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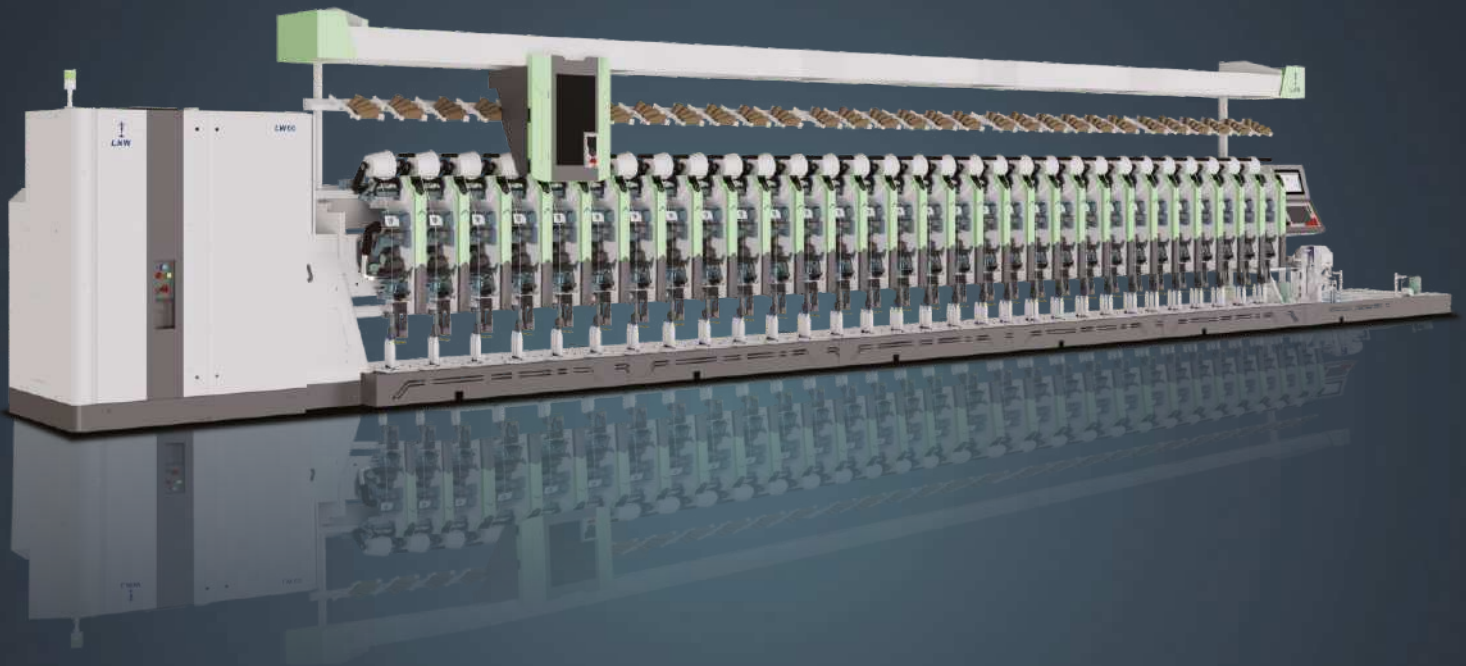
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Threads of Resilience Amidst Global Conflict

Dear Readers,
Greetings!!

Threads of Resilience Amidst Global Conflict

In 2026, the textile industry continues to play a major role in India's economy, particularly in employment, exports, rural development, manufacturing, and sustainable growth. The sector is increasingly shifting from traditional textiles to technical textiles, man-made fibres, smart textiles, recycling, and high-value manufacturing. For the Support of manufacturing and investment, the Union Budget 2026–27 placed textiles at the centre of India's manufacturing strategy. It introduced an integrated approach covering fibres, manufacturing, apparel, technical textiles and traditional textile sectors. The PM MITRA parks, for example, are intended to create integrated manufacturing ecosystems and generate substantial direct and indirect employment.

One of the most important changes in 2026 is the movement toward technical textile materials designed for specific functions rather than simply clothing. These include textiles used in healthcare, automobiles, construction, agriculture, sports, defence and protective equipment. Government policy is increasingly encouraging MMF and technical-textile production.

Recently, Bharat Tex 2026, the third edition of India's flagship global textile and apparel exhibition, was held from 14–17 July 2026 at Bharat Mandapam, New Delhi. Bharat Tex 2026 was more than a traditional trade fair. It served as a global B2B platform for Indian textiles, connecting manufacturers, exporters, international buyers, designers, technology companies, investors and policymakers. Its strongest message was that India's future textile competitiveness will depend not only on volume and low-cost manufacturing, but also on quality, sustainability, innovation, technology and value-added products.

Thus, the textile industry in 2026 serves as a bridge among agriculture, manufacturing, employment, exports, technology, and sustainable development in India.

With best wishes,

Dr. Aadhar Mandot

Hon. Editor

Journal of the Textile Association



R. K. VIJ, President

Growth of Indian MMF Industry

Next couple of years look positive for Indian MMF Sector with better margins. Following are the reasons:

- There are no major expansions in pipeline. Even today, if someone plans to produce fibre, filament, yarn then it will take next three to four years of commissioning the plants.
- China is going out from the low margin products, mainly in textile. Also, the cost of production in China has increased. So, the export of cheaper Chinese yarn, filament, fabric into India will be less.
- Indian cotton production for the last four to five year is coming down and in the next season also, production will be lesser as the overall hectarages has reduced.

World over, the total hectarages of cotton have also reduced. This will increase cotton prices in time to come. Cotton demands are increasing every year. So, the demand of cotton will be more, but supply will be less.

The closing stock of cotton by the end of July 2027 will be 5 to 6% lesser than the current year which means the total availability of cotton will be lesser as compared to this year.

- The growth of MMF fibre, filament, yarn is around 6 to 7% in India even during the difficult times. This growth will remain same or more for the next few years which means more local consumption of MMF fibre, filament, yarn. Indian Government understood that if we have to give more jobs to the country's youth, we have to concentrate on the textiles, mainly on MMF which is growing world over. So, the Government has come up with PLI Schemes 1, 2 in MMF. The Government is planning to bring PLI – 3 to promote small scale garment units so that our exports should grow. The Government should also re-introduce TUFS to strengthen production.
- If the Government shifts Manufacturers of PSF, POY, FDY, IDY under textile ministry then growth of MMF will be much faster as all these products are 100% used in the products under Textile ministry. A common policy will be made for all products used in textile growth in India.
- The development work of 7 PM Mitra Parks have already started and in next one to two years, these parks will be fully developed and ready for the new units.
- Indian Government is also promoting Technical Textiles where mostly MMF filament, yarns are being consumed. So, this will also increase the consumption of MMF.
- FTA with the United Kingdom has already been implemented and we hope that FTA with EU will also be implemented by end of this year or early next year. With this, Indian textiles export markets will grow much faster, and we can get back lost market of last 20 years after dismantling the MFN in 2005 which had given gain to LDC countries like Vietnam, Bangladesh, Laos, Cambodia
- From 24th July 2026, USA has kept India and Bangladesh at 10% Tariff and Vietnam, China which are the major exporters of textiles at 12.5% Tariff rates. Trade Agreement with USA is also under negotiation and we hope that the present tariff will be reduced, may be to 5% if not Zero.
- By the end of this year, the new PTA plants of GAIL will be commissioned, and IOCL plant is expected by end of 2027 or first week of 2028 with production of approx. 2.4 million Metric Tons per annum. RIL is also expanding PTA capacity by 3.2 million Metric Tons per annum by 2028/29. So, PTA will be sufficiently available in India which is at present in short supply. With the availability of PTA, growth of downstream MMF will also increase and we will be more competitive both in domestic and export markets.

Challenges industry is facing at present:

- **Capital Goods ITC Blockage: Composition of the Rs. 160 Crore in a new plant of Rs.750 Cr. :** For a representative 600 TPD greenfield PFY plant, the total project investment would be Rs. 1,500 Crores. Of this, approximately 50% (Rs. 750 Crore) represents the cost of machinery and equipment, and a further 10% (Rs. 150 Crore) covers project-related services such as architecture, engineering, and service fees. Both categories attract GST at 18%, generating a combined upfront ITC of ~Rs. 160 Crores on day one of commissioning. This GST is creditable in principle, but it cannot be used and cannot be refunded under the present structure. It therefore converts from a recoverable tax credit into a permanent addition to project cost.
- **What the project cost is made of** A greenfield PFY project splits into three cost blocks, each with a different GST treatment:

- **Machinery and equipment (50% of capex, Rs. 750 Crore):** spinning lines, draw-winding, extrusion, utilities and balance-of-plant equipment. These attract GST at 18%, generating an input tax credit of Rs. 135 Crore.
- **Project services (10% of capex, Rs. 150 Crore):** engineering, design, architecture, erection, commissioning and professional fees. These attract GST at 18%, generating an input tax credit of Rs. 25 Crore.

Table: Capital Goods ITC Composition, Representative 600 TPD PFY Plant

Cost block	Share	Capex (Rs Cr)	ITC at 18% GST (Rs. Cr.)	ITC Status
Machinery and equipment	50%	750	135	Blocked
Project services (engineering, design)	10%	150	25	Blocked

- **Why the credit is permanently blocked :** The blockage arises from the simultaneous failure of both recovery routes:
- **No offset route:** the plant sells PFY at an output GST of 5%. The credit on raw materials (PTA and MEG at 18%) already exceeds the output liability several times over, so output GST is fully absorbed by raw-material ITC. There is no residual output tax left against which the Rs. 160 Crore of capital goods credit can be set off.
- **No refund route:** the inverted duty refund under is restricted to ITC on input goods. The Rs. 160 Crore therefore has no path back to the manufacturer.

With neither offset nor refund available, the credit is stranded indefinitely.

- Under the pre-GST CENVAT regime, blocked capital goods credit was refundable within three years; the present framework offers no equivalent relief. So, please see after the GST implementation, there was no new plants came and there are no new plants are in pipeline. So, if we have to create more jobs, then we have to put more new plants / expansions which is only possible once the Government comes out with refundable scheme for the capital goods blockages. We are sure to achieve USD 350 Billion textile trade target by 2030/31 if the Government comes with some above refundable mechanism as soon as possible.
- The MMF Industry is also following up with the Government to reduce Customs Duty on Cotton, PTA and MEG for the next two to three years till the time products are available at international prices. Because at present the downstream users' industry is getting Rs.5.0 to Rs.6.0 per kg costly PTA / MEG as compared to international prices. Thailand, Vietnam, Malaysia, Egypt, Taiwan import PTA at 0% Customs Duty whereas India imports at 5% Customs Duty.
- At present the whole textile industry is fragmented. So, once the large companies come within the cluster, growth in the sector will be there as most of the facilities will be commonly used which will reduce the cost of production and produce high quality textile products which at present is not there even after we are having lesser wage bills compared to other countries including China to compete in the international markets.
- More production and better qualities also offset the higher wages in foreign countries and so they still can compete in the international markets.

Way forward

- (1) Manufacturing to increase in India for more production / jobs.
- (2) We have to increase the scale of industry to reduce cost per unit and better quality
- (3) Focus on garment industry for more value-added exports.
- (4) To take the benefit of FTAs for increased focus on exports and Joint Ventures with Foreign Companies.
- (5) To spend on R & D by the industry owners.
- (6) To go for Artificial Intelligence for fast decisions and reduction of cost.

Looking to the above points, we hope that we will not miss the bus this time and the MMF sector will grow and the industry will have good margins.

R. K. VIJ

National President

The Textile Association (India)

A Review of Lightweight Functional Fabrics for Coastal Apparel

Gunalaxmi Gaitonde, Bhawana Chanana*

Amity School of Fashion Technology, Amity University Mumbai, Pune Expressway, Bhatan, Post-Somathne,

Abstract:

The coastal societies are surrounded by water, and especially in the tropical zones, they have high humidity. The dressing practices of the coastal community are influenced by many factors, high salinity, continuous staying in and out of water due to their livelihoods, like fishing or boating. These people prefer a breathable fabric; some of these are locally made in natural fibres. Due to high heat during the daytime the people prefer simple silhouettes in a minimal clothing style. In time, tourism has changed the dressing cultures of these regions. A new category of ensembles called resort wear emerged due to this trend. A reinterpreted version of traditional attire appeared on the scene as resort wear, souvenirs or comfort clothing for tourist consumption. Due to a global design aesthetics of resort wear, it encouraged standardisation and a hybrid style. This study examines the traditional fabrics and changes in dressing in coastal areas and the factors leading to this change. The influencing factors are environment, cultural norms and tourism. As the world has become smaller and tourism has increased, the coastal dressing has changed its style, which has evolved between tradition and modernity. The emphasis on genuine local goods is on rise, and the market demands need to be satisfied, where socio-cultural transformations have taken place within coastal communities.

Keywords: Coastal communities, Coastal fabrics, Cultural continuity, Textile characteristics, Textile traditions

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1. Introduction

The coastal region of the world has beautiful beaches and seashores. Coconut and banana trees grow there. The weather is highly humid, saline air, heavy monsoon rainfall, and temperatures ranging between 30 to 40 degrees Celsius. The human living patterns are directly affected along with livelihoods, and clothing culture. The countries which fall between the tropic of Cancer and the tropic of Capricorn are known as tropical countries. This has resulted in shared cultural patterns across coastal communities in different countries such as Coastal India, Southeast Asia, East Africa, the Caribbean, and parts of South America. The people living there also have similar lifestyles. Their main occupation is fishing alongside other maritime activities. Their food culture is pescatarian, with rice and coconut-based curries and sauces. This zone also has a very heavy monsoon. During this period, the people of this region prefer trade or other activities. As the rain ebbs, the tourists begin to come over, and the cycle begins all over again. This research intends to analyse the dressing patterns and the fabrics used in coastal communities and see a pattern emerge during the process of this research. Tourism and a global exposure have changed the patterns of traditional dressing in these coastal communities. The paper aims to study the fabrics that are produced along the coastline and analyse how coastal dressing patterns have evolved and the factors influencing this change.

1.1 Coastal Environment and Its Influence on Dress

The climate along coastlines around the world is characterized by high temperatures, intense humidity, seasonal monsoons, and saline air, which is a tropical climate. These conditions posed challenges such as discomfort, fungal infections, and fabric deterioration. The coastal communities prefer wearing clothing that is minimalistic without compromising on modesty or cultural norms, in accordance with cultural norms that varied across different historical eras. The fabrics used in the coastal areas were quick drying. They wore drapes and simple garments that allowed ventilation in these humid areas. We often think earth in terms of its land area, but 71% of the Earth's surface is covered while only 29% is land [1]. The beaches are within the torrid zone of the Earth, where the sun shines throughout the year. The ocean is warm to swim in the torrid zone. The climate influences the dressing. The high temperatures, the intense humidity and the salinity are the characteristics of the tropical climate. These weather conditions pose challenges to coastal communities, and hence the dressing style is developed keeping these aspects without compromising on modesty or cultural norms. The traditional dressing practices allow fabrics to have good sweat absorption, ventilation and not body-fitted silhouettes to allow breathability to the clothing.

2. Traditional Fabrics of Coastline

The textiles production on coastal areas was community based. Cotton is a fabric, that was worn by the coastal communities. It was cultivated in regions near the coast, and it is hand spun.

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2.1 Cotton

The textile that is most used in the world is cotton. The cotton production dates back to almost 4000 BC in India and Mexico. The oldest cotton fabric ever found to date is in Huaca Prieta in Peru which is even dated to around 6000 BC! [2]. Indian weavers, since ancient times had mastered the art of weaving exquisite fabric of cotton Indian farmers domesticated cotton and developed the technology to weave it at least seven thousand years ago, the cotton thread dating from 5,000 BCE was found in modern Pakistan, in Mehrgarh [3]. This fabric was originally woven on pit looms. The cotton fabric is durable, soft and comfortable, but the most important feature as a fabric for the coast is that it is porous and sweat absorbent and is ideal for humid conditions. Natural dyes derived from plants, minerals, and marine sources were used to colour textiles. Indigo, turmeric, myrobalan, and iron-rich mud were commonly employed, producing earthy and climate-appropriate hues. Kunbi fabric is also a checked cotton fabric from the state of Goa on the western coast of India, it is a traditional fabric used by the farmers and the fisherfolk. A sustainable fabric and dyed with a local jani fruit, iron ore and rice starch. The production of this indigenous fabric was banned during the Portuguese era. There is a slow revival of the fabric due to the initiatives by the government along with locals.

2.2 Chintz

Cotton textiles developed over a period. Chintz was either printed or painted, with the former being done at workshops along the western coast of India [4]. Chintz that is hand-painted is called usually as kalamkari; it was made on the southeastern coast of Masulipatnam (now Machilipatnam). This name is derived from the Hindi word "chint" which means spotted. It is the Indian chintz, though (which used the innovative technique of dyeing cotton naturally with permanent colours), that earned itself the tag of having 'changed the worlds [5]. India has mastered the art of cotton spinning and weaving. Indians also have learnt the technique of patterning fabrics with natural dyes. As per Rosemary Crill, these were named as Chintz or Indian Chintz. These cotton fabrics were hand-painted fabrics with mordant and resist using natural dyes. These were made by natural dyes, Indigo, madder, and Chay. Indian chintz is characterised by its printed or painted floral designs and vibrant, durable colours [4]. The other kind of Chintz is kalamkari, where Kalam means pen and kari means art. Srikalahasti is famous for kalamkari art, the textiles are literally painted on cotton with pens made from bamboo, in the Machilipatnam style, blocks and kalam are both used [6].

2.3 Indigo-Dyed Cottons (Western and Eastern Coasts)

Indigo plant is native to India and is grown on both the east and west coasts. It is known as blue gold and its cultivation which traces back to 2500 BCE.

As Indigo was produced in the coastal belt, Indigo-dyed cottons were easily available along coastal India. The maritime trade routes took these indigo dyed fabrics to Europe, making them a sought-after fabric. The blue shade of

Indigo helped the fisherfolk to conceal stains during their fishing expeditions and salt-making processes. Not only did it concealed stains but also resisted fading in sun and salt exposure.

2.4 Calico

The southern coast of India produces Calico textile even today. It was produced in Kozhikode (Calicut) in the 11th century CE. Calico is, a coarse, unbleached cotton fabric, sometimes even including bits of cottonseed husks. Calico fabric was printed with Indian designs that were big and bold, was imported to England as early as 1630 [7]. The word Calico means 'typically plain white or unbleached' fabric similar to muslin. [8]. The properties of this fabric are durability, breathability, and it is inexpensive. Calico was used for everyday garments, underlayers and utilitarian clothing. It was especially strong, as it was frequently washed and in heavy usage in coastal occupation.

2.5 Kasavu Cotton

Kasavu textile from Kerala is a sustainable unbleached cotton. It is slow fashion and has a history of handloom weaving. The people of Kerala value it for its understated elegance. It has a subtle grace with its cream body and a gold or zari border and is associated with Kerala's coastal culture. The thin gold border reflects ritual purity and status. This breathable cotton fabric is always in cream colour. This fabric is perfectly suitable for the humid conditions of Kerala. This is an environmentally friendly fabric and has a ceremonial significance. The word "kasavu" means, the beautiful zari embroidery that adorns the border of the saree, which is made from fine gold or silver threads [9].

2.6 Madras Checks (Coromandel Coast)

Madras checks as the name suggests were originally produced along the Coromandel Coast in and around Madras (Chennai). This is a coastal material suited for a hot, humid climate, influenced by the climate and the dressing. It is a lightweight cotton material made in different coloured checks. And woven on pit looms. Vegetable dyes, along with indigo dye, were used to make Madras checks. Initially, the yarns were carded by hand and had visible slubs. Its slubs creates imperfections within the weave, a characteristic of handmade work, are what give the fabric its distinctive texture [10]. The bright coloured checks are associated with summer. Indigo is one of the main dyes in these checks. It is a breathable and lightweight fabric and is perfect for the coastal climate. In the village of Madraspatnam in 12 century CE the peasants of the Coromandel coast wore this fabric as a lungi, a drape tied around the waist by men.

3. Other Yarns and fabrics used by coastal communities.

There are many other bast fibres used by these communities for everyday products that are produced from locally available trees.

3.1 Coconut Fibre

India has a long coastline, and coconut trees grow on the shores of these coastlines. This is a natural fibre, and the fibre

of the coconut has many uses from household items to coir. The use of coconut fibre dates back over 2,000 years which is known as coir. Coconut fibre stands out as a sustainable, versatile, and durable natural fibre with a rich history and numerous applications [11]. Coconut fibre is used to make bags, mats, coir beds and coir Geo- Textiles.

3.2 Banana Fibre

The banana stem is a pseudo stem, that looks like a stem and the fibre is obtained from this stem of banana plant. The stem is a waste product of banana cultivation as the stem needs to be cut after fruiting. This pseudo stem produces fruit only once and dies; therefore, it is cut without any additional cost.

The fibres extracted from the stalk after harvesting the banana fruits are found to be stronger than those extracted before harvesting the fruits [12], it's mainly made in India, and many manufacturers in this country focus extensively on sustainable and organic practices [13]. This fibre has many uses. Banana fibre is an ecofriendly fabric and is also a sustainable fabric. It is used to make fabrics, paper, home décor and industrial materials. It is also used as a thread to tie and make floral articles like gajras and venis in coastal areas.

3.3 Palm Fibre

Palmyra trees don't need any special care and grow well in the coastal areas, as the coastal conditions are conducive to their growth. The fibre is extracted from the leaves of this tree. This use of this fibre from the Palmyra tree has been in use since pre-historic times; it is called palmyra fibre. This fibre is extracted from the leaf of Palmyra trees. It is a natural fibre. The leaves of palm trees are used for shelter by weaving them together. Many decorative craft forms can be made by weaving the fronds of the palm tree. These leaves were also used as manuscripts to preserve the story from mythological events [14].

4. Silk and Ritual Textiles

The Indian people love silk fabric. It is an important fabric for them, as it is said in Indian scriptures, that silk fabric has natural properties to absorb and transmit positive energies. All religious scriptures of Hinduism, Islam, Christianity or Buddhism do find a mention about silk, connecting this holy fibre to their eschatology [15].

In many coastal societies, cotton was preferred to be worn for everyday wear because of the humid climate. However, silk is still worn in India for ceremonial, festive, and ritual garments. Silk sarees and shawls are warm during religious ceremonies in coastal regions like Goa, Malabar coast and Coromandel coast. Elite merchant communities and temple traditions often used silk fabrics to signify status and prosperity.

4.1 Silk–Cotton Blends for Coastal Climate

To adapt silk to humid coastal environments, weavers developed silk–cotton blends. These textiles maintained the sheen and prestige of silk while becoming lighter and more breathable for tropical climates. this is also cheaper than pure

silk. Such blended fabrics were commonly traded through ports and circulated in coastal markets.

5. The dressing style of the coastal people

Coastal people traditionally wear minimalistic clothing. Every day, coastal attire emphasised simplicity, comfort, and adaptability. The reason is the hot and humid climate, and hence, they perspire more. These people wear sarongs, lungis, short knee-length dhotis and mundu. Men wore these without an upper garment. When needed they carried a light cotton cloth draped over the shoulder. The fishermen also tied headcloths to protect against the sun and sea spray. The women wore short nine yards, sarongs and simple wraps which were paired with a breast cloth or a short choli. Some of these attires are worn even today. These dressing styles depended on the region and community. Most of these clothes were made from fabric that was dark in colour or undyed to mask stains. Since most of these were draped and not tailored, they could be easily washed, dried and reused. They were required to be frequently laundered due to humidity and physical labour. Therefore, cotton textiles were preferred over any other fabric

5.1 Impact of maritime trade and colonial encounters

Maritime trade in the Indian ocean during 1500 – 1700 CE, played an important role in shaping the coastal textiles and contemporary fashion through centuries of exchange between India and other parts of the world. When the British East India Company and the other European explorers came to India, these fabrics became prized possessions. The coastal regions of India, the Coromandel Coast, Malabar Coast, and Goa were major centres where textiles, and clothing practices were taken to different countries through maritime networks. Textiles such as cotton textiles, indigo, silk, spices, and precious stones were exported from India to Persia, the Ottoman Empire, and the Arabian Peninsula. Even today, we see chintz, soft mulmul dresses and calico from India in British Museums as costume displays becoming commodities in international fashion systems.

The mango motif of India is known as paisley when the Manchester began manufacturing chintz in U.K. as India was ruled by the British, Portuguese, Dutch and French, traditional Indian fabrics influenced both regional clothing practices and global fashion trends, through maritime trade eventually contributing to modern coastal and resort wear aesthetics. Resort wear and beach fashion, continue the use of light cottons, handloom fabrics, and natural dyes. Thus the trend of hybrid clothing styles or fusion wear commenced which combine local traditions with global fashion aesthetics. Tourism in coastal regions, has further transformed traditional attire into contemporary resort wear, and lifestyle fashion, blending heritage textiles with modern design. The coastal fabrics in India had exceptional quality. It was durable, long lasting and vibrant. The dyeing was complex and weaving was specialised. The chintz printing was especially sought after by the nobles (16) Coastal fabrics in historical India were highly valued during the maritime trade of the spice route. They were prized luxury goods, bought by the nobles.

5.2 Changes over time

The hippie culture influenced coastal communities of India to lean towards a fusion garment. Tourism encouraged cross cultural exchanges, leading to hybrid indigenous textiles and motifs. Globalization brought a change to the traditional coastal dressing practices, and it underwent a gradual transition. Traditional draped garments changed to a more modern lifestyle, and the classic stitched garments were commonly worn by the locals. Due to changes of dressing after the British era and industrialisation, the affordability increased, but the local textile economy and the ecological balance were disrupted.

