet essential detail in the shopping experience – the Fabric tag. The signature pink Liva tag serves as a mark of authenticity, enabling consumers to identify garments crafted with Liva fabrics. Through this engaging narrative, the campaign aims to build awareness around the significance of checking garment labels and encourage shoppers to make it- an essential part of their shopping routine while championing greater transparency, consumer awareness and confidence in fashion choices.

Commenting on the campaign, Mr. Sreecharan, Vice President, Global Head – Brand Marketing, Birla Cellulose, Aditya Birla Group, said, "While checking a garment tag may seem like any simple step, but it can help consumers make more informed decisions about their purchases. Through this campaign, we hope to turn this small action into a conscious shopping habit and encourage consumers to be more mindful of the clothes they choose to wear."

The 'Tag Check Kiya Kya?' campaign aims to create awareness amongst consumers through a simple yet memorable tagline. The campaign is live across Liva's digital platforms, including YouTube and Instagram, to reach a wider audience and drive greater consumer awareness.

THE TEXTILE ASSOCIATION (INDIA)

Professional Award Committee

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The Textile Association (India) recognises and honours textile professionals for their outstanding contributions through innovation, industrial development, promotion, research, training, manpower development, and other allied activities related to the textile trade and industry.

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The Association offers prestigious recognitions to members who have made significant contributions to the textile trade and industry:

- **ATA – Associate Textile Association**
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- **M. TEXT. A – Member Textile Association**
  Direct recognition for professionals who have contributed to the growth and promotion of the textile industry through R&D, manufacturing, training, and development, particularly those working in middle-management positions.
- **FTA – Fellow Textile Association**
  The highest level of recognition for members who have made significant contributions to innovation, industry promotion, and manpower development in the textile field.

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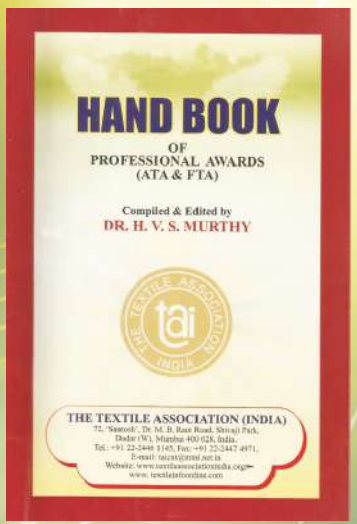
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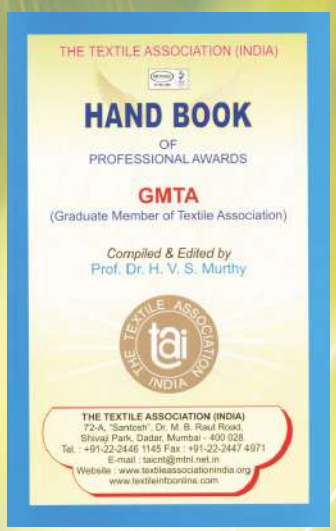
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