Table 1 – Please suggest the caption

Coastal Textile	Region	Primary Use	Key Feature
Madras Checks, cotton checks	Coromandel Coast	Export, casual wear	Breathable cotton, checks with the use of Indigo dye
Chintz	Coromandel Coast	Garments, furnishings	Colorfast natural dyes
Calico	South Indian coast	Everyday clothing	Plain, durable cotton
Kasavu	Kerala coast	Ritual wear	Unbleached cotton, zari
Indigo cotton	Both coasts	Workwear	Stain-resistant, dyed
Coarse handspun cotton	Both Coasts	Daily labour	Strength and absorbency
Kunbi cotton	Western coast	Ritual wear/work wear	Checked durable cotton

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Due to increase in tourism of the coastal areas of India, the local textiles have now got a boost, as they are highly artisan-based and beautifully made, exclusive products.

Economic Growth & Employment: This has created jobs in different sectors of the local textile Industry (weavers, artisans, guides), increases local income, generates foreign exchange, and boosts GDP. This also gives a boost to the preserving Indian fabrics and promoting the culture of India to the world. This has helped in the demand for traditional textiles. This also promotes Indian crafts and textiles to a global audience and also aide's cultural preservation.

6. Conclusion

The traditional fabrics from the coastal area depict an intricate relationship between ecology, craft knowledge and cultural identity. The humid climate, the salinity in the air and very high sun intensity have made these textiles evolve into lightweight, breathable fabrics and highly absorbent, mostly cotton fabrics, which are perfect for the climatic conditions in coastal areas. During the period 1600 - 1700 CE, Indian textiles and spices were sought after by Europe. The intricate craftsmanship of India was in demand for these beautiful fabrics. During this period, India emerged as the world's leading exporter of cotton textiles. thereby positioning cotton no as a global commodity which came in vogue with the European elite.

Due to climate change, the world has become more aware of sustainability and slow fashion. Indian cotton is a model for slow production and biodegradability. Since India has been growing cotton and making fabrics since ancient times, it helps to keep cultural continuity helps ecological balance. Preserving the traditions of these coastal textiles, ensures that sustainable practices rooted in regional knowledge. This helps to keep integral Indian textiles carry forward into the future textile narratives.

Development of Sustainable Herbal Healthcare Textile Products for the Management of Skin Disorders

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Abstract:

Human skin, which is the largest organ of the body constitutes the first line of our defence system. Skin issues affect people of all ages, from young children to the elderly. Hyper pigmentation is one the most frequently seen skin disorders which has a very high prevalence among Indian population. There are often a multitude of risk factors and adverse effects associated with conventional treatments like chemical peel and laser therapy. Plant based natural medicines have fewer side effects, less toxic, less expensive and has better patient tolerance. Given the increasing number of patients with complaints on hyper pigmentation, there is a need to develop herbal formulations that can be encapsulated into eco-friendly textile fibers, making the medicinal herbal composition safer and more sustainable for human use. The present study focuses on developing sustainable healthcare products incorporating traditional medicinal herbal proportions for the management of skin problems.

Keywords : Eco-friendly fibers, Human skin, Hyper-pigmentation, Medicinal herbs, Sustainable products

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1. Introduction

A healthy skin is an indicator that the epidermal barrier is functioning properly and the loss of its functions results in the impregnation of micro-organisms causing dermatological diseases [1]. Regularly occurring health diseases which affect all the age groups from new born to elderly people is the skin diseases. Hyper pigmentation is a common skin condition affecting many people. It can cause spots or patches on the skin making it appear darker than the surrounding areas. Dark circles around the eye known as periorbital melanosis, is a common skin condition seen in both males and females. The causes for dark circles can be aging, excessive hyper pigmentation, lack of sleep, stress and sun exposure [2]. Long exposure to sunlight causes dark patches on the skin known as sun tanning. Medicinal plants with cooling and anti-stress properties helps in curing and prevents many skin problems like acne, dark patches, scars and pigmentations [3]. Today, eighty per cent of the population depends on traditional medicines for their primary needs [4]. The herbal medicinal preparations are more effective to people who have hyper-allergic skin, since they are less expensive, easier to use, has minor side effects, less irritant and adjust easily to all skin types [5]. Several herbs are prescribed in Ayurveda texts which can be used for treating skin problems [6].

With the improvement of science and technology, the phyto-chemical constituents of the Indian herbs have been identified, which helps to alleviate many of the disease

conditions. Dyeing of textile materials with medicinal herbs devoid the use of any chemicals and do not pollute the environment. It helps to restore the body's balance which will strengthen the immune system [7]. Eco-fibers like soy and milk are hypoallergenic and they have natural antibacterial properties. Medicinal herbs can be incorporated into these eco-fibres to develop sustainable herbal health care textile materials.

2. Material and Methods

2.1 Selection of Yarns

Hundred per cent soy (100% S) and hundred per cent milk (100% M) yarns were taken for the study. The hundred per cent yarns selected were blended with cotton in the ratio 50:50 to get blended yarns namely 50:50 Cotton Soy (50:50 CS), 50:50 Cotton Milk (50:50CM) yarns. The four selected yarns were subjected to yarn strength and yarn elongation tests. The developed hundred per cent and 50:50 blend yarns

Table 1 - Nomenclature of Developed Fabrics

Handloom Fabrics		Powerloom Fabrics		Knit Fabrics	
100% pure	50:50 Blend	100% Pure	50:50 Blend	100% Pure	50:50 Blend
Soy (HS)	Cotton Soy (HSC)	Soy (PS)	Cotton Soy (PSC)	Soy (KS)	Cotton Soy (KSC)
Milk (HM)	Cotton Milk (HMC)	Milk (PM)	Cotton Milk (PMC)	Milk (KM)	Cotton Milk (KMC)

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were then converted into fabric by handloom, power loom and knit method of fabric construction. The nomenclature of the developed materials is given in Table 1.

2.2 Selection of Skin Diseases

Diseases that affect the skin can be ranged from mild or acute conditions. It can be inflammations, rashes, itchiness, or other skin changes. Skin disorders like hyper pigmentation and sun tan were taken for the study.

2.3 Extraction and Optimization of Selected Medicinal Herbs

Medicinal herbs namely Rubia Cordifolia (Indian Madder), Curcuma Longa (Turmeric)

Santalum Album (Sandalwood) were taken to study the properties of each herb and to understand its effectiveness in treating skin diseases. The selected three medicinal herbs were taken separately, dried, grinded under hygienic conditions and the powder obtained was subjected to ethanolic extraction. In order to identify the secondary metabolites, present in each of the selected medicinal herb, phytochemical screening was conducted. The extracts of the herbal solutions were taken in four different proportions namely 1:1:1, 1:2:1, 1:2:3 and 2:3:2 and subjected to antibacterial activity to select the best proportion for herbal dyeing. To find out the functional groups present in the medicinal herbal combination FTIR spectroscopy was conducted in the selected optimized ratio.

2.4 Application of the optimized medicinal herbal extracts to the developed fabrics

The selected optimized herbal extracts were applied to the developed hundred per cent and blended soy and milk fabrics of handloom, powerloom and knit by dip pad dry method and micro encapsulation methods. The original and dyed fabrics were subjected to visual inspection to evaluate the colour, texture, lustre, odour and general appearance. SEM analysis was carried out in the micro encapsulated handloom fabrics to study the fixation of the dye.

2.5 Developing herbal finished products for Dark Circles and Sun Tan

The hundred per cent and 50:50 blend handloom, powerloom and knit herbal finished dip pad dry and micro encapsulated soy and milk fabrics were used for developing an eye pillow for dark circles and a pair of hand gloves for sun tan. The developed herbal finished products were evaluated for its performance by wear study among the selected patients.

3. Results and Discussion

3.1 Analysis of Yarn strength and Elongation

The results of the yarn strength and yarn elongation of 100% S, 100%M, 50:50 CS and 50:50 CM is given in Table 2.

Table 2 - Yarn Strength and Yarn Elongation of Selected Yarns

Selected Spun Yarns	Single Yarn Strength		Single Yarn Elongation	
	Avg. Strength (g/tex)	CV % of Strength	Avg. Elongation (g/tex)	CV % of Elongation
100% S	280.9	10.92	14.95	7.20
50:50 CS	351.8	14.76	15.43	9.56
100% M	214.1	12.62	16.23	15.18
50:50 CM	287.6	14.89	16.3	18.98

The results from Table 2 showed that all the developed spun yarns had good strength and elongation which makes it suitable for weaving and knitting methods. 50 :50 Cotton Soy and 50:50 Cotton Milk yarns exhibited good strength and elongation when compared to 100% Soy and 100% Milk yarns.

3.2 Results of Phytochemical Screening of Selected Medicinal Herbs

The Phytochemical analysis of the selected medicinal herbs Rubia Cordifolia, Curcuma Longa, Santalum Album is given in Table 3.

Table 3 - Phytochemical Screening of Selected Medicinal Herbs

Phytochemical Screening Tests									
Selected Medicinal Herbs	Alkaloids			Flavonoids	Glycosides	Saponins	Tannins and Phenols		Sterols and Terpenoids
	Mayer's Test	Wagner's test	Dragondroff's test	Shinoda Test	Salkowski's Test	Froth Test	Lead Acetate test	Ferric Chloride test	Libermann Burchard Test
Rubia Cordifolia	+	-	-	-	+	-	-	+	-
Curcuma Longa	-	+	-	-	+	+	+	-	-
Santalum Album	+	-	-	+	-	+	-	-	+
Note	+ present - Absent								

The results from the phytochemical screening of the selected medicinal herbs indicates that all the medicinal herbs selected are good in advantageous phyto-constituents. The alkaloids present in the medicinal herbs have anti-bacterial and anti-microbial properties [8]. Flavonoids, free alizarin as well as glycosides are described to have important functions like alleviating uneven discoloration in skin hyper pigmentation, allergies, sunburn, and eczema. Glycosides are known to be anti-microbial, anti-fungal anti-inflammatory, neuro protective and destressing agents. Curcumin present in Curcuma Longa has anti-inflammatory, anti-fungal, anti-viral and anti-oxidant activities.

3.3 Analysis of Antibacterial Activity of the selected Medicinal Herbs

100% HS, 100% HM, 50:50 HCS and 50:50 HCM blend fabrics as handloom fabrics consists of same type of yarn in both warp and weft directions. Agar Diffusion Test was conducted using Bacillus Subtilis (Gram Positive) organism and Escherichia coli (Gram Negative) micro-organisms for the selected herbal combination in four ratios 1:1:1, 1:2:3, 3:2:1 and 2:3:2. The results of antibacterial activity for the selected medicinal herbal combination consisting of Curcuma Longa (C), Santalum Album (S), Rubia Cordifolia (RuC) to optimize the herbal ratios 1:1:1, 1:2:3, 3:2:1 and 2:3:2 is recorded in Table- 4, Figure 1 and Figure 2.

Table- 4 Analysis of Antibacterial Activity of Selected Medicinal Herbs

Analysis of Herbal Extracts for Antibacterial Activity								
Herbal Combination (CL)(SA)(RC)	Zone of Inhibition							
Selected Ratios of Medicinal Herbs	Treated Samples							
	Gram Negative Organism (Escherichia Coli)				Gram Positive Organism (Bacillus Subtilis)			
	100% HS	100% HM	50:50 HCS	50:50 HCM	100% HS	100% HM	50:50 HCS	50:50 HCM
1:1:1	28	25	27	25	29	28	29	27
1:2:3	27	25	30	27	30	30	28	30
3:2:1	26	26	30	30	27	27	31	26
*2:3:2	30	27	31	30	30	34	32	34

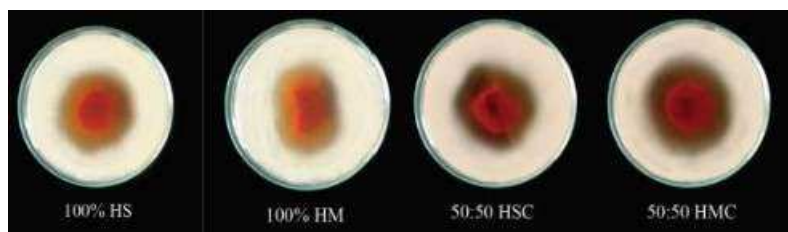


Figure 1 - Antibacterial Activity of Gram-Positive Bacteria in the Ratio 2:3:2

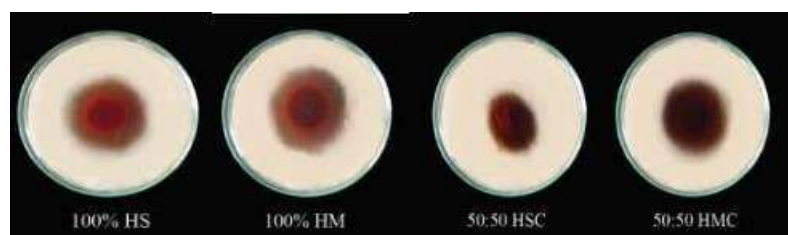
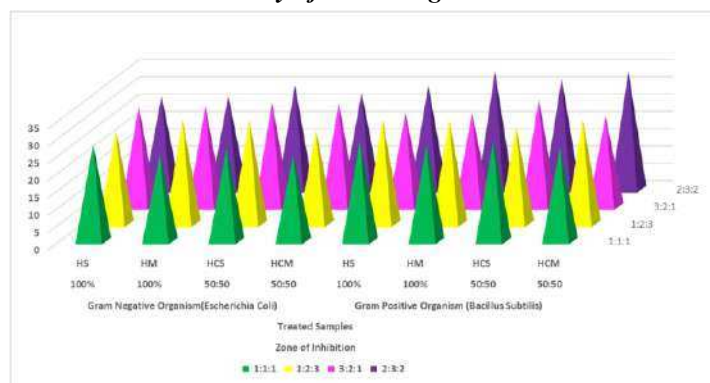


Figure 2 - Antibacterial Activity of Gram-Negative Bacteria in the Ratio 2:3:2



Analysis of Herbal Extracts for Antibacterial Activity

3.4 Results of FTIR Spectroscopy of selected Medicinal Herbs

FTIR spectrum of the synthesized polymer. The x-axis represents Wavelength (cm⁻¹) from 0 to 4500, and the y-axis represents Transmittance (%) from 40 to 120. The spectrum shows characteristic absorption bands for the polymer, including a broad peak around 3300 cm⁻¹ (N-H stretch), a sharp peak at 2950 cm⁻¹ (C-H stretch), a strong peak at 1650 cm⁻¹ (C=O stretch), and several peaks in the fingerprint region (1500-600 cm⁻¹).

Figure 4 - FTIR Spectroscopy of Optimized ratio 2:3:2

Table 5 - FTIR Spectral Peak Values and Functional Groups of Herbal Combination

Herbal Combination (Ruc, Cl Sa) in the Ratio 2:3:2		
Peak values	groups	Compound class
3310	C-H stretching	Alkyne group
2907	C-H stretching	Alkane group
2849	N-H stretching	Amine Salt
2662.9	C-H stretching	Aldehyde
2352	O=C=O stretching	Carbon dioxide
2139	S-C≡N stretching	Thiocyanate
1722.8	C=O stretching	carboxylic acid

From Fig- 4 and Table- 5, it is noted that the FTIR peak values from herbal combination consisting of *Rubia Cordifolia*, *Curcuma longa* and *Santalum Album* in the optimized ration 2:3:2 shows characteristic bands of 3310cm⁻¹, 290cm⁻¹, 2849cm⁻¹ indicating the presence of alkyne, alkane groups and amine salt. The wavelengths 2662.9cm⁻¹, 2139cm⁻¹ and 1722.8cm⁻¹ indicates the presence of aldehyde, thiocynate and carboxylic acid and the wavelength 2353cm⁻¹ shows O=C=O stretching of carbon dioxide.

3.5 Analysis of Visual Evaluation of Original and Treated Handloom, Power loom and Knit Fabrics

Table 6 - Visual Inspection of Treated Handloom, Powerloom, Knit Dip-pad dry and Micro Encapsulated Fabrics

VISUAL EVALUATION OF H, P, K DIP PAD DRY FABRICS														VISUAL EVALUATION OF H, P, K MICROENCAPSULATED FABRICS																		
H, P, K DIP-PAD DRY FABRICS	COLOUR			TEXTURE			LUSTURE			ODOUR			GENERAL APPEARANCE			H, P, K MICRO- ENCAPSULATED FABRICS	COLOUR			TEXTURE			LUSTURE			ODOUR			GENERAL APPEARANCE			
	Good	Fair	Poor	Soft	Medium	Rough	High	Medium	Dull	No Odour	Pleasant	Unpleasant	Even	Partially	Uneven		Good	Fair	Poor	Soft	Medium	Rough	High	Medium	Dull	No Odour	Pleasant	Unpleasant	Even	Partially	Uneven	
100% HS ^D	100	-	-	100	-	-	100	-	-	-	100	-	100	-	-	100% HS ^M	100	-	-	100	-	-	-	100	-	-	-	100	-	100	-	-
100% HM ^D	100	-	-	100	-	-	100	-	-	-	100	-	100	-	-	100% HM ^M	100	-	-	100	-	-	-	100	-	-	-	100	-	100	-	-
50:50 HSC ^D	100	-	-	100	-	-	100	-	-	-	100	-	100	-	-	50:50 HSC ^M	100	-	-	100	-	-	-	100	-	-	-	100	-	100	-	-
50:50 HMC ^D	100	-	-	100	-	-	100	-	-	-	100	-	100	-	-	50:50 HMC ^M	100	-	-	100	-	-	-	100	-	-	-	100	-	100	-	-
100% PS ^D	100	-	-	100	-	-	100	-	-	-	100	-	100	-	-	100% PS ^M	100	-	-	100	-	-	-	100	-	-	-	100	-	100	-	-
100% PM ^D	100	-	-	100	-	-	100	-	-	-	100	-	100	-	-	100% PM ^M	100	-	-	100	-	-	-	100	-	-	-	100	-	100	-	-
50:50 PSC ^D	100	-	-	100	-	-	100	-	-	-	100	-	100	-	-	50:50 PSC ^M	100	-	-	100	-	-	-	100	-	-	-	100	-	100	-	-
50:50 PMC ^D	100	-	-	100	-	-	100	-	-	-	100	-	100	-	-	50:50 PMC ^M	100	-	-	100	-	-	-	100	-	-	-	100	-	100	-	-
100% KS ^D	100	-	-	100	-	-	100	-	-	-	100	-	100	-	-	100% KS ^M	100	-	-	100	-	-	-	100	-	-	-	100	-	100	-	-
100% KM ^D	100	-	-	100	-	-	100	-	-	-	100	-	100	-	-	100% KM ^M	100	-	-	100	-	-	-	100	-	-	-	100	-	100	-	-
50:50 KSC ^D	100	-	-	100	-	-	100	-	-	-	100	-	100	-	-	50:50 KSC ^M	100	-	-	100	-	-	-	100	-	-	-	100	-	100	-	-
50:50 KMC ^D	100	-	-	100	-	-	100	-	-	-	100	-	100	-	-	50:50 KMC ^M	100	-	-	100	-	-	-	100	-	-	-	100	-	100	-	-

The feedback received for visual evaluation of H, P, K dip-pad dry (D) and micro encapsulated (M) fabrics from Table - 6 reveals that, the handloom, power loom and knit dip pad dry and micro encapsulated fabrics were good in color, soft in texture, had high lustre and pleasant odour. The general look of the dip pad dry and micro encapsulated treated fabrics altogether had an even appearance.

3.6 SEM Analysis of Micro Encapsulated Fabrics

Handloom (H) and knit (K) materials consisted of the same type of yarn in both warp and weft, wales and course directions. Hence to understand the binding of herbal micro capsules to the fabric surfaces, handloom fabrics in the optimized ratio 2:3:2 were subjected to SEM analysis to confirm the binding of micro capsules. The findings showed that the handloom blend fabrics, 50:50 HSC, and 50:50 HMC, displayed a uniform deposition of the herbal capsules with a reduced pore size on the surface of the fabrics, while the 100% HS and 100% HM images revealed the herbal deposition on the surface of the fabrics with some protruding fibres and gap in the capsules.

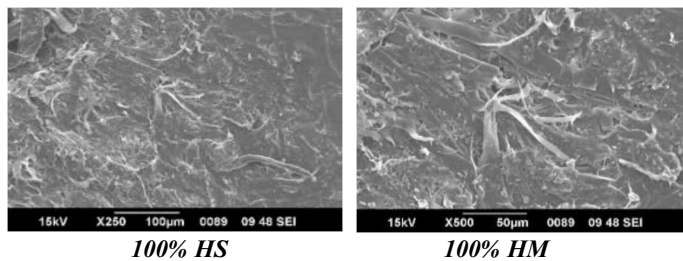


Figure 5 - SEM Analysis of 100% Pure Fabrics

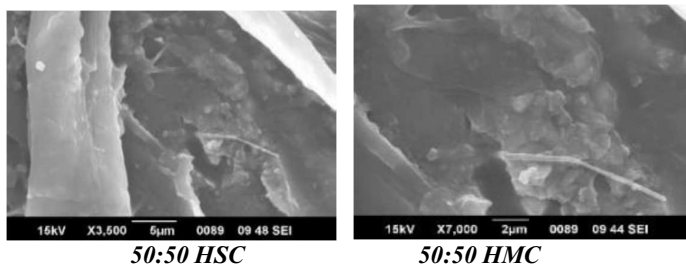


Figure 6 - SEM Analysis of Blend Fabrics

3.7 Aesthetic and Performance Analysis of Developed Herbal Dyed Health Care Products

The developed health care products aesthetic properties like design, comfort of wearing the product, texture and suitability to the ailments were evaluated by the selected patients.

From Table-7, it is noted that the design and suitability of the handloom, power loom and knit health care products were ranked as excellent whereas the texture and comfort of wearing the health care products were rated as very good by all the subjects for all the treated products. The developed herbal dyed handloom (H), power loom (P), and knit (K) healthcare products were given to ten patients with the corresponding conditions selected for wear study. They were instructed to wear them for a certain amount of time, and the outcomes were noted.

The results of the wear study of Hand gloves (Fig-7a) made from dip pad dry and micro encapsulated handloom, power loom and knit fabrics given to subjects who had sun tan in their hands due to exposure to sun, discloses that all the subjects were of opinion that after using the herbal finished product for a period of one month for 8 hours, there was a considerable reduction of tanning of the hands and itching in the tanned areas. Most of the subjects remarked that there was also improvement in the complexion of the skin.

The results of the evaluation of wear study of eye pillows (Fig-7b) for dark circles reveal that after using the herbal finished dip pad dry and micro encapsulated handloom, powerloom and knit eye pillows for a period of one month for 8 hours during night, the dark circles and puffiness under the eyes were reduced considerably. Most of the subjects revealed that there was improvement of complexion of the skin under the eyes.



Figure - 7a,7b Wear Study of Hand Gloves and Eye pillow

4. Conclusion

Herbal dyeing is one step ahead of organic life style, where the core concept is to eliminate impact of harmful chemicals and pesticides [9]. The present study focused on improving

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

Aesthetic Properties of the Developed Herbal Health care Products												
Healthcare Products	Handloom(H)				Power loom (P)				Knit (K)			
	Design	Comfort	Texture	Suitability	Design	Comfort	Texture	Suitability	Design	Comfort	Texture	Suitability
Hand Gloves	5	4	4	5	5	4	4	5	5	5	4	5
Eye Pillows	5	4	4	5	5	4	4	5	5	5	4	5

Key: Excellent-5, Very Good-4, Good-3, Fair-2, Poor-1

the effects of hyper-pigmentation by using herbal health care products like hand gloves and eye Pillows. The wear study showed considerable reduction in the symptoms caused by hyper-pigmentation. The herbal finished clothes or garments come in prolonged contact with the human body providing

relief from infectious diseases, mental depressions and gives overall wellbeing to the human body. The treatment not only means consuming medicines, but one can actually wear the medicated fabric and get better results without any side effects from within one self and both for flora and fauna.

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Digital Intelligence Integration in the Textile and Apparel Sector for Industry 4.0: A Review

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Abstract :

The textile and apparel sector is experiencing a major structural shift as advanced Industry 4.0 technologies are increasingly adopted to enhance operational efficiency, production flexibility, product quality and sustainability performance. Conventional textile and apparel manufacturing systems largely depend on labour-intensive processes and fragmented supply networks with limited real-time monitoring, often resulting in longer production lead times, inconsistent product quality and suboptimal resource utilization. Industry 4.0 establishes a digitally enabled manufacturing paradigm by integrating cyber-physical systems, artificial intelligence, data analytics, the Internet of Things, cloud platforms, digital twin technologies and intelligent automation to create smart, interconnected and data-driven production environments. This comprehensive review systematically explores the role of Industry 4.0 technologies in textile and apparel manufacturing through a structured synthesis of recent academic research and industrial studies. The review analyses key technological enablers and their practical applications across major manufacturing stages such as product design and development, production planning, manufacturing execution, quality assurance, supply-chain integration and sustainability management. The findings indicate that the adoption of Industry 4.0 significantly enhances operational efficiency, manufacturing agility, data-driven decision-making, supply-chain visibility, resource recovery, waste reduction and environmental performance. In addition, the study critically examines key implementation challenges, including high initial investment requirements, system integration complexities, workforce skill deficiencies, and data security risks, with particular emphasis on small and medium-sized enterprises. Finally, the review identifies future research directions, emphasizing the development of scalable implementation frameworks, empirical assessment of performance outcomes, targeted workforce development strategies, and sustainability-oriented digital transformation initiatives. Overall, the review highlights the importance of developing scalable implementation frameworks and workforce development strategies to facilitate Industry 4.0 adoption among Small and Medium-sized Enterprises (SMEs).

Keywords: Artificial Intelligence, Cyber-Physical Systems (CPS), Fashion Digital Twins, Smart Manufacturing, Sustainable Manufacturing

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1. Introduction

The textile and apparel industry are among the most globally distributed and labour-intensive sectors, marked by short product life cycles, rapid design changes, and growing demands for cost efficiency, speed, and sustainable production practices. Conventional textile and apparel production systems rely heavily on fragmented supply chains, manual operations, and experience-based decision-making, which often result in extended lead times, inconsistent product quality, and inefficient utilization of resources. These challenges are further intensified by rapidly changing consumer preferences, demand volatility, and growing expectations for transparency and responsible manufacturing practices across global value chains [1, 2]. Industry 4.0 integrates advanced digital technologies to

enable smart, interconnected, and data-driven manufacturing systems with real-time communication, automation, and predictive decision-making [3, 6, 8 & 11]

While Industry 4.0 technologies have been extensively implemented in automotive, electronics, and composite manufacturing sectors, their adoption within the textile and apparel industry has progressed at a comparatively uneven pace [12, 13]. Structural characteristics, including high product variability, fabric flexibility, labour-intensive operations, and the predominance of small and medium sized organizations, present significant challenges to large-scale automation and digital integration [14-16]. Nevertheless, recent studies indicate a gradual transition toward Textile 4.0, Apparel 4.0, and Fashion 4.0, reflecting the growing acceptance of digital technologies across textile production, clothing manufacturing, and fashion supply chains [17, 18]. Advanced digital tools used for product development, such as computer-supported design and automated manufacturing

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CAD/CAM (Computer-Aided Design/Computer-Aided Manufacturing), three-dimensional garment simulation, and virtual prototyping, have significantly transformed design and development processes in the textile and apparel sector. These technologies improve pattern accuracy, reduce sampling iterations, shorten product development cycles, and enhance coordination between design and production teams [17, 18 & 1]. The use of digital platforms also supports improved communication across geographically dispersed manufacturing units, enabling quicker decision processes and shortening the overall product launch cycle. Artificial intelligence now plays a pivotal role in supporting evidence-based decisions across textile and apparel manufacturing processes. AI (Artificial Intelligence) based applications are increasingly employed for demand forecasting, production planning, quality inspection, ergonomic assessment, and trend analysis, helping manufacturers adjust more efficiently to fluctuations in market demand and operational variability [19-23]. When supported by machine learning algorithms and predictive analytics, AI systems improve operational efficiency, product consistency, and manufacturing reliability by obtaining actionable inputs from vast volumes of production and supply-chain data [13, 24].

The integration of Internet of Things (IoT) technologies further enhances manufacturing transparency by enabling real-time data monitoring of machine performance, material flow, and energy consumption across textile and apparel production systems [8, 9]. Vast amounts of data produced by interconnected devices are analysed through cloud-enabled big data technologies, which support optimized production scheduling, inventory management, predictive maintenance, and real-time collaboration among supply-chain partners [21, 24 & 25]. Emerging digital twin technologies extend these capabilities by providing virtual representations of physical manufacturing systems, enabling simulation, performance evaluation, and risk-free optimization of textile and apparel operations [10, 11 & 26]. Intelligent manufacturing systems enable optimized use of resources while minimizing material losses and energy requirements, thereby promoting environmentally responsible and sustainable production processes [13, 27]. Digital traceability and blockchain-based systems further enhance transparency and accountability across textile and apparel supply chains, supporting responsible sourcing, emissions monitoring, and compliance with environmental and social standards [2, 28-30]. These capabilities play a vital role in addressing sustainability challenges and advancing circular economy initiatives within the global apparel sector [26, 31]. Despite these advantages, the implementation of Industry 4.0 in textile and clothing manufacturing is constrained by several practical barriers. High capital investment requirements, limited digital infrastructure, workforce skill gaps, cybersecurity risks, and resistance to organizational change remain significant challenges, particularly for small and medium-sized organizations [14-16, 32 & 33]. Recent research emphasizes the importance of structured readiness assessment models, targeted workforce development strategies, and supportive policy frameworks to enable

effective and inclusive digital transformation across the textile and apparel industry [15, 20 & 32]. While existing studies often focus on individual technologies or specific operational domains, an integrated perspective that connects technological enablers, manufacturing applications, sustainability outcomes, and implementation challenges across the textile and apparel value chain remains limited [31]. Therefore, this review aims to systematically analyse Industry 4.0 technologies in textile and clothing manufacturing by highlighting key applications, benefits, limitations, and research gaps, thereby providing a holistic foundation for future research and industrial implementation.

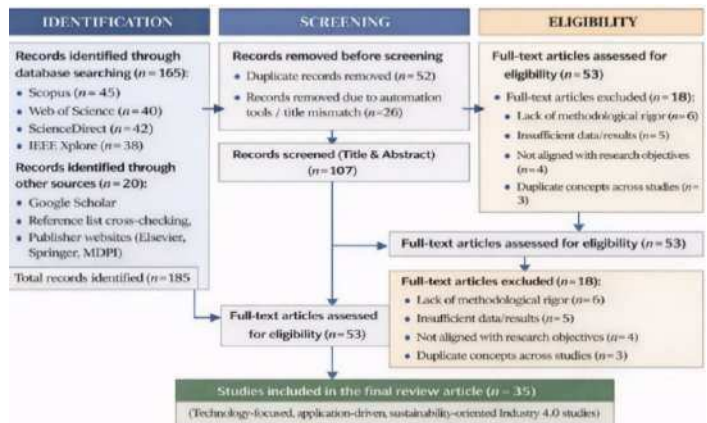


Figure 1 - PRISMA diagram for study screening and literature selection

The PRISMA flow diagram shown in Figure 1 outlines the systematic selection of literature for this review. From 185 records initially identified, duplicates and irrelevant studies were removed through structured screening. After title, abstract, and full-text evaluation, thirty-five high-quality and relevant studies were retained for the final qualitative analysis.

2. Industry 4.0 and its Progressive Integration into Textile and Apparel Manufacturing

The concept was originally introduced as a strategic initiative to strengthen industrial competitiveness through the convergence of information technologies, automation, and data-driven decision-making [3, 4]. Unlike earlier industrial revolutions that emphasized mechanization, electrification, or computer-based automation, Industry 4.0 focuses on real-time connectivity, decentralized control, and autonomous system behaviour enabled through advanced digital technologies [5, 6 & 7].

In textile and apparel manufacturing, cyber-physical systems form the basis of intelligent production environments where parameters such as machine performance, material flow, and quality indicators can be continuously monitored and optimized [9-11]. In textile and apparel manufacturing, IoT-enabled systems enhance visibility across processes including spinning, weaving, knitting, cutting, sewing, and finishing, thereby improving coordination, traceability, and

Table 1 - Evolution of industrial revolutions and relevance to textile and apparel manufacturing

Industrial Revolution	Core Technologies	Manufacturing Characteristics	Relevance to Textile & Apparel Sector	Key References
1.0	Steam power, mechanization	Manual to mechanized production	Mechanized spinning and weaving	[3 4]
2.0	Electrically powered large-scale production	Large assembly lines, standardization	Large-scale textile mills	[4, 7]
3.0	Computers, automation	Programmable machines, IT integration	Automated looms, CAD/CAM adoption	[5]
4.0	IoT, AI-CPS, data analytics, cloud, digital twins	Intelligent network enabled self-operating systems	Smart textile, apparel manufacturing	[6, 8, 10, & 20]

production control across complex and geographically dispersed supply chains [34, 35]. Big data analytics supports pattern identification, performance prediction, and informed decision-making across production and supply-chain activities [21, 24]. Cloud computing complements these capabilities by enabling scalable data storage, real-time access, and collaborative platforms for designers, manufacturers, and supply-chain partners, resulting in flexible production planning, inventory optimization, and improved responsiveness to market changes [13, 25]. Artificial intelligence further extends the industry 4.0 framework by enabling predictive and prescriptive decision-making. AI-driven systems analyse past and real-time data to support demand forecasting, quality inspection, ergonomic optimization, and production scheduling [22, 23]. In textile and apparel manufacturing environments characterized by high variability in materials and styles, AI applications enhance accuracy, consistency, and adaptability, allowing manufacturers to transition from reactive control to proactive and optimized production management [13, 24]. Digital twins use continuous data streams combined with simulation frameworks to accurately replicate the functioning of individual machines, manufacturing systems, or complete industrial facilities [10, 11, 19 & 26]. Automation and smart, self-directed machines form a central pillar of the industry 4.0 paradigm. Although full automation remains challenging due to fabric flexibility and product variability, selective

automation has been successfully implemented in processes such as material handling, cutting, inspection, and logistics [12, 16]. When integrated with digital monitoring and control systems, these technologies improve process consistency, reduce manual workload, and enhance overall production efficiency [13]. From an organizational perspective, successful Industry 4.0 adoption requires alignment between technological capabilities, workforce skills, and strategic objectives. Research highlights that successful implementation is shaped not just by introducing new technologies, but also by factors such as an organization's preparedness, the skill development of its workforce, and the effectiveness of change management strategies [14, 15 & 32]. Readiness assessment models and maturity frameworks assist textile and apparel manufacturers in evaluating current capabilities and planning systematic digital transformation pathways [15, 20].

Figure 2 illustrates a conceptual model that explains how key Industry 4.0 technologies are embedded within textile and apparel manufacturing environments. The framework underscores the importance of seamless data flow, iterative feedback loops, and close collaboration between human expertise and automated systems as essential factors for successful digital transformation in the textile and apparel sector [3, 6, 8, 9, 10 & 13].

Figure 2 - Industry 4.0 conceptual framework and evolution in textile and apparel manufacturing

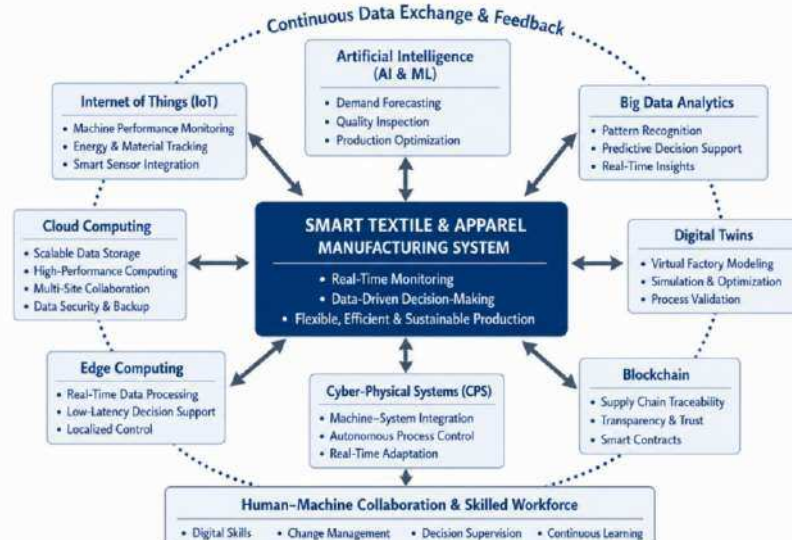


Table 2 - Industry 4.0 concepts and their roles in transforming textile and apparel manufacturing

Industry 4.0 Technology	Primary Function	Application in Textile & Apparel Manufacturing	Representative References
Automation & Intelligent Machinery	Process efficiency	Cutting, material handling, inspection	[12, 16]
CAD/CAM & 3D Simulation	Digital product development	Pattern design, virtual sampling	[7, 17 & 18]
Artificial Intelligence	Data-driven decisions	Demand forecasting, quality inspection	[21-23]
IoT	Real-time integration	Machine, energy monitoring/tracking	[8, 9]
Big Data Analytics	Performance optimization	Scheduling, inventory planning	[21, 24 & 13]
Cloud Computing	Data storage & collaboration	Multi-site coordination	[25, 34]
Digital Twins	Virtual system modelling	Process simulation, optimization	[10, 11 & 19]
Blockchain	Transparency & traceability	Ethical sourcing, emissions tracking	[28-30]

3. Key Industry 4.0 concepts in Textile and Apparel Manufacturing

The implementation of Industry 4.0 in textile and apparel manufacturing is driven by the integration of multiple digital technologies that collectively enable intelligent, connected, and data-driven production systems. Unlike conventional manufacturing approaches that rely heavily on manual operations and sequential workflows, Industry 4.0 technologies facilitate real-time communication, adaptive control, and autonomous decision-making across various industries [3-6, 7].

Automation and smart machine systems form a core pillar of Industry 4.0, significantly transforming operations within textile and apparel manufacturing. Although full automation remains challenging due to fabric flexibility, product diversity and frequent style changes, selective automation has been successfully implemented in such areas [12, 16]. The integration of these systems with digital monitoring tools facilitates ongoing assessment of machine performance and enables maintenance to be anticipated in advance, resulting in more efficient equipment usage and a significant reduction in operational interruptions [13, 25]. Within Industry 4.0-driven textile and apparel systems, CAD/CAM technologies form the foundation of digital product development by enabling precise pattern creation, marker optimization, and production planning, while strengthening coordination between design and manufacturing [17]. The use of 3D (Three Dimension) garment simulation and virtual prototyping allows early assessment of fit, construction, and visual appeal, reducing physical sampling, material waste, development time, and improving collaboration across distributed production networks [1, 18]. Among the digital technologies associated with Industry 4.0, artificial intelligence stands out for its significant influence on how textile and apparel manufacturing operations are designed and managed. AI-based applications are increasingly employed for demand forecasting, production planning, quality inspection, ergonomic optimization, and trend analysis [21-23]. AI-based visual inspection systems significantly outperform conventional human inspection in

identifying product defects, offering more reliable and repeatable results, which in turn enhance overall quality and minimize reprocessing requirements [13, 24]. These capabilities are particularly valuable in the clothing industry, where product variation and short life cycles demand rapid and highly reliable decision processes.

The integration of IoT technologies significantly enhances connectivity in Industry 4.0-oriented textile and apparel production systems by linking equipment, operations, and information networks. IoT technologies enable machines, materials and products to be embedded with sensors and connected through communication networks, facilitating continuous data acquisition and real-time visibility across production processes [8, 9]. This real-time connectivity improves operational transparency and supports faster responses to disruptions or demand fluctuations [24]. Big data analytics provides tools for extracting actionable insights from complex datasets, supporting optimized production scheduling, inventory management, and process improvement [21, 24]. Cloud computing further enhances these functions by enabling flexible data storage, instant information sharing, and collaborative digital environments that seamlessly connect multiple manufacturing units and supply-chain stakeholders [25]. In textile and apparel manufacturing, cloud-based systems facilitate agile decision-making, enhanced coordination, and improved responsiveness to market changes [13]. Blockchain-based systems improve traceability, transparency, and trust across textile and apparel supply chains by enabling secure and immutable data sharing among stakeholders [28, 29, & 30]. These systems support responsible sourcing, emissions monitoring, and compliance with environmental and social standards, which are increasingly important in global apparel markets [2]. When combined with data analytics and IoT, blockchain technologies strengthen supply-chain resilience and accountability [34, 36-38]. Industry 4.0 in textile manufacturing is driven by the integration of advanced digital technologies enabling smart and connected production systems.

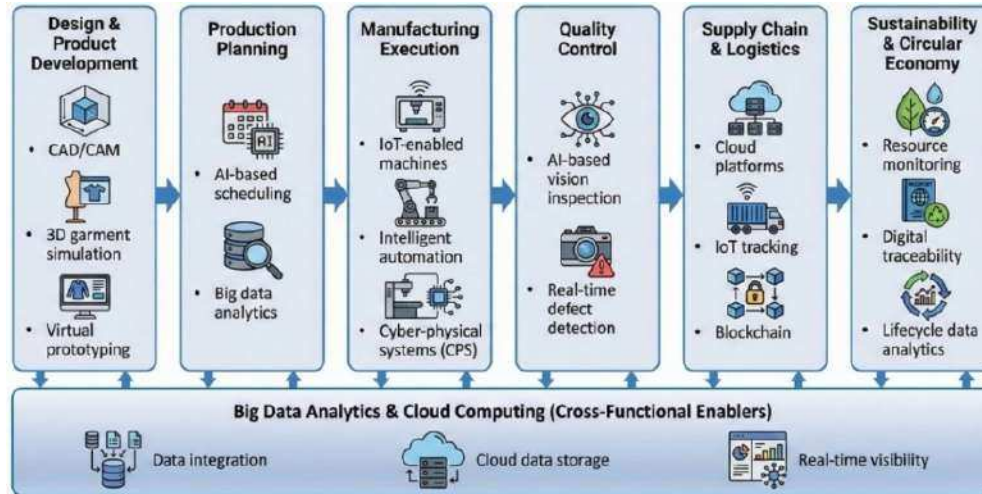


Figure 3 - Applications of industry 4.0 in textile and apparel manufacturing

4. Use of Industry 4.0 concepts in textile and garment manufacturing

Industry 4.0 solutions are applied throughout the textile and clothing sector, influencing activities from design and production scheduling to shop-floor operations, quality monitoring, supply coordination, and sustainable practices. These applications address long-standing industry challenges related to speed, flexibility, quality consistency, and resource efficiency. It emphasizes the integrative role of big data analytics and cloud platforms in supporting real-time information flow, process coordination, and seamless data connectivity across the entire value chain. [16, 17, 21, 22, 26, 30 & 31].

During the design and product development phase, Industry 4.0 has reshaped conventional practices by introducing digital-first workflows. The integration of CAD/CAM systems with 3D garment visualization and virtual prototyping enables designers to create, test, and improve apparel products digitally before moving to actual manufacturing [17, 18]. Cloud-based platforms further enhance collaboration by enabling real-time data sharing across geographically dispersed production networks [25]. During production planning and manufacturing execution, Industry 4.0 applications enable enhanced coordination and operational control through real-time data acquisition and intelligent scheduling. IoT-enabled machines and cyber-

physical systems continuously generate data related to machine performance, work-in-progress status, energy usage, and material flow, allowing manufacturers to monitor production processes dynamically [8, 9]. Big data analytics tools process this information to support optimized line balancing, predictive maintenance, and adaptive production scheduling, reducing downtime and improving overall equipment effectiveness [13, 21 & 24]. Smart automation supports efficient manufacturing by standardizing processes and reducing manual work in areas such as cutting, material transfer, and inspection [16]. Conventional inspection practices depend largely on manual checks, making them slow and susceptible to inconsistencies. In contrast, AI-driven vision technologies combined with machine learning models allow automated identification of defects by evaluating fabric surfaces, stitching precision, and garment measurements with improved reliability and uniformity [22-24]. These systems support early identification of quality deviations, reducing rework, minimizing waste, and improving product uniformity. Continuous quality monitoring also enables feedback-driven process improvement, contributing to higher manufacturing reliability and customer satisfaction [13].

Advanced Industry 4.0 concepts improve how logistics and supply-chain activities are connected in the textile and apparel sector. The global and fragmented nature of apparel

Table 3 - Applications of industry 4.0 across textile and apparel manufacturing stages

Manufacturing Stage	Industry 4.0 Application	Outcome Achieved	Supporting References
Design & Development	3D garment simulation	Reduced sampling time	[1, 17 & 18]
Production Planning	IoT-based scheduling	Improved line efficiency	[8, 24]
Manufacturing Execution	Intelligent automation	Reduced downtime	[16]
Quality Control	AI-based inspection	Lower defect rates	[22, 23]
Supply Chain	Digital tracking systems	Enhanced transparency	[34]
Sustainability	Resource monitoring systems	Reduced waste & emissions	[27]
Circular Economy	Digital traceability	Improved lifecycle tracking	[26, 31]

supply chains requires effective coordination among suppliers, manufacturers, and distributors. IoT-based tracking systems and cloud-enabled information platforms improve visibility into inventory levels, material movement, and production status across the supply chain [24]. Big data analytics further supports demand forecasting, inventory optimization, and risk assessment by integrating data from multiple supply-chain partners, thereby enhancing resilience and responsiveness to market fluctuations [21, 24]. Blockchain adds value to these applications by making data sharing more reliable and transparent, helping build trust and clear traceability throughout the textile and apparel supply chain resource usage [28, 29 & 30].

Intelligent manufacturing systems enable continuous monitoring of energy consumption, material usage, and waste generation, supporting more efficient and environmentally responsible production practices [13, 27]. Digital traceability technologies enhance transparency across the value chain, facilitating responsible sourcing, emissions monitoring, and compliance with environmental and social standards [2]. Industry 4.0 applications also support circular economy initiatives by improving product traceability, enabling data-driven lifecycle assessment, and reducing overproduction and material losses [26, 31]. Digital twin technology further extends Industry 4.0 applications by enabling virtual representation and simulation of textile and apparel manufacturing systems. Digital twins integrate real-time operational data with simulation models to mirror the behaviour of machines, production lines, or entire factories [10, 21 & 26]. These applications support scenario analysis, performance optimization, and risk-free testing of production strategies, allowing manufacturers to identify inefficiencies and improvement opportunities without disrupting physical operations [19].

Advanced Industry 4.0 concepts improve how logistics and supply-chain activities are connected in the textile and apparel sector. The global and fragmented nature of apparel supply chains requires effective coordination among suppliers, manufacturers, and distributors. IoT-based tracking systems and cloud-enabled information platforms improve visibility into inventory levels, material movement, and production status across the supply chain [24]. Big data analytics further supports demand forecasting, inventory optimization, and risk assessment by integrating data from multiple supply-chain partners, thereby enhancing resilience and responsiveness to market fluctuations [21, 24]. Blockchain adds value to these applications by making data sharing more reliable and transparent, helping build trust and clear traceability throughout the textile and apparel supply chain resource usage [28, 29 & 30].

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5. Advantages of Implementing Industry 4.0 in Textile and Clothing Production

The findings indicate that the adoption of Industry 4.0 significantly enhances operational efficiency, manufacturing agility, predictive analytics capabilities, autonomous decision-making, supply-chain visibility, and sustainability through improved resource efficiency, waste reduction, and circular manufacturing practices. Real-time monitoring, predictive analytics, and intelligent automation improve productivity by reducing downtime, optimizing equipment utilization, and enabling early detection of process deviations [13, 21 & 24]. Digital production planning, IoT-based monitoring, and cloud platforms further enhance manufacturing flexibility, supporting small-batch production, mass customization, and rapid response to changing market demands while minimizing overproduction and inventory losses [17, 34]. Industry 4.0 also improves product quality through AI-based inspection and machine vision systems that enable accurate defect detection, reduce rework, and support continuous process optimization [13, 23-24]. By bringing together data from design to delivery, big data analytics and cloud computing help organizations make quicker decisions while improving visibility and coordination [13, 25 & 34]. In addition, intelligent monitoring systems and digital traceability technologies promote sustainability by optimizing resource use, reducing waste, and supporting responsible sourcing and regulatory compliance [2, 13, 24 & 26-29 & 31]. Industry 4.0 further enhances supply-chain resilience through IoT-enabled tracking, analytics, and blockchain-based collaboration, improving visibility, trust, and disruption management across global apparel networks [34, 29 & 30]. Collectively, these benefits strengthen competitiveness and long-term performance, establishing Industry 4.0 as a robust foundation for sustainable and resilient textile and apparel manufacturing systems.

6. Practical Difficulties in Applying Industry 4.0 Technologies to Textile and Apparel Manufacturing

Although Industry 4.0 offers clear benefits, its implementation in textile and apparel manufacturing remains constrained by technical, financial, and managerial

Table 4 - Prospects and constraints of Industry 4.0 integration in the textile and Clothing sector

Dimension	Benefits	Challenges	Key References
Productivity	Reduced downtime, higher efficiency	High capital investment	[21, 13 & 15]
Flexibility	Faster style changeover	Integration with legacy systems	[17, 16 & 20]
Quality	Automated defect detection	Skill gaps in workforce	[22, 32 & 23]
Sustainability	Efficient resource utilization	Data security risks	[28, 33]
Supply Chain	Improved resilience	Fragmented global networks	[30, 34]

limitations. The substantial upfront cost of digital systems, smart equipment, sensors, and integration makes adoption challenging, particularly for small and medium enterprises with limited budgets. As a result, the extent of adoption differs widely depending on location and organizational scale, with large, vertically integrated firms advancing more rapidly than small-scale suppliers [12, 14 & 15]. Moreover, aligning Industry 4.0 solutions with older, established systems remains a major challenge. The absence of standardization across equipment, software platforms, and data formats further increases interoperability challenges and implementation risks [16, 20 & 33].

Workforce-related challenges significantly limit effective Industry 4.0 implementation in textile and clothing manufacturing, as digital systems require skills in data analytics, automation, system integration, and digital maintenance, while the industry traditionally depends on labour-intensive practices with limited exposure to advanced technologies, thereby constraining effective implementation [14, 15, 28, 29, 32 & 33]. In addition, internal challenges such as traditional decision-making mindsets, lack of a defined digital roadmap, and limited leadership support slow the shift toward analytics-driven operations [15, 16, 20 & 36-38]. At the supply-chain level, fragmented global networks, varying technological maturity, and limited trust among partners restrict seamless digital integration and reduce the potential benefits of enhanced visibility and resilience [30, 34, 39-41]. Moreover, difficulties in quantifying return on investment and long-term value creation create uncertainty,

discouraging investment in cost-sensitive markets [13, 15].

7. Conclusion

This review underscores how Industry 4.0 has reshaped textile and apparel manufacturing by offering effective solutions to long-standing issues such as low efficiency, limited adaptability, quality variation, sustainability pressures and complex supply networks. The adoption of smart cyber-physical systems, IoT, artificial intelligence, data analytics, cloud platforms, digital twins and blockchain has facilitated more intelligent, interconnected and insight-driven production systems. As a result, firms gain improved process transparency, more informed decision-making and stronger coordination throughout the value chain, contributing to enhanced competitiveness and operational resilience. Despite these advantages, widespread implementation is still limited by substantial capital requirements, challenges in integrating existing infrastructure, shortages of digitally skilled personnel, cybersecurity risks and resistance to organizational change, particularly within small and medium-sized organizations. Future studies should prioritize practical and scalable deployment approaches, real-world performance validation, targeted skill-development frameworks and interoperable digital ecosystems. Additionally, deeper exploration of sustainability-focused Industry 4.0 concepts is necessary to assess their long-term environmental and social benefits and to promote resilient and responsible manufacturing practices in the textile and apparel sector.



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Sustainable Patchwork Fabrics from Pre-Consumer Waste : Assessment of Physical, Mechanical and Comfort Properties

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Abstract :

Pre-consumer waste in the textile industry refers to material that is created during the process of making textiles, but is not used by consumers. Pre-consumer textile waste is one of the biggest problems in resource-efficient textile production that is generated in the process of making textiles, but not consumed by consumers. During the process of pattern cutting, sampling and making garments, small scale garment manufacturing units and boutique stores create a lot of cotton fabric remnants. Although the original material properties remain good, these remnants are generally thrown away, which leads to material loss and higher environmental burden. The study explored patchwork fabric making techniques by using pre-consumer cotton waste from small-scale garment manufacturing units and their characteristics.

Fabric scraps of cotton were gathered, sorted by size and fabric type and then transformed into patchwork fabrics using a set of standard patchwork construction techniques. Physical, mechanical and comfort related properties of developed patchwork fabrics were characterized and compared with conventional cotton fabric. The physical properties of the fabrics involved were determined by fabric mass per unit area (GSM) and thickness, and mechanical properties were measured based on tensile strength, seam strength and abrasion resistance. The properties being assessed regard comfort were the air permeability and the moisture transmission. All the testing was carried out by following the appropriate standard textile testing methods and the experimental results were analysed statistically and the significance of the differences between the textile samples was determined.

This study is intended to assess the applicability of patchwork fabrics made from pre-consumer cotton waste materials for clothing and/or home fabrications. The outcome is anticipated to offer insights into how the patchwork construction affects the performance and durability of the fabric. Moreover, the material utilization efficiency obtained by converting the cutting waste for the creation of value-added textile structures is quantified in order to gain an insight into the potential for this process as a waste minimization strategy. The results add to the sustainable production of textile materials by combining waste utilization and textile engineering in the production of textile materials and provide a practical approach towards increasing the efficiency of the use of resources in small-scale garment production systems.

Keywords: *air permeability, cotton fabric remnants, fabric characterization, patchwork fabrics, Pre-consumer textile waste, resource efficiency*

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1. Introduction

Textile and apparel industry is one of the greatest engines of the economic growth in the world, but at the same time, the industry has significant environmental problems like overconsumption of resources and generation of waste. Pre-consumer textile waste has become a major concern among other types of textile waste, because it is directly related to the inefficient production process. Pre-consumer waste is defined as textile material that is rejected in the production of textile products, including during fabric spreading, pattern cutting, sampling, stitching and garment assembly before they are consumed by the customer. While these wastes may still have their intended purpose, they are commonly dumped in landfills or burned in incinerators and are therefore a

resource lost and environmental burden added. While often these wastes still have a useful function, they are still often disposed of in landfills or incinerators, and thus are a loss of resources and an added burden to the environment [1, 2].

Pre-consumer textile waste is also generated in significant amounts at the small-scale garment manufacturing units, and in the boutique production systems, especially in the form of cotton fabric remnants. Unlike big industries with complex waste management systems, these businesses may not have established mechanisms for the utilization and recycling of waste. As a result, significant amounts of cotton fabric scraps are gathered in large numbers and then disposed of which have satisfactory strength and durability properties that are desirable for other uses, yet are not suitable for re-use as a final product [2]. There is therefore a need to design strategies that can be practically implemented and be

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economically viable to use these waste streams for sustainable production and making efficient use of resources in the textile sector [5, 6].

Patchwork is a traditional textile making method that is used to join small pieces of fabric to make a bigger surface for textiles. Patchwork has traditionally been used to create art, clothing and home fabrics, and is now becoming the focus of increasing interest in creating sustainable design solutions where textile waste can be minimized and materials life cycles can be extended [3]. Patchwork technique is a method to make use of pre-consumer fabric waste to make value-added textile products. The number of seams and fabric interfaces involved in patchwork construction, however, could change the physical, mechanical and comfort characteristics of the patchwork fabrics, which might impact their use in apparel and home textile applications [4, 7].

The literature related to the textile waste management has been mainly focused on fibre recycling, mechanical shredding and chemical recovery processes [6, 9 & 10]. The direct upcycling of pre-consumer cotton wastes to functional textile structures has been little explored, and the performance properties have not been systematically assessed. To investigate if patchwork-constructed fabrics can be used as alternative fabric, knowledge about the patchwork construction and its impact on fabric behaviour is required [7, 8]. Hence, the present work is to create eco-friendly patchwork fabrics from pre-consumer cotton waste collected from small scale patchwork production unit and to assess the performance characteristics of such patchwork fabrics.

Developed patchwork fabrics properties were evaluated with regard to physical properties (fabric mass per unit area and thickness), mechanical properties (tensile strength, seam strength and abrasion resistance), and comfort related properties (air permeability and moisture transmission). Additionally, this research aims to estimate the potential of patchwork construction as a waste reduction method which increases the efficiency of material use and is an element of sustainable textile production. The results will help to gain insights for the use of patchwork fabrics made from waste and facilitate the implementation of circular and resource-efficient processes in the small-scale production systems of garments [5, 9 & 10].

2. Review of Literature

The existing knowledge about textile waste management, upcycling application, patch work and performance of reconstructed fabric is explained by reviewing the available studies. In the literature, it is reported that sustainable use of pre-consumer textile waste is increasingly gaining more importance and that there is a need for innovative solutions for improving the use of textile products with regard to their resources. The studies followed below were reviewed to determine the gap in the research and to set the stage for the current investigation.

Pre-Consumer Textile Waste and Sustainable Waste Management

There are several textile recycling methods, and found that direct reuse and upcycling of textile waste required less energy than did fibre reprocessing methods. The study highlighted the importance of using textile waste for value added products to minimize waste dumping in landfills and save resources [1].

The fabric utilization efficiency in the apparel industry and determined that around 10–20% of fabric is wasted in the pattern cutting processes. It was pointed out the importance of developing innovative design and production solutions to reduce the textile waste generated before consumption [2].

The waste reduction and resource efficiency are key elements of the circular economy in the fashion and textile industry in order to solve sustainability challenges. It was proposed the utilization of the re-use and re-design techniques to reduce the use of materials in the textile value chain [5].

The global supply chain of recycling waste cotton and found that there are millions of tonnes of cotton waste produced worldwide every year. Because of its lower energy consumption and environmental impacts, it was suggested direct reuse methods as environmentally friendly alternative [6].

Upcycling and Patchwork as Sustainable Design Strategies

The sustainable fashion practices and suggested that up cycling and zero waste design concepts are effective methods to curb generation of textile wastes. The study has reflected the patch work and redesigning techniques as the practical methods of prolonging the life cycle of textile materials [3].

Some of the parameters influencing the upcycling of waste cotton and polyester/cotton textiles. They shared that discarded cotton textiles are still very useful for their functional properties and can be converted to more useful and valuable products if suitable design interventions are made [4].

The upcycling of cotton waste from textile waste and found that upcycling helps to achieve sustainability while providing economic value to the products. It was suggested that there is great potential for innovative product development with waste textiles [7]. The importance of recovering value from the cotton based textile waste has been rising. It was shared that waste to value can offer an alternative to virgin fibre use to help sustainable production systems [9].

Mechanical Performance of Stitched and Reconstructed Fabrics

The study showed that there is significant effect of seam construction on stress distribution, deformation characteristics and tensile performance of the stitched textile

structures which warrants careful evaluation of the stitched textile before end-use applications [8].

The previous studies on seam performance also suggested that the stitch density, seam types and the characteristics of the threads have significant effects on the strength of the seams and the durability of the fabric. The results are of special interest for patchwork fabrics, where the several seams are an integral part of the textile structure [8, 14].

The technologies used in cotton textile waste recycling in a circular economy is a desirable option in comparison to mechanical and chemical recycling of cotton as they are using fewer processing steps and keep the intrinsic properties of the cotton. [10].

The review also noted that small-scale and localised waste-recycling schemes are particularly significant, particularly in developing economies in which formalised recycling facilities are scarce. [5, 10].

Research Gap

The reviewed research studies show the significant advancement of textile waste management, sustainable fashion and cotton recycling technologies. But the effort to use pre-consumer cotton waste produced from small-scale boutique production facilities has received little dedicated research attention on the use of the cotton waste for fabric patchwork. Moreover, a thorough characterization of the physical, mechanical and comfort characteristics of these fabrics is still not complete [7, 8]. Hence, the present research aims to overcome this by creating patchwork textile materials using pre-consumer cotton waste and evaluate the materials for apparel and home textile applications by systematically characterizing their performance properties.

3. Materials and Methods

The present study was an experiment research design which aimed to investigate the feasibility of using pre-consumer cotton textile waste for patchwork fabrics and to determine the performance characteristics of the patchwork fabrics. The study focused on the collection of cotton fabric scraps produced in the garment manufacturing processes in small scale garment manufacturing units and boutique outlets. These waste materials were used to develop patchwork fabrics which were systematically characterized and compared with conventional cotton fabrics to find its suitability in apparel and home textile applications.

Collection of Pre-Consumer Cotton Waste

Small scale Garment manufacturing units and boutique production system were selected and pre consumer cotton fabric remnants were collected from these. Almost all wastes collected were cotton scraps produced during spreading, cutting patterns, taking samples, stitching and assembly of garments. The material for the study was selected to be clean and uncontaminated and of consistent quality, with only cotton fabric scraps used that were free from obvious defects, stains and damage.

Sorting and Preparation of Fabric Scraps

Cotton scraps were gathered and sorted by hand based on fabric type, colour match, fabric texture and size. Because the study was only concerned with cotton waste, materials other than cotton were not included. The chosen fabric was then split into various size categories for patchwork use. Remaining fragments were then cut into regular geometric shapes for uniform assembly and minimize the variation in fabric development.

Development of Patchwork Fabrics

Standard patchwork construction techniques used in textile patchwork applications were employed to develop patchwork fabrics. After being prepared, the cotton pieces were laid out in accordance with the predrawn patterns and sewn together by a lockstitch sewing machine under controlled sewing conditions. All the sewing parameters such as stitch type, stitch density, seam allowance and the specification of the sewing thread were kept consistent during the process of fabrication of the samples to create uniformity between the developed samples.

Conventional cotton samples of similar end use and fabric composition were chosen as control samples. Standard atmospheric conditions were used for conditioning all of the developed patchwork fabrics and control fabrics before testing.

Evaluation of Fabric Properties

The developed patchwork fabrics and conventional cotton fabrics were tested for physical, mechanical, and comfort properties to evaluate using standard textile testing techniques.

Physical Properties

The physical properties of the fabrics were evaluated by determining the following: The effect of patchwork construction on fabric weight is measured by: Fabric mass per unit area (GSM)

- Fabric thickness: Used to measure bulkiness changes due to many seam interfaces.
- Mechanical Properties The materials developed were tested for mechanical properties such as: Tensile strength: This is measured to assess the tensile strength of the fabrics. The strength of the seams (strength and integrity): It was evaluated to determine the integrity and durability of stitched patchwork constructions.
- Abrasion resistance: Designed to test the ability of the fabrics to withstand abrasion in use.
- Comfort-related Properties The fabrics' comfort properties were evaluated by measuring:
- Air permeability: Tested to find out how easily air can pass through the cloth structure. The Moisture transmission is evaluated to determine the moisture vapour transmission rate of the fabrics and thus the wearer's comfort.

Testing Procedures: The relative humidity for the standard testing environment was $65 \pm 2\%$, and the temperature was $20 \pm 2^\circ\text{C}$, before testing all the fabric specimens were kept in the standard testing environment for at least 24 hours. The tests were carried out as per the accepted standard textile testing methods and multiple specimens were tested for each measurement to get better reliability and repeatability of results.

The standards used in the study were represented as follows:

- Fabric width: ASTM D1778 or equivalent
- Tensile strength: ASTM D5035/ISO 13934
- Strength of the seal: ASTM D1683 or other similar tests
- Abrasion resistance: ASTM D4966/ISO 12947
- Air permeability: ASTM D737/ISO 9237
- Moisture transmission: ASTM E96 or Equivalent.

Material Utilization Efficiency Assessment

The material utilization efficiency was used to quantify the effectiveness of the patchwork construction as waste minimization technique, by dividing the weight of cotton wastes used in patchwork fabric production by the total weight of the cotton wastes collected as pre-consumer cotton wastes. The percentage utilization was determined by the following equation:

Material Utilization Efficiency (%) = $[(\text{Weight of cotton wastes used for patchwork fabric production} / \text{Total Weight of cotton wastes collected}) \times 100]$.

The results obtained from the calculations gave a good indication of the potential for reduction in textile waste that could be achieved by the patchwork approach.

Statistical Analysis Data from all the tests were statistically analysed with the help of appropriate statistical software. Means and standard deviations were computed for each of the measured properties. Independent sample t-test or one-way analysis of variance (ANOVA) were used to perform comparative analysis between patchwork fabrics and conventional cotton fabrics depending on the number of sample groups. A confidence level of 95% ($p < 0.05$) was used for determining statistical significance.

The study involved post-consumer textile waste from the participating production units with their permission. Hazardous chemicals and environmentally harmful treatments were not used in fabric development. The methodology was developed to enable the efficient use of resources and offer a practical approach to lower textile waste generation in small-scale garment production systems.

Physical, mechanical and comfort characteristics of the resultant patchwork fabrics were tested and compared to those of the conventional cotton fabric for their suitability to apparel and home textile applications. The results of the experiments, in terms of the mean values, are given in Table 1.

Table 1 - Comparison of properties of conventional cotton fabric and patchwork fabric

Property	Conventional Cotton Fabric	Patchwork Fabric
Fabric Mass (GSM)	152 ± 2.8	178 ± 3.5
Thickness (mm)	0.42 ± 0.01	0.56 ± 0.02
Tensile Strength (N)	485 ± 8.6	452 ± 7.9
Seam Strength (N)	365 ± 6.4	428 ± 5.8
Abrasion Resistance (cycles)	$21,500 \pm 320$	$19,800 \pm 285$
Air Permeability ($\text{cm}^3/\text{cm}^2/\text{s}$)	138 ± 4.2	112 ± 3.7
Moisture Transmission ($\text{g}/\text{m}^2/\text{day}$)	785 ± 15	742 ± 12

4. Results and Discussion

Fabric Mass per Unit Area (GSM)

The results showed that the patchwork fabrics obtained showed higher GSM value ($178 \text{ g}/\text{m}^2$) than conventional cotton fabric ($152 \text{ g}/\text{m}^2$). The extra weight of fabric is due to the seaming allowances as well as the multiple seams made during patchwork construction. Overlap areas of fabric pieces added to fabric density and weight.

Higher GSM indicates that patchwork fabrics have relatively compact structure and hence may enhance their dimensional stability and durability [3, 8]. These findings have been reported in reconstructed textile materials where further stitching materials led to a higher fabric mass. The results show that pre-consumer cotton offcuts can be effectively converted to high quality textile products with minimal use of external resources.

Fabric Thickness

The thickness of the patchwork fabric was measured as 0.56 mm which is greater than the thickness of the control cotton fabric of 0.42 mm. This can be caused by the thickness of seams and the sewing of several pieces of fabric together, which adds up to a certain thickness in the fabric structure.

The thicker the fabric, the more resistant it will be to deformation and the more durable it will be. However, too much thickness can have an effect upon drape and comfort characteristics. The increase in thickness, as in the present study, was still within acceptable limits, which meant that the created patchwork fabrics were still usable for various purposes: casual clothing, bags, cushion covers and other home furnishings products etc.

Mechanical Properties

Tensile Strength

The tensile strength analysis, which revealed the breaking strength of conventional cotton fabric was slightly higher than that of patchwork fabric, was 485 N and 452 N

respectively. Multiple stitched joints may be the reason that the patchwork samples exhibited a decrease in tensile strength compared to the single stitch sample.

For tensile loading, the stress distribution of patchwork fabrics is affected by intersections of seams and these intersections may cause local concentration of strain [8]. Even though this has been reduced, the tensile strength values achieved for patchwork fabrics were still adequate, meaning that the patchwork fabrics have the capacity to endure normal use. Hence, the functional performance of the cotton patchwork fabrics did not significantly downgrade as they were formed from the cotton remnants.

Seam Strength

It is found that the strength of the seam of the patchwork fabrics is higher than the strength of the conventional cotton fabric, that is 428 N and 365 N respectively. The result shows that the technique of joining fabric pieces (called lockstitch construction) was effective. This increased seam strength could be due to seam stitching and the correct seam allowances.

The product life of patchwork structures is influenced by a number of factors, among which is the seam durability because patchwork structures are made of many stitched parts. The results indicate that developed fabrics have sufficient seam slippage and seam failure resistance which makes them suitable for application in practice [8].

Abrasion Resistance

The tests of abrasion resistance revealed that conventional cotton fabric could resist about 21,500 times abrasion while patchwork fabric could resist 19,800 times abrasion before it was worn.

The lower abrasion resistance of patchwork fabrics could be linked to uneven surface texture and seams where there are intersections that are subjected to higher abrasion during repeated rubbing. However, this difference between the two samples was not so significant and the patchwork fabrics showed good wear resistance to be used in products that are moderately stressed.

Comfort Properties

Air Permeability

Air permeability is a significant parameter of the thermal comfort, especially in apparel. The air permeability value for the conventional cotton fabric was 138 cm³/cm²/s, while the patchwork fabric had a lower air permeability value of 112 cm³/cm²/s.

The reduction in airflow may be explained by the increased fabric thickness and denser construction resulting from multiple seams. Such changes reduce the amount of air space in structures. The air permeability of the patchwork fabric was still within the acceptable range, even though it was lower than that of the control fabric, which means that the

patchwork fabric developed in this study can be used for various end uses that require air permeability

Moisture Transmission

The moisture transmission values of patchwork fabric and conventional cotton fabric found are 742g/m²/day and 785g/m²/day respectively. This slight reduction seen in the patchwork samples could be attributed to the dense structure and thickness of the fabric, which may have limited the ability of moisture to permeate the fabric.

But with the developed patchwork fabrics, the moisture transfer properties remained in a relatively good state, due to the natural hygroscopic property of cotton fibres. The results suggest that patchwork construction did not significantly reduce the wearers' comfort and the fabrics were appropriate for the medium moisture management application.

The results of the present investigation show that patchwork construction with pre-consumed cotton waste (PCWW) has an effect on the performance of the patchwork textile structure. The obtained patchwork fabrics exhibited higher GSM, thickness and seam strength which resulted in increased structural integrity and resistance to seam failure. Some slight decreases in tensile strength, abrasion resistance, air permeability and moisture transmission were noted, but were not large enough to restrict their practical use.

The results indicate that the pre-consumer cotton waste produced in small-scale boutique production units can be effectively transformed to value-added textile products with little deterioration of the functional properties, supporting the concept [1, 4]. From the results of this study, it has been concluded that the patchwork fabrics can be used for moderately durable apparel items and for home textile applications like cushion covers, table runners, storage organizers and decorative furnishings.

Additionally, patchwork will help minimize waste by keeping textile materials in use for longer and by diverting less waste to landfills. This will help in the direct re-use of cotton scraps, which is consistent with the principles of sustainable production and circular economy practices [5, 9 & 10]. Thus, creation of patchwork fabrics using the pre-consumer cotton waste is a viable and eco-friendly solution which can improve the efficiency of resources in the small-scale garment industry.

5. Conclusion

The present study proved that the pre-consumer waste cotton yarn of small scale special production units could be effectively used for the production of sustainable patchwork fabrics. Waste from the cotton fabric cutting process, from the sample and stitching processes were successfully converted into value added structures in the form of cotton patches by using conventional patchwork techniques. In this way, an efficient way to remove valuable textile waste from waste dumps and make better use of the resources used in the garment production process [1, 6] is provided.

The patchwork fabrics not only had more fabric mass, thickness and seam strength than the conventional cotton fabrics, but also demonstrated more structural integrity and seam fail resistance among the developed patchwork fabrics. It was noticed that the tensile strength, abrasion resistance, air permeability and moisture transmission properties of the fabrics slightly decreased, but they are still within acceptable limits and did not affect the functional performance of the fabrics significantly. Based on the findings, the patchwork fabrics can be recommended for use in various applications including apparel, tote bags, cushion

covers, and decorative home furnishings, due to their satisfactory physical, mechanical and comfort properties.

A patchwork development can be viewed as a practical and affordable low-cost waste minimization approach which will help to implement the principles of the circular economy by extending the life cycle of the textile material, and by promoting the direct re-use of pre-consumer cotton waste [5, 9 & 10]. Consumer acceptance, the potential for economic viability and the use of a variety of textile waste streams for patchwork applications could be explored in future studies.

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Development and Experimental Validation of an Indigenous State-of-the-Art Radiant Heat Tester for Protective Textiles

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Abstract:

This paper presents the development and experimental validation of an indigenous and state-of-the-art radiant heat tester for the assessment of radiant heat transfer properties of protective textiles according to ISO 6942 requirements. The designed system was aimed to offer a cost-effective, technologically advanced substitute for imported radiant heat testing instruments. Several advanced features including the ability to predict second-degree burns, automated space adjustment of radiant source to calorimeter, and chiller-supported water-saving cooling system were incorporated to improve measurement accuracy, operational efficiency, and practical use of the instrument. Performance of the developed radiant heat tester was experimentally evaluated at heat flux levels of 20 kW/m² and 40 kW/m² through repeatability and reproducibility analysis. Statistical parameters including standard deviation, coefficient of variation, repeatability coefficient, reproducibility coefficient, and one-way ANOVA were employed to assess measurement precision and inter-operator consistency. The obtained reproducibility values were 10.0% and 8.56% at 20 kW/m² and 40 kW/m², respectively, while repeatability values were 12.15% and 13.09%. ANOVA analysis showed no statistically significant operator-induced variability ($p > 0.05$). The results confirmed the robustness of the instrument, acceptable accuracy of measurement, and repeatable operational reliability for the two heat flux scenarios. The developed instruments were also incorporated Stoll curve second degree burn prediction model to evaluate thermal protective performance of textile sample under the exposure of radiant heat. The HTI-T24 values decreased from 45.05 s at 20 kW/m² to 27.66 s at 40 kW/m², indicating faster heat transfer and earlier burn injury at higher heat flux levels. Overall, the developed radiant heat tester was found to be satisfactory compliance with ISO 6942 requirements and offers a sustainable, economical, and scientifically reliable solution for radiant heat exposure testing and thermal protective performance evaluation applications.

Keywords: Burn injury prediction, Chiller-assisted cooling, Indigenous instrumentation, Protective textiles, State of art, Thermal protective performance

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1. Introduction

Protective workwear used in foundries, oil and gas industries, firefighting, and other fire-prone environments plays a vital role in personal protective equipment (PPE). Such clothes give thermal protection in case of fire accidents and high heat exposure while improving worker safety and operational efficiency. The effectiveness of protective textiles is primarily depends on their resistance to the three principal ways of heat transfer: convection, conduction, and radiation [1]. Among these, radiant heat transfer takes place by way of electromagnetic radiation from flames or high temperature surfaces without any direct contact [2]. Hence, the design and evaluation of protective textiles require reliable assessment of radiant heat resistance to provide optimum thermal protection for workers, firefighters, and military personnel operating under hazardous conditions. ISO 6942 is one of the most accepted standards for radiant heat performance evaluation of protective materials and textiles. Radiant heat testers developed under this standard measures parameter like heat flux, exposure time, and heat transfer characteristics assess thermal protective performance. In a review of commercially available systems where most advanced radiant heat testers are made in China, Germany, and the USA. Companies like Qinsun

Instruments, Motis Fire Technology, Advance Instruments, and Dongguan Yuyang Instrument Co., Ltd. employ SiC rods or quartz lamps as heating sources along with copper calorimeters and thermocouple-based measurement systems[3-7]. The performance of these systems is generally discussed in a range of heat fluxes of 5–80 kW/m² and temperature limits up to 1100–1200°C. But the equipment available is imported, technologically limited and expensive, making research labs and industries heavily reliant on imported testing systems [8].

This dependence makes it harder to access and slows development of R&D, and quality assurance activities for the protective textiles. To address these issues, this study presents the development and experimental validation of an indigenous state-of-the-art Radiant Heat Tester for evaluating radiant heat transfer performance of protective textiles. The developed system has been designed in line with ISO/IS standards and includes improved measurement accuracy, advanced data acquisition, and the capability to predict second-degree burns. Emphasis has been placed on developing a cost-effective, reliable, and user-friendly alternative to imported systems, thereby strengthening indigenous testing capabilities and supporting research, standardization, and quality assessment of protective textiles in India.

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2. Materials and Method

The Methodology adopted for the development and validation of the indigenous radiant heat tester was based on ISO 6942 standard for assessment of radiant heat transfer through protective textiles. The radiant heat tester was originally designed and built from the main components including SiC heating rods, a copper calorimeter, specimen holding assembly, chiller-assisted cooling system, automated calorimeter positioning mechanism, and computerized data acquisition unit. The system implemented was integrated with automatic control and monitoring facilities for proper measurement of thermal exposure parameters. The instrument was calibrated for test temperature and heat flux before testing using standard calibration procedures to ensure measurement accuracy and heat flux uniformity. Textile samples were conditioned in normal laboratory atmosphere and positioned vertically between the radiant heat source and the copper calorimeter in the testing chamber. Tests were performed to determine the effects of exposure to radiant heat at heat flux levels of 20 kW/m² and 40 kW/m², where the increase in calorimeter temperature and the threshold time were continuously monitored via the data acquisition system. Various experimental trials were carried out under the same operating conditions to assess the repeatability and reproducibility performance of the developed instrument. The statistical analysis was performed according to ISO 5725-2 using arithmetic mean, standard deviation, coefficient of variation (CV%), repeatability and reproducibility coefficients, and one-way ANOVA to determine measurement precision, inter-operator variability, and overall reliability of the developed radiant heat tester. Figure 1 shows the overall methodology adopted in the present work.

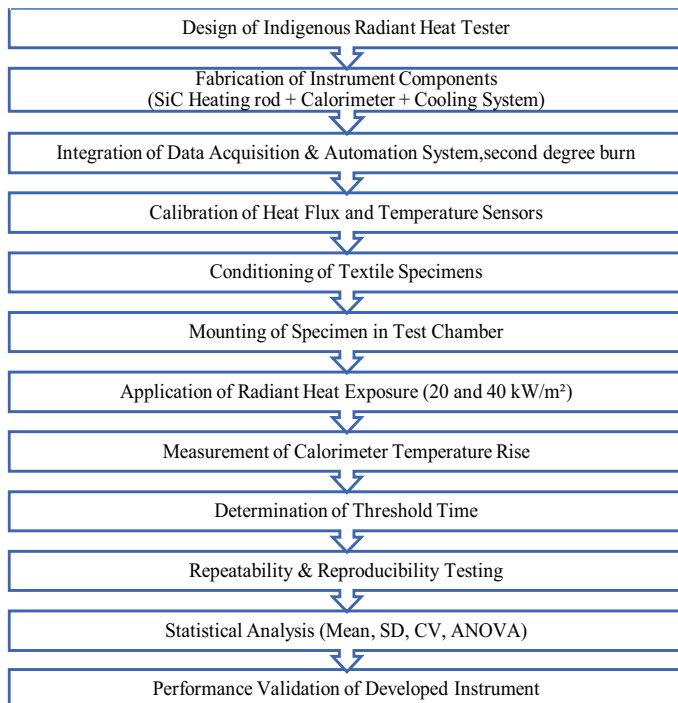


Figure 1 - Overall methodology flow diagram

a. Statistical Analysis Method

I. Mathematical models used for reproducibility analysis

Statistical analysis of the developed radiant heat tester was conducted in accordance with ISO 5725-2 to evaluate repeatability and reproducibility performance. Threshold time measurements obtained at 20 kW/m² and 40 kW/m² heat flux levels were statistically analysed using arithmetic mean, standard deviation, coefficient of variation (CV%), repeatability standard deviation, reproducibility standard deviation, repeatability coefficient, and reproducibility coefficient. The following mathematical models have been used to validate the developed instruments.

Mean threshold time

The overall mean threshold time is calculated as following [9]:

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i \quad (1)$$

Standard deviation is calculated using:

$$S_r = \sqrt{\frac{\sum n_i - 1 s_i^2}{\sum n_i - 1}} \quad (2)$$

Where: S_R = reproducibility standard deviation,
 S_i = standard deviation for each operator and
 n_i = number of observations for operator

Percent reproducibility

$$\% \text{ reproducibility} = \frac{S_R}{\bar{x}} \quad (3)$$

Coefficient of variation (CV%) [10]

$$S = \sqrt{\frac{\sum_{i=1}^n x_i - \bar{x}^2}{n-1}} \quad (4)$$

$$CV \% = \frac{S}{\bar{x}} \quad (5)$$

Where, S = sample standard deviation, x_i = each measured value, $\bar{x}$ = mean value, n = total number of measurements

Reproducibility coefficient

$$R = 2.77 X S_R \quad (6)$$

ii. One-way ANOVA for operator reproducibility

One-way ANOVA was additionally performed to evaluate inter-operator variability and determine the statistical significance of operator-dependent measurement differences. The ANOVA F-ratio was calculated using the ratio of variance between operators to variance within operators. A significance level of $p < 0.05$ was considered statistically significant. The statistical analysis confirmed acceptable precision, stable measurement consistency, and reliable operational performance of the developed radiant heat tester [11]. The ANOVA model is:

$$F = \frac{MS_{between}}{MS_{within}} \quad (7)$$

Where as $MS_{between}$ = variance between operators,
 MS_{within} = variance within operators

Determine Degrees of Freedom

$$df_1 = k - 1 \quad (8)$$

$$df_2 = N - k \quad (9)$$

Where: df_1 and df_2 are between group degree of freedom and within group degree of freedom, k no. of operators and N total number of measurements. The p -value is computed as:

$$P = 1 - F_{cdf}(1.46) \quad (10)$$

Where, F_{cdf} = cumulative distribution function of the F-distribution

The p -value was obtained from the cumulative F-distribution corresponding to the calculated ANOVA F-statistic ($F=1.46$) with degrees of freedom $df_1=2$ and $df_2=6$. The resulting p -value of 0.305 indicated that operator-induced variation was statistically insignificant.

b. Mathematical models used for repeatability analysis

The arithmetic mean threshold time was calculated using:

$$\bar{x} = \frac{\sum x_i}{n} \quad (11)$$

The repeatability standard deviation (S_r) was determined using:

$$S_r = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n-1}} \quad (12)$$

The percent repeatability was evaluated as:

$$\text{Repeatability} = \frac{S_r}{\bar{x}} \times 100 \quad (13)$$

The coefficient of variation (CV) was calculated using:

$$CV\% = \frac{S_r}{\bar{x}} \times 100 \quad (14)$$

The repeatability coefficient (r) was estimated from:

$$r = 2.77 S_r \quad (15)$$

3. Results and Discussion

a. Advanced instrument features

The designed radiant heat tester was successfully developed, built as an indigenous state-of-the-art thermal exposure testing system as specified by ISO 6942. In addition to complying with the measurement standard of radiant heat exposure, a variety of advanced functional changes were introduced to enhance the operational ability, testing accuracy, automation and sustainability of the instrument. A significant advancement introduced in the developed system was the integration of a second-degree burn prediction feature, allowing to estimate the thermal exposure conditions that lead to the formation of second-degree skin burns. Unlike traditional radiant heat testing systems generally limited to measurements of heat transfer and threshold time,

the developed instrument allows the thermal performance of material levels to be evaluated and physiologically relevant burn injury assessment for improved applicability for thermal protective clothing evaluation, firefighting protective equipment assessment and industrial heat hazard studies. The second-degree burn prediction approach designed into the system was extrapolated from classical concepts of thermal injury as reported by Henriques and Moritz(1947) [12], who derived the correlation for thermal exposure and formation of skin burns. Another great innovation was in the developed system was the automatic provision of space-adjuster between the calorimeter and the radiant heat source, while manual alignment is needed for traditional systems, with positions and incident heat flux being inconsistent exposure. The separation distance was controlled with accuracy and reproducibility with the automated positioning arrangement, thus increasing the accuracy of heat flux, experimental consistency, and overall operational reliability. Accuracy of positioning and uniformity of heat flux are important considerations in the measurement of radiant heat exposure and in calorimeter-based testing systems [13]. In addition, a chiller-assisted cooling arrangement was incorporated within the intermediate water circulation loop to reduce continuous water consumption while maintaining stable thermal control conditions during prolonged operation. The closed-loop recirculation configuration enhanced thermal stability and improved operational sustainability through effective water conservation. Similar thermal stabilization approaches have been reported to improve heat transfer control and operational efficiency in thermal systems[14]. The indigenous development of the complete testing system additionally provides significant economic and practical advantages, as commercially available ISO 6942-based radiant heat testers are generally associated with high procurement and maintenance costs. Indigenous and cost-effective scientific instrumentation development has also been recognized as an important approach for improving research accessibility and laboratory sustainability [15]. Overall, the developed radiant heat tester successfully combines ISO 6942-compliant thermal exposure measurement capability with advanced features including second-degree burn prediction, automated calorimeter positioning, and water-saving chiller-assisted cooling, thereby enhancing the scientific utility, operational efficiency, measurement accuracy, sustainability, and practical applicability of the instrument for radiant heat exposure studies and thermal protective performance evaluation applications.

b. Statical analysis

Statistical analysis of developed radiant heat tester was performed according to ISO 5725-2 to determine repeatability and reproducibility at 20 kW/m² and 40 kW/m² heat flux levels. The arithmetic mean, standard deviation, coefficient of variation (CV), repeatability standard deviation (S_r), reproducibility standard deviation (S_R),

Table 1 - Threshold time measurements at 20 kW/m² heat flux

Operator	Trial 1 (s)	Trial 2 (s)	Trial 3 (s)	Mean (s)	SD (s)	CV (%)
1	8.0	8.9	8.6	8.50	0.46	5.39
2	7.6	8.9	7.2	7.90	0.89	11.25
3	9.6	9.8	7.8	9.07	1.10	12.15

Table 2 - Threshold time measurements at 40 kW/m² heat flux

Operator	Trial 1 (s)	Trial 2 (s)	Trial 3 (s)	Mean (s)	SD (s)	CV (%)
1	8.0	8.9	8.6	8.50	0.46	5.39
2	7.6	8.9	7.2	7.90	0.89	11.25
3	9.6	9.8	7.8	9.07	1.10	12.15

Table 3 - Summary of reproducibility parameters

Parameter	20 kW/m ²	40 kW/m ²
Overall Mean Threshold Time (s)	8.49	7.48
Standard Deviation, <i>S</i> (s)	0.90	0.87
Coefficient of Variation, CV (%)	10.7	11.65
Reproducibility Standard Deviation, <i>S_R</i> (s)	0.85	0.64
Percent Reproducibility (%)	10.0	8.56

repeatability coefficient (*r*), and reproducibility coefficient $\bar{R}$, were calculated to assess measurement precision and consistency. In addition, one-way ANOVA was conducted to evaluate inter-operator variability. The obtained statistical results confirmed acceptable precision, stable instrument performance, and reliable operational consistency of the developed radiant heat tester.

i. Analysis of reproducibility performance

Performance of the developed radiant heat tester in reproducibility was evaluated against the needs of ISO 6942 at two levels of incident heat flux, i.e. 20 kW/m² and 40 kW/m². The threshold times were measured from three different operators, with three trials repeated by each operator under the same experimental conditions. The statistical analysis was done to assess inter-operator variability, measurement consistency and overall instrument reliability. Table 1 and Table 2 represent the threshold time measured at 20kW/m² and 40kW/m² heat flux. The summarized reproducibility parameters for both heat flux levels are presented in Table 3.

Figure 2 shows reproducibility Comparison Among Operators. The reproducibility graph compares the mean threshold times obtained by different operators at 20 kW/m² and 40 kW/m² heat flux conditions. The graphical results show that the measured threshold times obtained by different operators followed a consistent trend without extreme deviations. At 20 kW/m², Operator 3 produced slightly higher threshold times compared with Operators 1 and 2, whereas at 40 kW/m², Operator 2 showed comparatively higher threshold values. However, the overall differences among operators remained moderate, indicating good inter-operator consistency. The graphical comparison supports the ANOVA findings, which indicated no statistically significant operator-dependent effect (*p*>0.05). Therefore, the developed radiant heat tester demonstrated acceptable

reproducibility and operator-independent measurement performance.

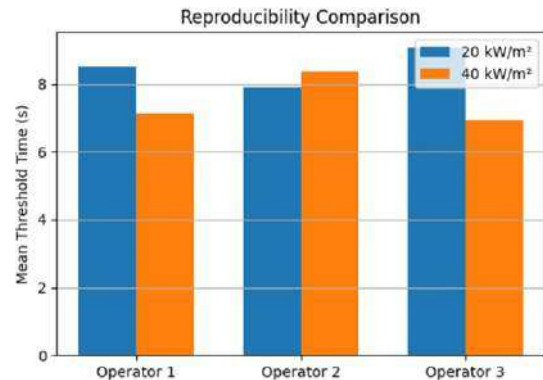


Figure 2 - Reproducibility comparison among operators

ii. ANOVA analysis

A one-way analysis of variance (ANOVA) was performed to determine whether operator-induced variability significantly affected the threshold time measurements. The ANOVA results for both heat flux levels are presented in Table 4. The ANOVA F-ratio was determined using [11].

$$F = \frac{MS_{\text{between}}}{MS_{\text{within}}}$$

Table 4 - One-Way ANOVA results

Heat Flux	F-value	p-value	Interpretation
20 kW/m ²	1.46	0.305	No significant operator effect
40 kW/m ²	4.41	0.066	No significant operator effect

Since all p-values were greater than 0.05, no statistically significant differences among operators were observed at either heat flux level. The reproducibility analysis conducted

according to ISO 6942 demonstrated that the developed radiant heat tester exhibited acceptable measurement consistency at both 20 kW/m² and 40 kW/m² incident heat flux conditions. The obtained coefficient of variation values ranged from 10.7% to 11.65%, indicating acceptable experimental precision for a laboratory-developed thermal exposure instrument[9]. At 20 kW/m², the instrument exhibited a reproducibility standard deviation of 0.85 s and a percent reproducibility of 10.0%. The corresponding reproducibility coefficient was 2.35 s, indicating acceptable agreement among measurements performed by different operators. Similarly, at 40 kW/m², the reproducibility standard deviation decreased to 0.64 s with a percent reproducibility of 8.56%, suggesting improved inter-operator consistency at higher heat flux conditions. The ANOVA results also confirmed operator variability was not statistically significant for both heat flux intensity, as all p-values were above the 95% confidence criterion ($p > 0.05$). The p-value obtained at 40 kW/m² was relatively closer to the significance threshold against the 20 kW/m² condition, the observed variation was within the permissible limits. Overall, the statistical analysis confirms that the developed radiant heat tester meets the stipulated reproducibility requirements in accordance with ISO 6942 and provides stable, reliable and operator independent measurements performance. The obtained results confirm the suitability of the instrument for radiant heat exposure testing and applications for thermal protective performance evaluation.

c. Analysis of repeatability performance

The repeatability of the developed radiant heat tester was evaluated in compliance with the ISO 6942 requirements at two levels of impinging heat flux, i.e 20 kW/m² and 40 kW/m². Repeatability tests were performed under identical experimental conditions with identical test setup and operator. Three measurements were repeated at each heat flux level, and the threshold times obtained were subjected to statistical analysis for assessment of short-term

Table 5 - Repeatability test at 20 and 40 kW/m² heat flux

Trial No.	Threshold Time (s)	
	Measurement at 20 kW/m ² Heat Flux	Measurement at 40 kW/m ² Heat Flux
1	9.6	7.3
2	9.8	5.9
3	7.8	7.6

Table 6 - Summary of repeatability parameters

Parameter	20 kW/m ²	40 kW/m ²
Mean Threshold Time, $\bar{x}$ (s)	9.07	6.93
Repeatability Standard Deviation, S_r (s)	1.10	0.91
Percent Repeatability (%)	12.15	13.09
Coefficient of Variation, CV (%)	12.15	13.09
Repeatability Coefficient, r (s)	3.05	2.52

measurement precision and stability of the instrument. The repeatability performance at both the heat flux levels exhibited in the Table 5 while Table 6 represents the summary of repeatability parameters.

The graphical trend shown in the Figure 4 indicates that the developed radiant heat tester was stable short term measurement behaviour at the two heat fluxes. The slightly higher fluctuation at 40 kW/m² is caused by the higher intensity of thermal exposure, which can increase sensitivity to specimen positioning and variations in thermal response.

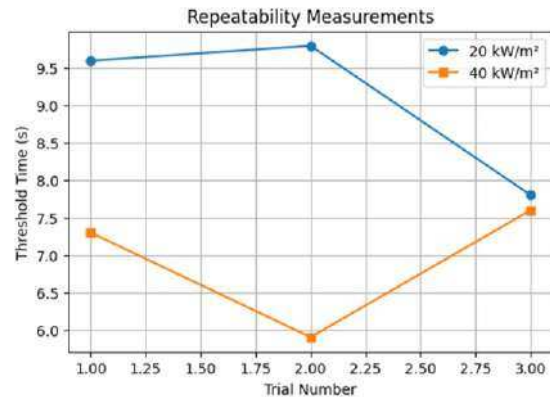


Figure 3 - Repeatability measurements at 20 kW/m² and 40 kW/m²

But the spread of measurements results was within permissible experimental limit, validating acceptable repeatability performance. Repeatability The analysis showed that the developed radiant heat tester had good short term precision at heat flux values of 20 kW/m² and 40 kW/m² [9]. The mean threshold time was 9.07 s for 20 kW/m² with repeatability standard of 1.10 s. The associated percent repeatability and coefficient of variation were both calculated as 12.15%, showing moderate but acceptable variation among repeated measurements taken at the same conditions. The mean threshold time at 40 kW/m² decreased to 6.93 s due to the enhanced incident heat flux, which enhanced thermal response. The repeatability standard deviation at this heat flux level was 0.91 s, while the percent repeatability and coefficient of variation were calculated as 13.09%. Although the variability at 40 kW/m² was slightly higher compared with the 20 kW/m² condition, the obtained values remained within acceptable experimental limits for laboratory-developed thermal exposure instruments [9]. The repeatability coefficient gives an estimate of the expected largest difference between two repeated measurements under the same testing conditions for approximately 95% of observations. Repeatability coefficient was found as 3.05 s at 20 kW/m² and 2.52 s at 40 kW/m², indicating good agreement between the measurements repeated. Overall, the repeatability parameters obtained are confirmed that the developed radiant heat tester demonstrates consistent and reliable measurement performance under repeated testing conditions. The calculated repeatability values fulfil the actual repeatability specifications for radiant heat exposure testing specified in ISO 6942 and validate the suitability of the instrument

developed for use in thermal protective performance evaluation. The comparison graph shows the relationship between reproducibility and repeatability percentages at the two levels of heat flux.

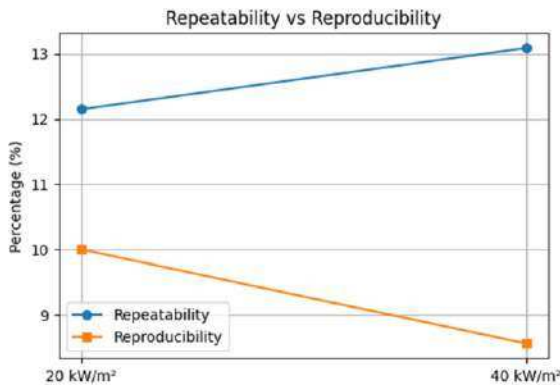


Figure 4 - Comparison of repeatability and reproducibility percentages

The repeatability values were 12.15% at 20 kW/m² and 13.09% at 40 kW/m², while the reproducibility values were 10.0% and 8.56%, respectively. The graph depicts reproducibility values were somewhat lower than the repeatability, which implies that the inter-operator variability stayed under control and did not affect much instrument performance. Also, the reproducibility percentage dropped at higher heat flux, suggesting better operator consistency in high thermal exposure conditions. Overall, graphical analysis supports that the developed radiant heat tester is stable repeatability and reproducibility properties at heat fluxes of 20 kW/m² and 40 kW/m², thereby validating the suitability of the instrument for radiant heat exposure testing in accordance with ISO 6942 requirements.

d. Second degree burn prediction using stoll curve

To assess the thermal protective performance (TPP) with reference to skin burn injury of the textile materials tested, the experimentally determined heat transfer data were evaluated based on the Stoll second-degree burn criterion. The Stoll curve is a commonly accepted method predicting the onset of second-degree skin burns according to the relationship between skin exposure temperature and exposure time under thermal loading conditions.

In this study, the temperature response recorded from the calorimeter during radiant heat exposure tests was associated with the Stoll burn injury curve to calculate time to reach the second degree burn conditions. The testing system developed is integrated with the Stoll curve, enabled real-time assessment of prediction of burn injury and enhanced practical relevance of the instruments for assessment of protective textiles for high temperature environment. The corresponding burn prediction curves from the developed instruments are shown in Figure 5 and Figure 6, while the tabulated experimental results are summarized in Table 7 and Table 8, respectively.

Results show that the multilayer textile assembly revealed improved protection against heat from radiation exposure, with higher Heat Transfer Index (HTI) values observed at lower heat flux conditions. For an exposure of about 20 kW/m², the multilayer sample presented HTI-T24 values of 45.05 s and 43.35 s for Test 1 and Test 2, respectively, indicating long standing resistance to heat transmission and delayed onset of second degree burn symptoms. However, when the radiant heat exposure was increased to approximately 40 kW/m², the HTI-T24 values decreased to 27.66 s and 27.08 s, showing a relatively faster rate of heat transfer through the textile assembly because of the higher thermal load. Likewise, the Time to Threshold Index (TTI) values also decreased with an increase in heat flux, reducing from approximately 44 s at 20 kW/m² to nearly 27 s at 40 kW/m². This decrease is clearly indicative of the protective performance of the textile assembly, is strongly dependent on the intensity of the radiant heat. The results also suggest that even though the multilayer structure provides substantial thermal insulation, accelerates the transfer of thermal energy a significant increase in the incident heat flux thus reducing the time before a second degree burn injury may occur. Overall, the integration of the Stoll burns prediction model with the developed indigenous radiant heat tester successfully enabled reliable prediction of skin burn injury behaviour and provided a comprehensive assessment of the thermal protective performance of the tested textile assemblies. The developed system demonstrated satisfactory capability for evaluating protective textiles under realistic thermal exposure conditions and may serve as a cost-effective alternative to imported testing equipment.

Table 7 - Multilayer sample tested at 20kW/m²

Sample	Specimen	Exp Energy (kW/m²)	TTI (s)	HTI-T12 (s)	HTI-T24 (s)
Multi-Layer	Test1	20.135	44.71	28.78	45.05
Multi-Layer	Test2	20.146	43.04	27.4	43.35

Table 8 - Multilayer sample tested at 40kW/m²

Sample	Specimen	Exp Energy (kW/m²)	TTI (s)	HTI-T12 (s)	HTI-T24 (s)
Multi-Layer	Test1	40.34	28.02	18.94	27.66
Multi-Layer	Test2	40.746	26.45	18.21	27.08



Figure 5 - Sample tested at 20kW/m²

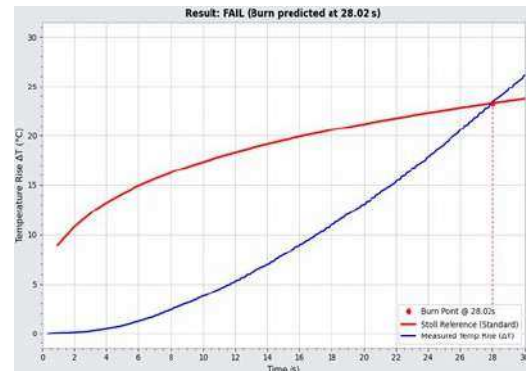


Figure 6 - Sample tested at 40kW/m²

4. Conclusions

An indigenous and state-of-the-art radiant heat tester was designed, constructed and experimentally verified successfully as per requirements of ISO 6942 for radiant heat transfer analysis of protective textiles. The instrument thus developed was very much advanced features capability to forecast second degree burns, automated calorimeter positioning, and chiller-assisted water-saving cooling arrangement, and hence improved operational capability, measurement accuracy, automation, and sustainability of the system. The analyses performed for repeatability and reproducibility at heat fluxes 20 kW/m² and 40 kW/m² showed acceptable consistency of the measures and stable performance of instruments. The achieved reproducibility, 10.0% and 8.56%, and repeatability values 12.15% and 13.09%, laboratory scale heat exposure showed acceptable accuracy measurements. Moreover, one-way ANOVA analysis revealed no statistically significant operator dependent variability, confirming reliability and inter-operator consistency of the developed instrument. The

integration of the Stoll second-degree burn model enabled reliable prediction of the behavior of burn injury under conditions of thermal exposure. The HTI-T24 values decreased from approximately 45 s at 20 kW/m² to 27 s at 40 kW/m², showing lower thermal protective performance at high heat flux levels. The indigenous development of the testing system additionally provides substantial economic and practical advantages by reducing dependence on costly imported testing equipment. Overall, the developed radiant heat tester demonstrated reliable performance and practical suitability for radiant heat exposure testing, thermal protective performance evaluation, and protective textile research applications.

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Valorization of *Typha domingensis* Pers. fibers for Sustainable Mustard Microgreen Cultivation

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Abstract:

*Invasive aquatic species, often seen as a burden, can actually offer surprising benefits as renewable resources in sustainable agriculture. The research focuses on *Typha domingensis* pers, which has been largely overlooked in agricultural innovations. The aim of the study is to explore its potential by transforming its fibers into needle-punched nonwoven mats for the environmentally friendly cultivation of mustard microgreens.*

Typha mats were made by needle punching technique and incorporated natural elements such as aloe vera and NPK (Nitrogen, Phosphorus, Potassium) coatings to promote plant growth and enhance the nutritional profile of the microgreens. To assess their effectiveness, the performance of our innovative Typha mats was compared with that of untreated mats, commercial coir mats, and standard tissue paper substrates. Physical evaluations were conducted to measure the strength, stiffness, and moisture management of the mats.

The Typha mats demonstrated adequate strength and effective moisture management, proving their viability as cultivation substrates. Notably, the untreated Typha mats outperformed all other substrates, yielding an impressive 13.13 grams of microgreens per tray. This represented a 119.6% higher yield than the tissue paper control (5.98g) and a 217.9% higher yield than the commercial coir mat (4.13 g). Additionally, the NPK-treated mats showed a significant increase in bioactive compounds, with heightened levels of total phenolic content, chlorophyll, and β -carotene. Interestingly, sensory evaluations indicated that the quality and acceptability of microgreens grown on all types of mats were similar, meaning the innovative mats did not compromise taste or quality. No statistically significant differences were observed in the sensory values of the microgreens ($p > 0.05$).

This research underscores the potential of biomass-derived nonwoven substrates as sustainable alternatives to traditional growing media in agriculture. By utilizing these biodegradable materials, advanced circular bioeconomy initiatives can be met, reduce human dependence on non-renewable inputs, and inspire innovation in urban and controlled-environment agricultural practices. Together, these efforts contribute to a more sustainable and greener future.

Keywords: Agro- textiles, biodegradable grow mats, microgreens cultivation, needle-punched nonwovens, *Typha domengensis* Pers. fibers

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1. Introduction

In light of the growing energy demand and heightened environmental concerns, scientists and researchers have undertaken initiatives to enhance processes and materials that serve as sustainable energy solutions, as well as eco-friendly options [1]. Among the innovative approaches being explored, invasive plant biomass has emerged as a promising source for various applications, including bio-fertilizers, biochar, and bio-composites. The potential use of this biomass can significantly reduce the carbon footprint by providing sustainable resources [2]. For instance, the invasive plant biomass, such as *Typha domengensis* Pers, grows rapidly, often overwhelming entire aquatic ecosystems and hindering the ecological balance [3]. This

research is focused on extracting fibers from *Typha domengensis* Pers. Pers and transforming them into non-woven mats through a needle punching process. This innovative approach is aimed at creating bio mats specifically designed for microgreens cultivation. Furthermore, the increasing population, urbanization, and climate change have led to a notable decline in arable land. As agricultural land becomes scarcer, the challenge of ensuring food sustainability to meet the nutrient needs of a projected global population of 9.7 billion by 2050 becomes increasingly daunting [4]. This situation, characterized by a reduction in farmland and an increase in micronutrient deficiency, calls for the adoption of urban farming as a viable solution. Urban farming leverages technology and automation to optimize land use while addressing nutritional needs, effectively emerging as a response to the intertwined issues of land scarcity and food insecurity. This strategy not only aims to boost productivity but also seeks to minimize

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environmental impacts through the use of climate-controlled high-rise buildings. These innovations offer numerous advantages, including enhanced biosecurity, pest freedom, and reduced transportation needs for fresh produce [5]. Ultimately, this research endeavours to tackle the dual issues of providing fresh foods to urban communities in a sustainable manner while simultaneously converting invasive green biomass into a practical and eco-friendly solution as grow mats. Natural fibers such as jute, hemp, coir, and kenaf have been explored for sustainable fiber-based materials; however, their application as growing substrates for microgreens remains limited. Similarly, the potential of *Typha domengensis* Pers. as a needle-punched nonwoven growing medium has received limited attention, creating a research gap in its valorization for sustainable microgreen cultivation.

This study presents a novel interdisciplinary approach combining textile engineering and sustainable agriculture. The key contributions include: (i) the first reported application of *Typha domengensis* Pers. needle-punched nonwoven mats for microgreens cultivation, (ii) development of a mechanical fiber extraction method to enhance sustainability, (iii) functionalization of grow mats using aloe vera and NPK coatings to improve nutritional quality, and (iv) evaluation of physical, agronomic, and sensory properties to assess substrate performance. This research demonstrates a circular bio-economy pathway for converting invasive biomass into value-added agricultural substrates.

2. Methodology

2.1 Development of non-woven mats from *Typha domengensis* Pers. fibers

Typha domengensis Pers, an invasive aquatic plant, grows extensively and occupies puddles, negatively impacting the aquatic ecosystem [6]. Typically, this plant is removed by burning when the water in a pond or puddle recedes. Its growth disrupts development and causes imbalances in the ecosystem [7]. *Typha domengensis* Pers. contains fibrous materials that are similar to those found in jute and other unconventional fibers, and mostly finds application as reinforcement in composites [8].

Several methods for fiber extraction were tested. Water retting was not feasible due to its aquatic nature, and chemical retting raised sustainability concerns. Therefore, a new mechanical method of fiber extraction was developed, addressing the issues associated with the other two methods. The process for preparing *Typha* fibers initially involves cleaning and sun-drying. The leaves are then cut to 10 cm and boiled for three hours. After boiling, they are blended for 15 seconds to create a fibrous slurry, from which water is squeezed out to obtain the fibers, which are later dried in sunlight (28 °C to 30 °C) for a period of two days [9].

As a pilot study, the extracted *Typha* fiber is blended with jute into non-woven fabrics of various combinations. These

blends are made into non-woven needle-punched mats and tested for their basic physical properties [10]. The combination that exhibited the best physical properties was identified as the combination of 70% *Typha* and 30% Jute and was selected for further study. The needle-punching process was carried out at a needle density of 180 punches/cm², a penetration depth of 8 mm, a fabric density of 3.290 g, and a production speed of 600 strokes/min. These processing parameters were maintained consistently during the fabrication of the selected non-woven mats to ensure uniform fabric structure and reproducibility.

2.2 Value Added Finishing

The optimum fiber combination that performed well was selected based on the test results. As the developed mats are for growing mustard microgreens, a value-added finish was applied using aloe vera gel and an NPK solution.

2.2.1 NPK coating

For the study, commercially available NPK solution, Erwon® NPK 20:20:20 Liquid Growth Fertilizer was used. Five different concentrations of the liquid NPK solution 2 ml, 4 ml, 6 ml, 8 ml, and 10 ml of the fertilizer were mixed with 500 ml of tap water.

Five pieces of the developed non-woven mat (NP4) that performed well in the physical tests was cut to dimensions of 190 mm x 130 mm to fit the microgreens tray. These samples were soaked in the various diluted NPK solutions for 10 minutes. After soaking, the samples were removed, squeezed out, and dried at 70° C for 24 hrs [11].

2.2.2 Aloe vera gel coating

Similarly, Aloe vera gel was extracted from a fresh aloe vera plant and ground into gel. The gel measuring 2ml, 4ml, 6ml, 8ml, and 10ml was mixed with 500ml of tap water. Five pieces of the developed non-woven mat were cut to the dimensions of 190mm X 130mm to fit the microgreens tray. The samples were soaked in the diluted aloe vera gel solution for 10 minutes, after which the samples were removed, squeezed out, and dried at 70° C for 24 hrs [11].

2.3 Optimization of value-added finish- Germination study

In order to optimize the coating concentrations, a germination study was done. The coated samples were weighed, crushed, and mixed with distilled water 5 times the weight of the coated samples (1:5). The content was placed in a shaker incubator for 1 h. The mixed solution is filtered using Whatman filter paper. Two discs of Whatman filter paper are placed on a petri dish, and about 10 undamaged healthy mustard seeds are placed on the filter paper in the petri dish. 4ml of the filtered saturated solution is poured onto the petri dish at room temperature for 7 days. Care was taken to see that the petri-dish was not exposed to direct sunlight. Triplicates were made for each variation, and the Seed germination percentage and relative seed germination percentage were calculated using the following formula [12]. The primary roots that reached a minimum of 5mm were

considered to have germinated [13]. The sample with a high percentage of germination was selected for further study.

$$\text{Seed germination(\%)} = \frac{\text{No. of germinated seeds}}{\text{No. of total seeds}} \times 100 \dots (\text{Equation 1})$$

$$\text{Relative Seed germination(\%)} = \frac{\text{No. of germinated seeds(samples)}}{\text{No. of total seeds (control)}} \times 100 \dots (\text{Equation 2})$$

2.4 Physical Testing of the developed and commercial non-woven mats

The developed non-woven Typha mat with the optimized value-added finished mats is tested for its physical properties. The names of the samples taken for the study are depicted in Table 1.

Table 1 - Sample Nomenclature

Samples	Content
T1	Tissue paper (Control)
T2	Needle-punched Typha fiber mats
T3	Aloe vera-treated needle-punched Typha mat
T4	NPK-treated needle-punched Typha mat
T5	Commercial coir mat

2.4.1 GSM

A GSM cutter was used to cut the fabric using rotating blades, typically 100cm² in a circular motion. The cut sample is then weighed on an electronic balance. A total of 10 random samples were taken, and the values are consolidated [14].

2.4.2 Tensile Strength

The tensile index indicates the maximum force required to break a standard-width test strip and is measured in megapascals (Mpa). The samples were evaluated for tensile index and elongation in accordance with ASTM D828-97. A constant-rate-of-elongation tensile testing machine was used for the assessment. The test specimens, which measured 2.54 ±0.5 cm in width and 25.4 ±0.5 cm in length and were free of creases, holes, or wrinkles, were held securely between the machine's jaws. A total of ten specimens in each principal direction were tested, and both tensile strength and elongation were recorded.

2.4.3 Stiffness

Stiffness serves as a crucial factor for assessing the rigidity and bending strength of a material. To measure the stiffness, the Shirley stiffness tester was utilized. Samples of needle-punched fabric were cut to match the dimensions of the template (15cm x 2.5cm). The prepared sample was placed under the template, and both were positioned on the tester's platform. The template is then gradually moved until the sample bends and aligns with the index line visible in the mirror. This process was repeated for all four sides. Ten repetitions for each variation were conducted to calculate the average stiffness value.

2.4.4 Thickness

A thickness gauge was employed to determine the thickness of the needle-punched non-woven fabrics, following the

ASTM D 5729 - 97 method. The gauge comprises a base component known as an anvil and a presser foot that applies a specific pressure to the sample. The thickness of the material is measured as the distance between the anvil and the presser foot. A load of 5 kPa was applied to the gauge, and thickness readings were taken at ten different locations across the fabric. The average value obtained indicates the thickness of the mat.

2.4.5 Sinking

Following the AATCC Test Method 17-1994, the sinking test was performed. The Typha needle-punched fabrics were cut to dimensions of 25mm by 25mm. A 1000 ml beaker was filled with deionized water, into which each sample was carefully dropped. The stopwatch was activated as soon as the fabric made contact with the water's surface, and the duration taken for the nonwoven to sink to the bottom of the beaker was recorded as the sinking time of the nonwoven mat. This procedure was repeated for the additional samples, and the average value was determined.

2.4.6 Wicking

A wicking test was performed to determine the moisture absorption capability of the non-woven fabrics. For each variant, 10 samples measuring 15 cm in length and 5 cm in width were cut. One end of each sample was connected to a 2g weight and positioned on a wooden block. The other end, which was immersed in a tray of distilled water for 2 cm, was observed for water rise. The height of the water above the immersed portion was recorded after maintaining a constant time of 1 minute. This procedure was repeated for the remaining replicas, and the average value was calculated.

2.4.7 Moisture content

A sample dimension of 2 inches by 2 inches was cut to assess the moisture properties of the samples. For each variety, ten replications were made. The initial weight of every sample is recorded and placed in a hot air oven set at 105°C for 1.5 hours. After that duration, the samples are removed and weighed. The percentage of moisture content is determined using the following equation.

$$\text{Moisture Content} = \frac{A - B}{A} \times 100 \dots \text{Equation 3}$$

A – Original weight of the sample (in grams)

B – Oven dry mass of the sample (in grams)

2.5 Plant culture study

2.5.1 Plant Culture Conditions and Growing Medium

The three developed non-woven mats were evaluated alongside commercial coir and tissue paper by growing mustard microgreens. The seeds were from the brand "allthatgrows". In August 2025, mustard microgreens, scientifically known as *Brassica juncea* [15], were cultivated in a shade net conditions for optimal growth. Each sample was subjected to four replicates to ensure the reliability of the results. The microgreens grown on tissue paper, commonly

used by urban populations for microgreen cultivation, served as the control group.

2.5.2 Growing Conditions

The sowings were carried out in a completely randomized manner across a total of 18 trays, with six treatments and three replications. The seeds for each tray were measured and placed randomly, ensuring that all seeds in each tray were of equal measure. The mats of all varieties were set on recycled polyethylene terephthalate (R-PET) trays, which have an area of 126 cm² and a weight of 6 grams. Each tray had eight holes at the bottom to allow for excess water drainage. For control trays, tissue papers were used.

The mats were pressed gently to achieve a uniform surface area before being watered. Approximately 2.5 grams of mustard seeds were sown in each tray, after which the mats were watered again, and the trays were covered with food-grade wraps to aid germination.

Once the microgreens had sprouted, the protective cover was removed, and they were placed under shade nets. The temperature inside the shade net was between 21.6^o C to 24.4^o C and the relative humidity was between 50% to 90% during the time of the study. Watering was conducted once a day at 9:00 AM, lasting for 10 minutes. A measured amount of water, approximately 100 ml, was sprayed onto each tray [16]. The mats and the microgreens grown on them are depicted in Fig. 1.

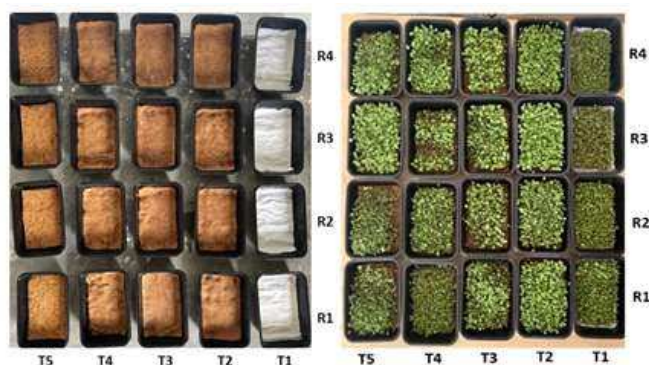


Figure 1 - Mustard microgreens in different grow medium

2.6 Determination of Yield

For harvesting, the mats were carefully removed from the trays and placed on a flat surface. Disinfectant scissors were used to trim the microgreens, ensuring that the cuts were made just above the mats. To measure the height, the average length of the microgreens from each tray was recorded. Measurements were taken from the tip of the leaf to the shoot just above the grow mats. A total of 40 microgreens were sampled from each variation (10 from each tray), and the average value was recorded. The total weight of the microgreens from each tray was measured with 4 replications for each variation.

2.7 Sensory Evaluation

Sensory assessments were carried out for all five treatments by a group of sensory specialists. The evaluations concentrated on different characteristics, such as appearance, texture, taste, color, and flavor. Thirty sensory specialists received samples without labels and were instructed to taste them. The findings were represented using a hedonic scale, with ratings of up to 9 points. Sensory perception and acceptability ballots were given to each participant. The intensity perception of microgreens' sensory characteristics was assessed using a nine-category horizontal line scale with labels ranging from none (1) to strongest imaginable (9), while overall acceptability, along with the liking/acceptability of appearance, texture, and flavor, was measured using a nine-point hedonic scale with verbal anchor labels ranging from highly unacceptable (1) to highly acceptable (9). Line scales were deemed a suitable option for consumer sensory and acceptability assessments of microgreens, as they can be utilized for both intensity and hedonic responses.

2.8 Determination of Total Phenolic Compounds

Evaluating the total phenolic compounds is crucial for assessing a plant's ability to act as an antioxidant, which is also beneficial for human health [17]. The analysis was conducted on five distinct samples of microgreens, following the protocols outlined by [18]. Approximately 1 gram of fresh microgreens was taken and blended with 10 ml of methanol and 1% formic acid. These were then centrifuged, and the total phenolic content was quantified using the Folin-Ciocalteu method. The test values are measured as mg of gallic acid equivalent per gram of fresh weight.

2.9 Determination of Chlorophylls

The chlorophyll levels of the five microgreen samples (T1 to T5) were assessed by collecting the microgreens from their individual trays. Approximately 1g of the microgreens was collected, frozen with liquid nitrogen, then homogenized with 80% acetone at a ratio of 1:10 (w/v) and mixed for 30 minutes, after which the chlorophyll a and b were calculated using the formula outlined by [19].

2.10 Determination of Beta Carotins

In plants, β -carotene plays essential roles in photosynthesis by acting as an accessory pigment that captures light and serves as a protective agent against detrimental light. It also functions as an antioxidant to help prevent cellular damage and generates precursors for plant hormones, thus affecting growth, responses to stress, and general plant well-being [20]. Following the procedure and formula stated by [18, 21] Beta carotene values were calculated.

2.11 Statistical Analysis

For the study, the data were collected and recorded in Microsoft Excel 2021, and statistical analyses were performed using the Statistical Package for the Social

Sciences (SPSS) software. The means obtained from various tests were compared using analysis of variance (ANOVA) at a significance level of 5% ($p \leq 0.05$). The statistical differences between sample groups were assessed using a t-test, also at a significance level of 5% ($p \leq 0.05$). The 'p' value represents the probability that any observed difference between groups is due to chance. Additionally, Post hoc test was conducted to identify significant differences in the growth analysis of the microgreens.

3. Results and Discussion

3.1 Optimization study – Germination test

The results of the germination study clearly show that the optimal concentrations were 4 ml for the NPK coating and 6 ml for the aloe vera gel. These two concentrations achieved a 100% germination rate, outperforming all other tested concentrations. Therefore, these two coating concentrations were selected for further study. The results of the germination study provide clear insights into the effectiveness of different coating materials on seed germination rates. This exceptional performance indicates that these specific concentrations are particularly suitable for enhancing seed germination among the selected concentrations.

3.1.1 Physical testing of various microgreens grow mats

The physical testing results of the selected grow medium are given in Table 2. The control sample tissue paper (T1) showed very low strength, stiffness, and stability, confirming its limited use as a grow mat. Needle-punched Typha mats (T2) performed significantly better, with higher strength and stiffness due to effective fiber interlocking. Bio-treatments further improved performance. The aloe vera-treated mat (T3) showed the highest strength among Typha samples, indicating improved fiber bonding, while the NPK-treated mat (T4) also exhibited enhanced mechanical stability without increasing thickness. Typha mats exhibited a longer sinking time than the control, indicating better structural integrity in water. Their moderate wicking behaviour supports sustained moisture availability rather than rapid water loss. The commercial coir mat (T5) had the highest strength and stiffness, but its high GSM and lower wicking may restrict uniform moisture distribution. Overall, treated Typha mats, T3 and T4, offer a good balance of strength, stability, and moisture management, making them promising sustainable alternatives to commercial grow mats.

Table 2 - Physical testing results

Samples	GSM (g)	Strength (MPa)	Thickness (mm)	Stiffness (cm)	Sinking (s)	Wickin g(cm)
T1- Tissue paper (Control)	1.523	70	5.12	2.4	6*	5.98*
T2- Needle-punched Typha fiber mats	3.290	181	5.85	6.1	195	3.03
T3 - Aloe vera-treated needle-punched Typha mat	3.457	234	5.26	6.4	181	3.16
T4 - NPK-treated needle-punched Typha mat	3.681	219	5.59	6.2	175	3.23
T5 - Commercial coir mat	8.552*	329*	7.73*	8.5*	265	2.10

3.2 Determination of Yield

3.2.1 Weight

The harvested microgreens were weighed using a high-precision electronic balance. Each tray, which contained different growing mediums and replications, was measured individually, and the corresponding values were recorded and presented in Table 3. Statistical analysis showed significant variations among the various growing media. Sample T2 exhibited the highest harvest weight at 13.13 g, while sample T5 showed the lowest harvest weight at 4.13 g. The higher yield may be due to the untreated Typha mat lacking additional coatings, which preserved its moisture-management and structural properties. Its moderate wicking behaviour likely provided consistent moisture to the microgreens, promoting growth and biomass accumulation. In contrast, the aloe vera and NPK coatings altered the mats' physical characteristics, affecting moisture distribution and yield. This indicates that the typha-grown mats, without any treatments, provided an optimum environment for mustard microgreen cultivation.

Table 3 - Weight of the mustard microgreens per tray during harvest

Sample	Weight (g)
T1	05.98 ^b
T2	13.13 ^a
T3	07.64 ^{bc}
T4	08.41 ^b
T5	04.13 ^c

3.2.2 Height

The harvested microgreens were measured from the base, just above the grow medium, to the tips of the shoots. A total of 25 samples were selected randomly to measure their height. These samples were placed on a perforated high-precision scale, and the readings were recorded and tabulated in Table 4. The sample with the maximum mean height was identified as T2, which had a mean height of 5.42 cm. In contrast, the samples T1, T3, and T5 had the shortest heights, and the differences among these three samples were not statistically significant.

Table 4 - Height of the mustard microgreens during harvest

Sample	Height (cm)
T1	3.67 ^c
T2	5.42^a
T3	4.22 ^c
T4	4.77 ^b
T5	4.10 ^c

3.3 Sensory Evaluation

The sensory evaluation of five microgreen samples showed consistently high acceptability across all evaluated attributes, with mean hedonic scale scores ranging from 7.2 to 8.0 and median values consistently at 8. The Shapiro–Wilk test indicated a non-normal distribution for most parameters; therefore, the Friedman test was applied. The Friedman analysis showed no statistically significant differences among the samples regarding appearance ($p = 0.067$), color ($p = 0.148$), flavor ($p = 0.534$), taste ($p = 0.131$), texture ($p = 0.598$), and overall acceptability ($p = 0.490$). Fig. 2 clearly shows that for most parameters, T2 demonstrated slightly higher values. These findings are indicated in Fig 2 and it shows that the sensory panel perceived all five microgreen samples similarly, with none demonstrating superior or inferior sensory qualities.

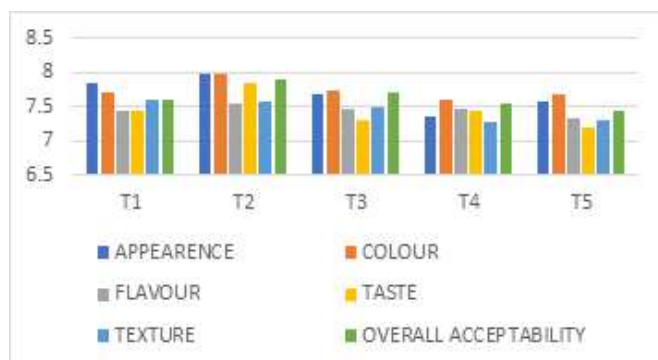


Figure 2 - Sensory evaluation of mustard microgreens grown on different growing media

3.4 Determination of Total Phenolic Compounds

The total phenolic compounds of all five microgreen variations are presented in Table 5. Among these samples, T4 exhibited the highest total phenolic content. This is likely due to the optimal growth conditions provided by its substrate, which ensured nutrient availability, adequate water retention, and favourable root-zone aeration. These substrate characteristics are known to enhance the biosynthesis of phenolic compounds, as they are produced in response to both nutrient supply and mild physiological stress. The increased total phenolic content of 1.34 mg/g observed in T2 suggests that its substrate created an environment conducive to the accumulation of bioactive secondary metabolites, thereby improving the overall nutraceutical quality of the microgreens.

Table 5 - Total Phenolic Compounds of mustard microgreens grown on different growing media

Samples	Total phenolic compounds (mg/g)
T1	1.28 ^a
T2	1.08 ^b
T3	1.05 ^b
T4	1.35^a
T5	1.34 ^a

3.5 Determination of Chlorophylls

The values of the pigment molecules chlorophyll a, chlorophyll b, and the total chlorophyll are represented in Table 6. In microgreens, chlorophyll measurement acts as a primary indicator of the bioactive density and photosynthetic efficiency. The values of the chlorophyll content vary depending on the medium and the environment in which the microgreens are cultivated. The results from the experiment depict that the chlorophyll values of mustard microgreens grown in T1, T4, and T5 are statistically significant from the chlorophyll values of the microgreens grown in T2 and T3.

Table 6 - Chlorophyll values of mustard microgreens grown on different growing media

Samples	Chlorophyll a (mg/g)	Chlorophyll b (mg/g)	Total Chlorophyll (mg/g)
T1	0.22 ^a	0.13 ^a	0.34 ^a
T2	0.17 ^b	0.08 ^b	0.25 ^b
T3	0.18 ^b	0.09 ^b	0.27 ^b
T4	0.23^a	0.12 ^a	0.35^a
T5	0.21 ^{ab}	0.14^a	0.35^a

3.6 Determination of Beta Carotens

β-carotene is an organic compound that plays an important role in neutralizing free radicals, promoting apoptosis in cancer cells, and increasing the production of natural killer cells, which in turn strengthens the immune system[22]. The beta carotene values per 100g of mustard microgreens are presented in Table 7. The T4 sample has the maximum beta carotene value of 134.20, while the minimum was noted for the T1 sample. From the values, it is clear that the addition of an NPK solution has a positive impact on the beta-carotene value of the mustard microgreen.

Table 7 - Beta carotene values of mustard microgreens grown on different growing media

Samples	Beta-carotene (mg/g)
T1	90.69 ^c
T2	47.34 ^d
T3	107.13 ^b
T4	134.20^a
T5	110.12 ^b

4. Conclusion

This research highlights the promise of using invasive *Typha domingensis* Pers. biomass as a sustainable substrate for growing microgreens. The study explored needle-punched

nonwoven mats, both untreated and treated with aloe vera and NPK nutrients, and found that the untreated mats yielded the best results. Interestingly, the NPK-treated mats boosted the levels of beneficial compounds. Sensory evaluations showed no significant differences in taste or acceptability among the various substrates. This innovative method not only offers an eco-friendly alternative to traditional growing media but also tackles urban food sustainability and land scarcity. By transforming invasive species into

biodegradable grow mats, this study supports circular bio-economy strategies and encourages sustainable farming practices in urban areas. The study had limitations, as it was conducted under controlled conditions and did not assess long-term performance, durability, or economic feasibility of the developed mats, highlighting the need for further research in diverse cultivation environments for large-scale agriculture.

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Thermal Resistance of Selected Knits Natural Dyed with Rubia Cordifolia and Caesalpinia Sappan

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Abstract:

Thermal resistance plays a critical role in determining the insulation and physiological comfort of performance textiles, especially in layered knit structures. The global textile industry is undergoing a significant paradigm shift toward sustainability, driven by the need to replace toxic synthetic dyes with eco-friendly alternatives. This research focuses on evaluating the dyeing potential of natural colorants extracted from Rubia Cordifolia (Manjistha) and Caesalpinia Sappan (Sappanwood) on Pique Airtex and Textured Bubble two distinct textured Knit fabrics. These fabrics, characterized by their unique three-dimensional structures and breathability, offer a challenging yet rewarding surface for natural dye uptake. Thermal conductivity tests were performed to evaluate the thermal comfort properties of the dyed fabrics, ensuring that the natural dyeing process maintains the inherent breathability and heat-regulation capabilities of the textured knit structures. Preliminary results indicate that the porous nature of Pique Airtex and the undulating surface of Bubble Knit fabrics significantly influence the visual aesthetics, creating unique tonal variations. Rubia Cordifolia provides rich earthy reds, while Caesalpinia Sappan offers vibrant pinkish-red hues, both showing promising affinity for the selected knit structures. This research evaluates the correlation between natural dye concentration and the thermal resistance of textured substrates to ensure functional efficiency remains uncompromised. This project concludes that integrating traditional plant-based dyes with modern textured knits provides a commercially viable, biodegradable, and non-toxic pathway for the functional apparel industry, fostering a more circular textile economy.

Keywords:Caesalpinia Sappan, Knitted materials, natural dyes, Rubia Cordifolia, Thermal Resistance

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1. Introduction

Thermal conductivity is the property of a material that indicates its ability to transfer heat from one surface to another. In textile materials, this property plays an important role in determining thermal comfort. Fabrics with high thermal conductivity allow heat to pass through them more easily. They tend to feel cooler when touched because heat from the human body is quickly transferred. In contrast, fabrics with low thermal conductivity restrict heat flow and therefore retain warmth, giving a warmer sensation [1]. Beyond mechanical and dimensional stability, thermal comfort is a primary factor in fabric performance. It is essentially determined by how effectively a fabric or garment manages the movement of heat, air, and moisture [2]. The Piqué Airtex(P°) is defined by its open, porous waffle-like texture, created using specific tuck and float stitches [3]. The Textured Bubble(T°) Knit Fabric, also often identified as popcorn knit stitch fabric, is constructed through the Weft Knit technique. This fabric is visually striking due to its three-dimensional 'bubble' or 'popcorn' effect created either directly by knitting sequence [4]. Natural dyes are colorants obtained from renewable biological and mineral sources, offering biodegradable and non-toxic alternatives to

synthetic dyes. Their environmental compatibility reduces hazardous effluent discharge during textile processing. These dyes are increasingly valued in sustainable textile systems due to lower ecological footprints [5]. Natural dyes have traditionally been used for coloring food, leather, and protein fibers such as silk, wool, and cotton due to their compatibility with natural materials. Growing environmental awareness has renewed interest in these dyes as safer and eco-friendly substitutes for hazardous synthetic colorants in sustainable textile markets [6]. Natural dyes originate from renewable resources and are biodegradable, resulting in a significantly lower environmental impact. Many natural colorants possess ultraviolet radiation absorption properties, thereby improving the UV protection performance of dyed cellulosic textiles [7]. Historically, most natural dyes were polar and water-soluble compounds derived from plants, insects, and marine organisms before the advent of synthetic dyes. These dyes are analytically classified based on their application techniques, which helps identify historical dyeing methods used by ancient and pre-industrial cultures [8]. Pique stands out in the textile industry due to its specialized knit structure and remarkable performance qualities. Renowned for its robust durability and superior ventilation, this material ensures the wearer stays cool and comfortable throughout the day. A key advantage of Pique is its moisture-management capability, which effectively wicks perspiration away from

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the skin, maintaining a fresh and dry feel [9]. Natural dyes are non-toxic, non-carcinogenic, recyclable, and environmentally safe, producing soft and aesthetically pleasing shades. However, many plant pigments are unsuitable for textile dyeing due to poor solubility, weak fiber affinity, or low resistance to light and atmospheric exposure [10]. The natural dyes possess lower ecological footprints compared to synthetic dyes because they originate from renewable resources. Traditional dyeing methods required minimal chemical processing. Natural dyeing practices also promoted circular use of agricultural waste. The importance of integrating traditional knowledge with modern science. This integration enhances dye performance without compromising sustainability. Natural dyes therefore support environmentally responsible textile systems [11]. Plant-based dyes provide eco-friendly coloration with reduced chemical consumption. The authors highlight mordant selection as a key factor influencing shade depth and fastness. Open-access case studies support sustainable dyeing methods [12]. Textured bubble knit is a specialized double-knit material engineered through a strategic blend of tuck and knit stitches. This specific structural combination is what gives the fabric its signature looks and durability [13]. By interlooping yarns into a flexible, stretchable structure that distinguishes it from woven textiles, the knitting process creates a highly adaptable fabric whose weight and performance are dictated by the specific technique used, making it perfect for intricate, form-fitting apparel [14]. This initiative focuses on substituting toxic synthetic pigments with eco-conscious, dermatologically safe alternatives that provide both aesthetic appeal and therapeutic benefits. While natural dyeing is inherently sustainable, integrating enzymatic pre-treatments further amplifies its environmental benefits, pushing the process toward a higher standard of ecological efficiency [15]. Indian madder (*Rubia cordifolia*) is an important natural dye-yielding plant of the Rubiaceae family. It is a perennial climber that can grow up to approximately 10 m in length. The plant is characterized by the presence of anthraquinone-based compounds in its extracts, which are known for diverse biological properties including anti-inflammatory, wound-healing, antidiabetic, anticonvulsant, antimicrobial, antiulcer, and antiviral activities. The roots of Indian madder serve as a major source of anthraquinone pigments responsible for its natural coloring potential [16]. Sappanwood is rich in antioxidant compounds and is widely recognized for its medicinal uses due to its anti-inflammatory and antimicrobial properties. The heartwood contains two principal colorants, brazilin and brazilein, which impart yellow and red hues, respectively. Structurally, brazilein differs from Brazilin by the presence of a carboxylic acid group, whereas brazilin contains a hydroxyl group at the corresponding position. Literature studies indicate that dyes obtained from sappanwood possess good resistance to light, highlighting their suitability for applications involving prolonged light exposure [17]. In this study, the thermal conductivity of the selected two Pique Airtex and Textured Bubble knitted fabrics before and after dyeing with selected natural dyes were emphasized.

2. Methodology

2.1 Selection of Fabric

Cotton is a skin-friendly, biodegradable, and renewable material known for its high moisture absorbency. Hence, cotton fabric is selected for the study. Piqué Airtex(P°) and Textured Bubble(T°) knit fabrics selected due to its advanced structural and performance features, placing it firmly within the Weft Knit category and selected for the study.

2.2 Selection of Natural Dyes and Natural Mordant

Rubia Cordifolia (R) and Caesalpinia Sappan (C) were taken in 15% as natural dyes and Myrobalan (m) in 3% for natural mordant was selected for the study.

2.3 Selection of Dyeing Medium

Aqueous dyeing medium was selected for the study.

2.4 Pilot Study

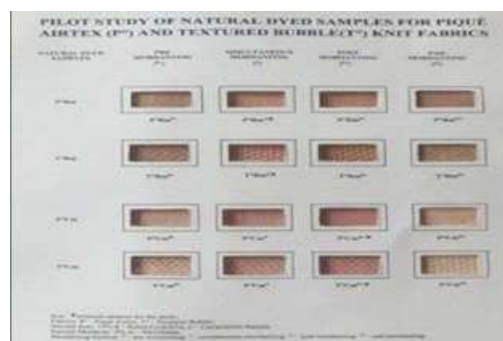


Plate 1: Pilot study for natural dyed samples

In the pilot study, two cotton woven fabrics Piqué Airtex fabric (P°) and Textured Bubble knit fabric (T°) were selected for natural dyeing. The P° and T° fabrics were dyed using two natural dyes, Rubia Cordifolia (R) and Caesalpinia Sappan (C), at a dye concentration of 15%. The natural mordant, Myrobalan (m) was taken as 3% was subjected to natural dyeing using four mordanting techniques like Pre mordanting (Pr), Simultaneous mordanting (S), Post mordanting (Po) and Pad mordanting (Pd) which gave Sixteen P°Rm^{Pr}, P°Rm^S, P°Rm^{Pd}, P°Rm^{Po}; T°Rm^{Pr}, T°Rm^S, T°Rm^{Pd}, T°Rm^{Po}; P°Cm^{Pr}, P°Cm^S, P°Cm^{Pd}, P°Cm^{Po}; T°Cm^{Pr}, T°Cm^S, T°Cm^{Pd}, T°Cm^{Po} natural shades (Plate 1) from dyed samples. Based on the pilot study results, four samples were selected for further study. The selection was based on the best shades of reproducibility, evaluated by 100 students from Chikkanna Government Arts College, Tiruppur, who assessed 16 natural dyed samples. From the feedback obtained, the highest recorded samples for the Rubia Cordifolia natural dyed simultaneous mordanting P°Rm^S and T°Rm^S and the Caesalpinia Sappan with post mordanting P°Cm^{Po} and T°Cm^{Po} were chosen for the study.

2.5 Actual Preparation and Extraction of Natural Dyes

For dyeing P° and T° grey fabrics, required grams of R in 15% natural dye powder and weighted grams of m in 3% natural

mordant powder were taken together and mixed in a dye bath with water at M:L ratio of 1:40. This mixture was heated and maintained to a temperature of 60 to 70°C for 50 minutes to extract the natural dye along with mordant solution. The solutions were stirred continuously to ensure a uniform mixture for the simultaneous mordanting dyeing process. For, Post mordanting process, required grams of Cin15% natural dye powder was mixed with water at a M:L ratio of 1:40. The extraction was carried out by boiling the mixture at 60 to 70°C for 50 minutes. Separately, the mordant solution was prepared by taking required grams of m in 3% in a 1:40 M:L of water. This mordant mixture was heated and boiled ranging from 60 - 70°C for 20 minutes to extract the natural mordant solution, which was kept ready for the post-mordanting stage.

2.5.1 Pre – Treatement of Cotton Knitted Fabric

The P° and T° knit fabrics were steeped into warm water for scouring treatment and later was soaked for 10 min, in cold soft water, taken out and excess liquor was squeezed.

2.5.2 Application of Natural Dyes to P° And T° Knit Materials

The selected simultaneous mordanted natural dyed P°Rm^s, T°Rm^s and post mordanted P°Cm^{po}, T°Cm^{po} samples which were chosen from the pilot study was undertaken for the final dyeing process for 2mof knit fabric each respectively. The natural dyeing process was carried out using a Jet Dyeing Machine for P° and T° Knit fabrics. Following the simultaneous natural dyeing process technique for R, the samples were natural dyed in Jet Dyeing Machine, following the parameters for simultaneous mordanting where required ml of natural dyeing liquor and mordant liquor was taken and the knit materials were steeped inside and boiled at 55°C for 50 minutes and for post mordanting process for C, the samples were natural dyed in Jet Dyeing Machine, where required ml of natural dyeing liquor was taken and the knit materials were steeped inside and boiled at 55°C for 45 minutes. After which the dye liquor was ejected out, and the

fabrics were treated in a separate mordant bath within the machine for 20 minutes. The four natural dyed knit materials P°Rm^s, T°Rm^s, P°Cm^{po} and T°Cm^{po} obtained are shade dried and subjected to tests.

2.6 Fabric Tests

The original P° and T° fabrics and four natural dyed P°Rm^s, T°Rm^s, P°Cm^{po} and T°Cm^{po} fabrics were subjected to objective testing such as fabric weight, bursting strength, crease recovery, stiffness, drape, abrasion resistance, shrinkage, spirality, capillary rise, water absorbency test - drop test, sinking test; colour fastness - sunlight, washing, crocking, perspiration and pressing; thermal conductivity test, antimicrobial test - antibacterial test and antifungal tests. The obtained readings were calculated and analyzed under result and discussion.

2.6.1 Thermal Conductivity Test

Thermal conductivity is the ability of a fabric to transfer heat to control temperature, determined by the rate of thermal transport through the material [18]. This was carried out using Lee's Disc method. The Rate of heat transfer at steady state through a given material is given by the following equation: $Q = k \cdot A \cdot (T_1 - T_2) / d$. The rate of cooling off at steady state temperature is given by this equation; $Q = m \cdot c \cdot (dT/dt)$. Since at steady state, the amount of heat entering a system is the same as the amount of heat leaving a system, the following equation may be produced; $k \cdot A \cdot (T_1 - T_2) / d = m \cdot c \cdot (dT/dt)$. The Thermal Conductivity constant may be isolated to produce the following; $k = [m \cdot c \cdot (dT/dt) \cdot d] / A \cdot (T_1 - T_2)$. Thermal conductivity in knitted fabrics has no fixed “best” value—it depends on use. Table 1 - For winter, lower values (<0.45 W/mK) are ideal since they trap heat and provide insulation, while for summer, higher values (>0.65 W/mK) are better as they transfer heat away for cooling. Medium values (0.46–0.65 W/mK) give balanced comfort suitable for casual wear.

Table 1: Thermal conductivity in fabrics

Reading Range (W/mk)	Desired Conductivity	Category	Fabric Feel & Season	Description
0.035 – 0.045	Lowest (λ lambda λ Value)	Hot / Warm	Winter Wear (Fleece, Heavy Knits)	High Insulation: Retains body heat and prevents it from escaping.
0.046 – 0.065	Medium (λ lambda λ Value)	Medium	Standard Comfort (T-shirts, Interlock)	Moderate Transfer: Balanced heat flow suitable for daily wear.
0.066 – 0.090+	Highest (λ lambda λ Value)	Cool	Summer / Activewear (Jersey, Mesh)	High Heat Transfer: Quickly releases body heat to keep you cool.



Plate 2: P°Cm^{po}



Plate 3: T°Rm^s

2.7 Construction of The Apparel

For the apparel construction, T-Shirt (unisex) garment for the age group 7 to 8 years was selected and constructed for P°Cm^{Po} and T°Rm^S. The constructed T-shirts was worn to AI model and is pictured in Plates 2 and 3.

3. Results and Discussion

The evaluation for the Original P° and T° knit fabrics and Natural Dyed P°Rm, T°Rm, P°Cm and T°Cm materials were carried out for mechanical, subjective tests, Thermal Conductivity test and for antimicrobial activity.

3.1 Visual Evaluation of the Natural Dyed Knit Samples

The results indicate that among the sixteen natural dyed samples, P°Rm^S and T°Rm^S natural dyed samples with Rubia Cordifolia using simultaneous Myrobalan mordanting were preferred by 10% and 11% of the respondents respectively. In the case of Caesalpinia Sappan natural dyed fabrics, post-mordanted samples Myrobalan P°Cm^{Po} and T°Cm^{Po} recorded higher preferences of 14% and 17% respectively. Based on the overall highest responses received P°Rm^S, T°Rm^S, P°Cm^{Po} and T°Cm^{Po} were selected for further study.

3.2 Analysis of Fabric Weight

The analysis of fabric weight (g/cm²) from Table 2A, P°Cm^{Po} recorded the highest fabric weight (1.638 g/cm²), while T°Rm^S and T°Cm^{Po} were lowest (1.378 g/cm²). P° measures remained consistent ($p > 0.70$), but T° varied significantly ($p < 0.05$). ANOVA confirmed internal consistency yet strong differences across variables ($F = 27.75$, $p < 0.01$), showing P° results are precise, whereas T° outcomes depend on variable choice. Overall, the findings highlight that P° related measures are statistically interchangeable and precise, while T° related measures vary significantly, and the choice of variable strongly influences fabric weight conclusion.

3.3 Analysis of Bursting Strength Test

The mean breaking strength (kg/cm²) as shown in Table 2B, indicate that P° derivatives showed higher strength than the original (P°Cm^{Po} = 7.803 kg/cm², +8.30%; P°Rm^S = 7.682 kg/cm², +6.62%). Similarly, T° derivatives exceeded the original (T°Cm^{Po} = 8.068 kg/cm², +3.30%; T°Rm^S = 8.163 kg/cm², +4.52%). Paired t-tests confirmed significant differences ($p < 0.05$), with ANOVA showing consistency within variables, no significant differences in P° ($p = 0.412$), but significant variation in T° ($p = 0.038$) and across all six variables ($p < 0.01$). Overall, the findings highlight that both P° and T° derivatives consistently elevate the original values, with T° derivatives showing the highest absolute means and precision, while P° derivatives show larger percentage gains relative to their original. This underscores the methodological impact of derivative measures in fabric weight analysis.

3.4 Analysis of Crease Recovery

From Table 2C, the mean crease recovery (°) indicates that the P° derivatives showed reduced crease recovery angles compared to the original, while T° derivatives improved slightly (+2.4% and +3.6%). Overall, P° had the highest crease recovery angle (114.1°), with P°Rm^S performing best among dyed samples (105.5°). Statistical tests confirmed significant differences for P° derivatives ($p < 0.05$), variation within T° ($p = 0.038$), and highly significant differences across all six variables ($p < 0.01^*$). Overall, the findings highlight that P° derivatives consistently underestimate the original values, while T° derivatives slightly elevate the original values, with T°Rm^S being the most stable and precise. This demonstrates clear methodological effects increase recovery angle measurement.

Table 2: Fabric Tests

Table A: Fabric weight						Table B: Bursting strength				
Samples	Mean	% Loss Or Gain Over Original	t-test (value, p, sig)	Two-way ANOVA (within group)	Two-way ANOVA (between all 6)	Mean	% Loss Or Gain Over Original	t-test (value, p, sig)	Two-way ANOVA (within group)	Two-way ANOVA (between all 6)
P°	1.627	—	—	F = 0.09, p = 0.92ns	F = 27.75, p < 0.01 **	7.205	—	—	p = 0.412 ns	p < 0.01 **
T°	1.470	—	—	F = 3.65, p = 0.047*	F = 27.75, p < 0.01 **	7.810	—	—	p = 0.038 *	p < 0.01 **
P°Rm ^S	1.634	+0.43%	t = -0.18, p = 0.86ns	F = 0.09, p = 0.92ns	F = 27.75, p < 0.01 **	7.682	+6.62%	t = 2.19, p = 0.049 *	p = 0.412 ns	p < 0.01 **
T°Rm ^S	1.378	-6.26%	t = 2.31, p = 0.046 *	F = 3.65, p = 0.047*	F = 27.75, p < 0.01 **	8.163	+4.52%	t = 3.02, p = 0.015 *	p = 0.038 *	p < 0.01 **
P°Cm ^{Po}	1.638	+0.68%	t = -0.38, p = 0.72ns	F = 0.09, p = 0.92ns	F = 27.75, p < 0.01 **	7.803	+8.30%	t = 2.41, p = 0.039 *	p = 0.412 ns	p < 0.01 **
T°Cm ^{Po}	1.378	-6.26%	t = 2.55, p = 0.031 *	F = 3.65, p = 0.047*	F = 27.75, p < 0.01 **	8.068	+3.30%	t = 2.65, p = 0.027 *	p = 0.038 *	p < 0.01 **

Table A: Fabric weight						Table B: Bursting strength				
Samples	Mean	% Loss Or Gain Over Original	t-test (value, p, sig)	Two-way ANOVA (within group)	Two-way ANOVA (between all 6)	Mean	% Loss Or Gain Over Original	t-test (value, p, sig)	Two-way ANOVA (within group)	Two-way ANOVA (between all 6)
Table C: Crease recovery						Table D: Stiffness				
P°	114.1	—	—	p = 0.412 ns	p < 0.01 **	2.916	—	—	p = 0.041 *	p < 0.01 **
T°	99.7	—	—	p = 0.038 *	p < 0.01 **	3.502	—	—	p = 0.032 *	p < 0.01 **
P°Rm ^S	105.5	-7.5%	t = -2.98, p = 0.015 *	p = 0.412 ns	p < 0.01 **	3.495	+19.85%	t = 4.05, p = 0.002 **	p = 0.041 *	p < 0.01 **
T°Rm ^S	103.3	+3.6%	t = 2.95, p = 0.016 *	p = 0.038 *	p < 0.01 **	3.691	+5.39%	t = 2.18, p = 0.049 *	p = 0.032 *	p < 0.01 **
P°Cm ^P _o	105.1	-7.9%	t = -3.12, p = 0.012 *	p = 0.412 ns	p < 0.01 **	3.498	+19.96%	t = 4.12, p = 0.002 **	p = 0.041 *	p < 0.01 **
T°Cm ^P _o	102.1	+2.4%	t = 2.01, p = 0.073 ns	p = 0.038 *	p < 0.01 **	3.694	+5.48%	t = 2.21, p = 0.048 *	p = 0.032 *	p < 0.01 **
Table E: Drape Test						Table F: Abrasion resistance				
P°	62.0	—	—	p = 0.041 *	p < 0.01 **	26.84	-27.3%	ns	ns	p < 0.01 **
T°	68.7	—	—	p = 0.032 *	p < 0.01 **	33.97	-33.5%	ns	ns	p < 0.01 **
P°Rm ^S	67.1	+8.2%	+8.2%	ns	p = 0.041 *	26.24	-26.5%	p < 0.05*	ns	p < 0.01 **
T°Rm ^S	72.0	+4.8%	t = 2.98, p = 0.014 *	p = 0.032 *	p < 0.01 **	32.03	-32.1%	p < 0.01**	ns	p < 0.01 **
P°Cm ^P _o	68.0	+9.7%	t = 3.21, p = 0.011 *	p = 0.041 *	p < 0.01 **	24.84	-25.0%	p < 0.01**	ns	p < 0.01 **
T°Cm ^P _o	72.1	+4.9%	t = 2.12, p = 0.064 ns	p = 0.032 *	p < 0.01 **	30.16	-30.4%	p < 0.01**	ns	p < 0.01 **
Table G: Spiraliry						Table H: Drop test				
P°	3.44	—	—	p = 0.041 *	p < 0.01 **	1.27	—	—	p = 0.041 *	p < 0.01 **
T°	3.78	—	—	p = 0.032 *	p < 0.01 **	1.48	—	—	p = 0.032 *	p < 0.01 **
P°Rm ^S	3.93	+0.49	t = 3.45, p = 0.008 **	p = 0.041 *	p < 0.01 **	0.88	-0.39	t = -6.45, p < 0.001 **	p = 0.041 *	p < 0.01 **
T°Rm ^S	4.02	+0.24	t = 2.38, p = 0.031 *	p = 0.032 *	p < 0.01 **	1.16	-0.32	t = -5.88, p < 0.001 **	p = 0.032 *	p < 0.01 **
P°Cm ^P _o	3.89	+0.45	t = 3.21, p = 0.011 *	p = 0.041 *	p < 0.01 **	0.81	-0.46	t = -7.12, p < 0.001 **	p = 0.041 *	p < 0.01 **
T°Cm ^P _o	3.98	+0.20	t = 2.12, p = 0.046 *	p = 0.032 *	p < 0.01 **	1.00	-0.48	t = -6.01, p < 0.001 **	p = 0.032 *	p < 0.01 **
Table I: Sinking test						Table J: Thermal conductivity test				
P°	1.402	—	—	p = 0.041 *	p < 0.01 **	0.5228	—	—	p = 0.041 *	p < 0.01 **
T°	1.425	—	—	p = 0.032 *	p < 0.01 **	0.5959	—	—	p = 0.032 *	p < 0.01 **
P°Rm ^S	1.099	-21.6%	t = -6.45, p = 0.0001 **	p = 0.041 *	p < 0.01 **	0.5966	+14.2%	t = 4.45, p = 0.001 **	p = 0.041 *	p < 0.01 **
T°Rm ^S	1.133	-20.5%	t = -6.01, p = 0.0002 **	p = 0.032 *	p < 0.01 **	0.5969	+0.17%	t = 0.57, p = 0.58 ns	p = 0.032 *	p < 0.01 **
P°Cm ^P _o	1.115	-20.5%	t = -6.12, p = 0.0002 **	p = 0.041 *	p < 0.01 **	0.5910	+13.0%	t = 4.12, p = 0.002 **	p = 0.041 *	p < 0.01 **
T°Cm ^P _o	1.154	-19.0%	t = -5.88, p = 0.0003 **	p = 0.032 *	p < 0.01 **	0.5910	-0.82%	t = -1.12, p = 0.29 ns	p = 0.032 *	p < 0.01 **

Table K: Shrinkage									Table L: Capillary rise							
Samples	Mean Shrink age		t-test (value, p, sig)		Two-way ANOVA (within group)		Two-way ANOVA (between all 6)		Mean Capillary Rise (mm)		t-test (value, p, sig)		Two-way ANOVA (within group)		Two-way ANOVA (between all 6)	
	Wales	Course	Wales	Course	Wales	Course	Wales	Course	Wales	Course	Wales	Course	Wales	Course	Wales	Course
P°	2.95	6.00	—	—	p = 0.041*	p = 0.041*	p < 0.01**	p < 0.01**	31.9	28.5	—	—	p = 0.041*	p = 0.041*	p < 0.01**	p < 0.01**
T°	2.23	4.56	—	—	p = 0.032*	p = 0.032*	p < 0.01**	p < 0.01**	32.4	30.0	—	—	p = 0.032*	p = 0.032*	p < 0.01**	p < 0.01**
P°Rm _s	2.52	5.67	t = -3.59, p = 0.0058**	t = -2.58, p = 0.0296*	p = 0.041*	p = 0.041*	p < 0.01**	p < 0.01**	33.1	28.3	t = 2.75, p = 0.021*	t = -0.89, p = 0.39ns	p = 0.041*	p = 0.041*	p < 0.01**	p < 0.01**
T°Rm _s	2.46	5.67	t = -2.08, p = 0.0670ns	t = -2.08, p = 0.0670ns	p = 0.032*	p = 0.032*	p < 0.01**	p < 0.01**	35.3	28.5	t = 3.88, p = 0.005**	t = -2.41, p = 0.041*	p = 0.032*	p = 0.032*	p < 0.01**	p < 0.01**
P°Cm _{Po}	2.74	5.83	t = -3.49, p = 0.0068**	t = -3.77, p = 0.0044**	p = 0.041*	p = 0.041*	p < 0.01**	p < 0.01**	33.3	28.7	t = 2.91, p = 0.017*	t = 1.12, p = 0.29ns	p = 0.041*	p = 0.041*	p < 0.01**	p < 0.01**
T°Cm _{Po}	2.48	5.55	t = -2.11, p = 0.0645ns	t = -2.08, p = 0.0670ns	p = 0.032*	p = 0.032*	p < 0.01**	p < 0.01**	34.8	29.9	t = 3.45, p = 0.008**	t = -0.22, p = 0.83ns	p = 0.032*	p = 0.032*	p < 0.01**	p < 0.01**

3.5 Analysis of Stiffness

The mean stiffness (cms) from Table 2D, reveal that the P° derivatives showed much higher stiffness (≈ 3.50 cms, +19.9%) compared to the original P° (2.916 cms), while T° derivatives also exceeded the original (≈ 3.69 cms, +5.4%). Variability analysis confirmed P° derivatives were most precise (CV $\approx 2.1\%$), whereas P° itself was most variable (CV = 8.33%). Paired t-tests and ANOVA revealed significant differences within both P° and T° groups ($p < 0.05$) and highly significant differences across all six variables ($p < 0.01$), underscoring the methodological impact of derivative measures in fabric stiffness testing. Overall, the findings highlight that both P° and T° derivatives consistently elevate the original values, with P° derivatives showing larger percentage gains, while T° derivatives show higher absolute means. This underscores the methodological impact of derivative measures in fabric stiffness testing.

3.6 Analysis of Drape Coefficient

The Table 2E, mean drape coefficient (%) show that the PP° derivatives showed higher moisture regain ($\approx 67\text{--}68\%$, +8–10%) compared to the original P° (62%), while T° derivatives also exceeded the original ($\approx 72\%$, +5%). Paired t-tests confirmed significant differences for P° derivatives ($p < 0.05$), with T°RmS significant ($p = 0.014$) but T°CmPo not ($p = 0.064ns$). ANOVA confirmed internal consistency, yet revealed significant differences within both P° and T° groups and highly significant differences across all six variables ($p < 0.01^*$). Overall, the findings highlight that both P° and T° derivatives consistently elevate the original values, with P° derivatives showing larger percentage gains, while T° derivatives show higher absolute means. This underscores the methodological impact of derivative measures in fabric drape testing.

3.7 Analysis of Abrasion Resistance

From Table 2F, the mean abrasion resistance (%) values before abrasion show before abrasion, P° derivatives

(0.160–0.162) and T° derivatives (0.156–0.158) were slightly higher than their originals. After abrasion, all variables dropped sharply (–25% to –33%), with P°CmPo retaining the best resistance (0.120). Paired t-tests and ANOVA confirmed significant differences within both P° and T° groups and highly significant differences across all six variables ($p < 0.01^{**}$). Overall, derivative methods improved resistance initially, but abrasion reduced performance, with P°CmPo showing the best durability.

3.8 Analysis of Shrinkage

The mean shrinkage from Table 2K, indicate among natural dyed samples, P°RmS in wales and T°CmPo in courses showed the least favorable shrinkage. P° derivatives improved dimensional stability, with P°RmS Wales recording the lowest shrinkage (2.52), while T° derivatives worsened it, with T°RmS Courses showing the highest shrinkage (5.70, +27.6% vs T°). Statistical tests confirmed significant differences within both P° and T° groups ($p < 0.01$), highlighting that derivative methods benefit P° but are detrimental for T° in shrinkage control.

3.9 Analysis of Spirality

The mean spirality (%) (Table 2G), Spirality values were consistently higher in derivatives (≈ 3.89 – 4.02%), compared to originals (P° = 3.44, T° = 3.77). Since lower spirality is better, originals outperformed derivatives. Statistical tests confirmed significant differences ($p < 0.01$ for P°, $p < 0.05$ for T°), with P° showing the best result (3.44) and T°RmS the worst (4.02). Overall, derivative methods increased spirality distortion, making original values more reliable for minimizing spirality in knitted fabrics.

3.10 Analysis of Capillary Rise

From Table 2L, the mean wicking heights (mm) reveal in Wales, derivatives improved wicking height, with T°RmS Wales showing the highest (35.3 mm, +9%), followed by T°CmPo Wales (34.8 mm). In Courses, results were mixed—P°CmPo showed a slight gain, while P°RmS and T°RmS recorded losses. Statistical tests confirmed significant differences in Wales but weaker effects in Courses. Overall, derivative methods strongly enhance wicking in Wales, while their impact in Courses is inconsistent.

3.11 Analysis of Drop Test

The Table 2H, the mean drop times (sec) depict that Original fabrics (P° = 1.27 s, T° = 1.48 s) had the slowest sinking times, while all derivatives showed strong reductions. P°CmPo (0.81 s, –36.2%) was the best performer, followed by P°RmS (0.88 s). T° derivatives also improved but less effectively. Statistical tests confirmed significant differences ($p < 0.01^{**}$), with P° derivatives outperforming T° derivatives, demonstrating that derivative methods greatly enhance sinking performance.

3.12 Analysis of Sinking Test

The mean sinking times (sec) from Table 2I, show that Original fabrics (P° = 1.402 s, T° = 1.425 s) had the slowest sinking times, while all derivatives showed clear reductions.

P°RmS (1.099 s, –21.6%) and T°RmS (1.133 s, –20.5%) were the best performers, followed closely by P°CmPo (1.115 s) and T°CmPo (1.154 s). Statistical tests confirmed highly significant improvements ($p < 0.01^{**}$), with ANOVA showing differences within both groups and across all six variables. Overall, derivative methods enhanced performance, with P°RmS and T°RmS achieving the lowest sinking times.

3.13 Analysis of Colour Fastness Tests

The colour fastness tests conducted for the four natural dyed P°RmS, T°RmS, P°CmPo and T°CmPo fabrics, when compared with grey scales for colour change (CC) and colour staining (CS) showed good colour fastness to sunlight, washing, crocking and pressing. Merge colour staining (CS) and no colour change (CC) was noted for perspiration.

3.14 Analysis of Thermal Conductivity Test

From Table 2J, the mean thermal conductivity values exhibit P° 0.5228W/mk, T° 0.5959W/mk, P°CmPo 0.5910W/mk, +13.0% and P°RmS 0.5966W/mk, +14.2% are substantially higher than P°, while T°CmPo 0.5910W/mk, –0.82% is slightly lower than T°, and T°RmS 0.5969W/mk, +0.17% is nearly equal to T°. Variability analysis shows that P°CmPo CV% = 0.10% is the most stable, while P° CV% = 0.48% is the most variable. Paired t-tests confirm significant differences between P° and its derivatives $p < 0.01^{**}$, while differences between T° and its derivatives are not significant (ns). Two-way ANOVA revealed significant differences within both the P° group $p = 0.041^{*}$ and the T° group $p = 0.032^{*}$, and highly significant differences across all six variables $p < 0.01^{**}$. For applications requiring warmth retention, higher conductivity values (e.g., P°RmS = 0.5966) may be advantageous. For applications requiring insulation/cooling, lower conductivity values (e.g., P° = 0.5228) are preferable. Thus, there is no single “best” variable; the optimal choice depends on whether the fabric is intended to retain heat or dissipate it. By comparing the average means, the P° derivatives P°CmPo and P°RmS show clear gains over the original P° +13.0% and +14.2%, indicating that these derived measures consistently elevate the fabric weight values. In contrast, the T° derivatives behave differently: T°RmS shows a slight gain +0.17%, while T°CmPo records a small loss –0.82% compared to the original T°. Among the four natural dyed samples, P°RmS has the highest mean 0.5966, while T°CmPo has the lowest 0.5910. This pattern highlights that P°-related measures are systematically greater than the original, whereas T°-related measures remain close to or slightly below the original, reflecting methodological differences in measurement.

3.15 Analysis of Antibacterial Test

From figures 4-15, when checked for antibacterial activity (mm), of the natural dyed knit materials, varied significantly between the two tested organisms, *S. aureus* gram +ve and *E. coli* gram - ve. Based on the mean readings for original and natural dyed fabrics, the P° fabric consistently showed the best antibacterial performance, in contrast, the Textured Bubble (T°) fabrics generally showed slightly lower activity. Piqué (P°) fabrics consistently showed superior antibacterial



Figure 4: P° Figure 5: T° Figure 6: P°RmS Figure 7: T°RmS Figure 8: P°CmPo Figure 9: T°CmPo
Figures 4-9: Antibacterial activity against S. Aureus



Figure 10: P° Figure 11: T° Figure 12: P°RmS Figure 13: T°RmS Figure 14: P°CmPo Figure 15: T°CmPo
Figures 10-15: Antibacterial activity against E. Coli

activity, with inhibition zones up to 15.6 mm against *S. aureus* and 15.05 mm against *E. coli*. Textured Bubble (T°) fabrics performed slightly lower, averaging around 14.0 mm. Some samples like T°RmS and P°CmPo showed no resistance against Gram-negative bacteria. Overall, Piqué series fabrics demonstrated stronger antibacterial properties compared to Textured Bubble. Overall, the observed antibacterial activity in the Piqué series fabric samples showed good antibacterial properties.

3.16 Analysis of Antifungal Test

From Figures 16-27, the antifungal activity (mm), of the knit materials varied significantly between the two tested organisms, *C. Albicans* gram +ve and *A. Niger* gram - ve. Against *C. albicans*, P°CmPo showed the strongest antifungal activity (21 mm), followed by T°CmPo (19.4 mm) and T°RmS (16.85 mm), while P° and P°RmS had no effect. For *A. niger*, P° was most effective (19.35 mm), with only T°CmPo showing moderate activity (13.45 mm). Other samples exhibited no resistance, though Positive Controls consistently confirmed higher antifungal effectiveness.

4. Conclusion

Natural dyeing processes significantly reduce the environmental burden caused by the textile industry by eliminating toxic chemical runoff into water bodies. Unlike synthetic alternatives, these plant-based dyes are biodegradable, ensuring that the byproducts of the dyeing process can be returned to the earth safely as organic waste. From a consumer health perspective, natural dyes are hypoallergenic and non-toxic, making them much safer for the skin and overall well-being compared to harsh chemical dyes. This sustainable approach promotes a circular economy by utilizing renewable resources that have a significantly lower carbon footprint. Furthermore, it adds a unique aesthetic value to textiles, creating organic tones that reflect the beauty of nature without compromising ecological integrity. With moderate heat transfer (0.52-0.59 W/mk), cotton knitted fabric provides a balanced cooling effect. This thermal efficiency makes it an ideal choice for comfortable, everyday breathable apparel. Ultimately, natural dyeing serves as a vital solution for the future of ethical fashion, balancing high-quality production with environmental responsibility.

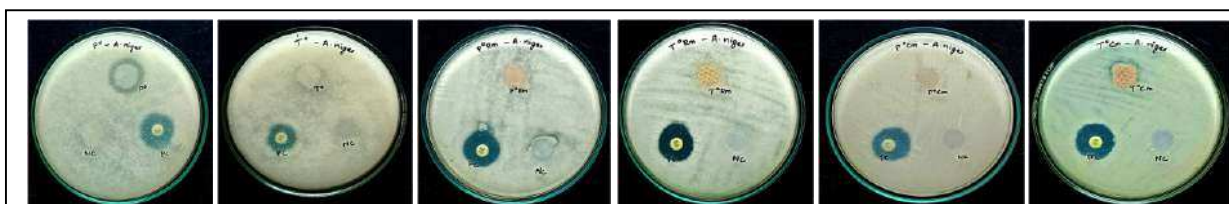


Figure 16: P° Figure 17: T° Figure 18: P°RmS Figure 19: T°RmS Figure 20: P°CmPo Figure 21: T°CmPo
Figures 16-21: Antifungal activity against A. Niger



Figure 22: P° Figure 23: T° Figure 24: P°RmS Figure 25: T°RmS Figure 26: P°CmPo Figure 27: T°CmPo
Figures 22-27: Antifungal activity against C. Albicans

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Nettle Fibre - A Sustainable Non-Conventional Bast Fibre for Textile and Allied Industrial Applications

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Abstract:

*Conventional textile fibres have been the backbone of the textile industry for decades. But growing concerns about their environmental impact have prompted the researcher to seek more sustainable alternatives. For example, cotton cultivation requires large amounts of water and pesticides, while synthetic fibres are petroleum-based and persist in the environment for longer. This has renewed interest in underexplored non-conventional plant fibres, which can provide sustainable raw materials for textile production. Nettle fibre, obtained from *Urtica dioica* and *Girardinia diversifolia* (Himalayan nettle), is a natural bast fibre with considerable potential. Because of its good strength and durability, it was used as a substitute for cotton during the First and Second World Wars. At present, nettle grows naturally in many parts of the world and is abundant in the Himalayan region of India, where it is mainly harvested from forest areas. The Himalayan nettle (*Girardinia diversifolia*) is a high-fibre-yielding bast plant that occurs abundantly in the Himalayan region, particularly in Uttarakhand, and extends into Sikkim at elevations between 1,300 and 3,500 m. This review covers the botany and agroclimatic requirements of nettle and highlights its traditional and emerging uses in food, medicine, agriculture, and applications in the textiles sector. The review discusses the steps involved in nettle fibre extraction, including harvesting, retting, decortication, and alkaline treatment, and also describes the chemical and mechanical properties of the fibre. With its renewable nature and wide range of applications, nettle fibre has strong potential to contribute to the development of a more sustainable textile industry while creating livelihood opportunities in rural regions.*

Keywords: *Himalayan nettle, microcrystalline cellulose, natural fibre composites, sustainable textiles, technical textiles*

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1. Introduction

"Nettle" is the common name which is used for different species of plants that belong to the family Urticaceae, generally known as *Urtica dioica* L. The name is derived from the Latin word *urere*, which means "to burn," in reference to the irritant stinging trichomes or spicule-type hairs present on the stem and the underside of the leaves, and release histamine-like compounds on contact with the skin [1, 2]. It is one of the oldest bast fibres known to civilisation. The commercial production of nettle fibres expanded in Europe in the 19th century. During the First and Second World Wars, when the conventional fibre supplies were disrupted, *Urtica dioica* was promoted and deliberately used as a substitute for cotton. Approximately 500 hectares of nettle fibre were cultivated for textile use in Germany and Austria [3, 4]. The destruction of dedicated processing facilities during the Second World War and the availability of cheaper synthetic and natural fibres after the war led to a sharp decline in commercial nettle fibre production; therefore, the large-scale processing technology was never fully re-established [5].

In the current scenario, the research community is once again looking to Nettle as a multifunctional, sustainable material for various end-use applications. Because of the increasing consumer and regulatory demand for biodegradable and renewable raw materials, the favourable mechanical performance of its bast fibre comparable with flax and hemp [6], the adaptability of the plant in a wide range of climatic conditions [7, 8], and the availability of large, under-exploited wild populations, particularly the Himalayan nettle, *Girardinia diversifolia*, across the Indian Himalayan belt has renewed the interest in global textile and material science community [9, 10]. Nettle is now increasingly recognised as a multipurpose crop with applications in food, nutraceuticals, pharmaceuticals, agriculture, and environmental remediation [11, 12]. This review first focuses on the botanical and agronomic context of the plant, then briefly surveys its utilisation across these allied sectors, before focusing on the technology of fibre extraction and the application of nettle fibre and its derivatives in the textile and allied industries (composites, technical textiles, and biomaterials)

2. Botanical Background, Taxonomy and Distribution

2.1 Taxonomy and Morphology

Urtica dioica L. belongs to the family Urticaceae, genus

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Urtica. It is a dioecious, rhizomatous, perennial herbaceous plant, as seen in Figure 1. Typically, it grows to 1-2 m in height under cultivation with erect, fibrous, four-angled stems and opposite, serrated, ovate to lanceolate leaves. Both stems and leaves are densely covered with stinging trichomes (hollow, silica-tipped hairs). When they come into contact, they release a mixture of histamine, serotonin, acetylcholine, and formic acid, which gives a burning sensation [2].

The commercially important species in the South Asian context is *Girardinia diversifolia* (Link) Friis, commonly known as Himalayan nettle, Himalayan giant nettle, or by various vernacular names such as Allo in Nepal and Bichhu Buti, Sisnu, Bacha, or Khujalli Patta in different parts of the Indian and Nepalese Himalaya [9]. Both species share the characteristic bast fibre architecture and stinging trichomes, and are frequently discussed in the literature.



Figure 1: “Nettle plant” (*Urtica dioica* L) [2]

Anatomically, the stem cross-section reveals a central lignified woody core surrounded by a cortical region containing bundles of long, strong bast fibres in the phloem, which is the same general architecture seen in other bast fibre crops such as flax, hemp and jute. The fibre bundles occur at the outer radius of the stem, and individual fibre cells exhibit a polygonal cross-section with a central lumen. This structural feature has made nettle a useful model species for comparative studies of bast fibre cell wall development [13].

2.2 Geographic Distribution

Urtica dioica is distributed across the temperate regions of Europe, Asia and North America, and is also found in parts of North Africa [12]. In India and the wider Himalayan region, including Jammu & Kashmir, Himachal Pradesh, Uttarakhand, Sikkim, Arunachal Pradesh, Nepal, Bhutan, and parts of Myanmar and China, the Himalayan nettle (*Girardinia diversifolia*) is widely distributed in forests at altitudes of approximately 1,200-3,500 m [14].

3. Agro-Climatic Requirements and Cultivation Practices

As a perennial, rhizomatous species, nettle possesses strong

regenerative capacity and multi-year field persistence, making it well-suited to long-term, low-input cultivation systems [8].

The well-drained loamy soils rich in organic matter, with a slightly acidic to neutral pH of 6.0-7.5 and temperate to subtropical climates between 15-25 °C and relative humidity of 60-75%, show optimal vegetative growth and fibre development. Adequate soil aeration promotes the rhizome expansion and stem elongation, whereas soil compaction and waterlogging impair root respiration and limit biomass production. The rhizomatous root system confers tolerance to mild frost and short drought, but prolonged temperatures above 30 °C or severe water stress reduce stem elongation and fibre quality [7]. The dry stem of the nettle plant typically yields a range of 3-12 tonnes per hectare per year, of which bast fibre constitutes approximately 10-15% of dry stem weight.

4. Nettle Production Scenario: Global and Indian Perspective

Nettle (*Urtica dioica* and *Girardinia diversifolia*) is cultivated and wild-harvested in many temperate and subtropical regions. However, its production is not recorded separately in most national and international agricultural databases. Europe remains the main region for nettle cultivation, particularly in Germany, Austria, Finland, and the United Kingdom, where it has traditionally been grown for medicinal and fibre applications [15].

In India, nettle is represented mainly by Himalayan nettle (*Girardinia diversifolia*; see Figure 2) and by wild populations of *Urtica dioica*. It grows naturally across the Himalayan region, particularly in Uttarakhand, Himachal Pradesh, Jammu & Kashmir, Sikkim, and Arunachal Pradesh [16, 17]. Unlike conventional fibre crops, nettle is not cultivated commercially and is primarily harvested from natural forests as a non-timber forest resource.



Figure 2: Himalayan Nettle plant (*Girardinia diversifolia*) [17]

Uttarakhand has been identified as the state with the highest potential for Himalayan nettle fibre production, with naturally growing nettle estimated to yield approximately 24,704.26 tonnes of raw dried fibre annually. The state has about 8,347.09 km² (33.75%) of its forest area under temperate forests. Assuming that only 0.5% of this area

supports nettle growth, nearly 16,694.18 ha would be available for nettle resources, with an estimated annual production of about 116,859.26 quintals of nettle [18]. At present, most fibre is harvested from wild populations, and community-based processing units largely depend on these resources. In recent years, local enterprises, particularly in Darchula (Pithoragarh, Uttarakhand), have promoted value addition by converting nettle fibre into yarn and fabrics for domestic and international markets [19].

5. Utilisation of the Nettle Plant Across Other Sectors

Before considering nettle fibre in detail, it is useful to appreciate the breadth of sectors in which the nettle plant is currently being investigated and used. This multifunctionality strengthens the case for nettle as an integrated, circular-bioeconomy crop in which fibre extraction can be combined with the food, pharmaceutical, agricultural and livelihood uses of the same plant.

5.1 Food and Nutraceutical Sector

Nettle leaves are rich in protein, dietary fibre, essential minerals (particularly calcium, iron and zinc), polyphenols, carotenoids, chlorophylls and other phytochemicals, supporting their classification as superfoods [20]. Nettle-enriched bread, durum wheat pasta, flatbread, and powder supplements have each been shown to enhance antioxidant activity, mineral content, and modulation of the glycaemic response relative to other supplemented controls [21]. Comparative nutritional evaluations of nettle flour and underutilised nettle products confirm that their protein, mineral and fibre profiles are favourable relative to those of conventional cereal flours (Table 1) [22].

Table 1: Chemical composition of wheat, barley and nettle powders [22]

Parameter	Unit of Measurement (UOM)	Wheat flour	Barley flour	Nettle powder
Moisture	%	12.37 ± 0.25	12.20 ± 0.19	7.04 ± 0.77
Crude protein	%	10.60 ± 0.23	11.84 ± 0.09	33.77 ± 0.35
Crude fibre	%	0.65 ± 0.13	1.03 ± 0.08	9.08 ± 0.14
Crude fat	%	1.68 ± 0.23	1.73 ± 0.67	3.55 ± 0.06
Total ash	%	0.56 ± 0.07	3.60 ± 0.08	16.21 ± 0.54
Carbohydrate	%	86.51 ± 0.27	81.80 ± 0.08	37.39 ± 0.72
Calcium	mg/100g	18.94 ± 0.08	17.51 ± 0.26	168.77 ± 1.47
Iron	mg/100g	3.37 ± 0.29	3.63 ± 0.11	227.89 ± 0.21

Stinging nettle has also been evaluated as a potential functional food additive more broadly, given its favourable phytochemical and antioxidant profile [23].

5.2 Pharmaceutical and Medicinal Sector

Phytochemical and pharmacological investigations confirm that nettle extracts exhibit significant antimicrobial, anti-inflammatory, hypoglycaemic, and lipid-regulating effects, along with immunostimulant and hair-loss-relief properties [11, 24 & 25]. Root extracts are widely studied for their role in managing inflammatory conditions and supporting prostate health [26]. At the same time, nettle-juice-based gels and other topical formulations have been explored for wound care and dermatological applications.

The European Medicines Agency has published a formal assessment of the herbal medicinal use of *Urtica dioica* L., reflecting regulatory recognition of its therapeutic potential [27]. Reviews of the plant's traditional pharmacological use in South Asia similarly document applications for arthritis, diabetes and general wound care [28].

5.3 Agricultural, Animal Feed and Environmental Sector

Nettle biomass and extracts are increasingly used in organic farming systems as green manure, bio-stimulant preparations, and slurry-based fertiliser, with demonstrated benefits for plant growth and stress tolerance [29,30]. Nettle, when used as an animal feed ingredient, has been shown to improve physiological performance, enhance feed conversion efficiency, and positively affect the mineral status of livestock and poultry. It is also suggested as a partial replacement for traditional protein meals in their diets [31].

Environmentally, nettle's ability to thrive on marginal and contaminated land, its low need for agrochemicals, and its rhizomatous growth habit make it valuable for phytoremediation, soil restoration, carbon sequestration, and agroforestry-based peat-substitution systems. Alley-cropping trials combining fibre nettle with tree rows have shown biomass yields sufficient to serve as a renewable alternative to peat in horticultural growing media [32]. Studies on drought stress and controlled hydroponic cultivation indicate that regulated growing conditions can boost the accumulation of nutritionally and pharmacologically valuable bioactive compounds compared to uncontrolled wild harvesting [33].

5.4 Socio-Economic and Livelihood Sector

In Himalayan communities, nettle holds significant socio-economic importance. Studies from Uttarakhand, Arunachal Pradesh, Nepal, Kenya, and Rwanda consistently report its traditional uses for food, fodder, fibre, fencing, and medicine. These studies also emphasise the central role women play in nettle collection, processing, and craft production [34]. Value-chain development programs, like the Nepalese Allo enterprise model, demonstrate that with proper training, market linkages, and product diversification, nettle can significantly contribute to rural livelihoods and the economic empowerment of women [22].

The remainder of this review centres on the key topic of this manuscript: extracting bast fibre from nettle stems and its use

in textile manufacturing and related industries, including fibre-reinforced composites, technical textiles, natural dyeing, and cellulose-derived biomaterials.

6. Nettle Fibre Extraction Technology

The transformation of nettle stems into textile-grade bast fibre involves a sequence of harvesting, retting, mechanical decortication, drying, and cleaning with some chemical surface modification. To maximize fibre yield, fineness, strength, and spinnability, proper physiological maturity at harvest and precise management of each subsequent processing step are crucial, as bast fibres are found in the phloem zone around the woody core [3].

6.1 Harvesting and Post-Harvest Handling

Nettle stems are typically harvested at the full-flowering stage, about 4-5 months after planting, when the fibres have reached their best quality. Himalayan nettle is an annual crop that begins to grow during July-August and reaches maturity between October and January, when it is harvested for fibre extraction [18]. The stems are cut close to the ground to maximise fibre yield while allowing the root system to regenerate for future growth. After harvesting, the stems are bundled and kept aligned to prevent fibre damage, and the leaves are removed to reduce microbial contamination during retting. The effect of harvest time on the properties of nettle fibre is shown in Table 2.

Harvesting nettle at the full-flowering stage provides the best fibre quality because cellulose content is at its highest while lignin content remains at an optimum level (10 to 11 %). Harvesting too early produces immature, weaker fibres, whereas delayed harvesting increases lignin content, resulting in coarser, more brittle fibres with lower dye absorption [35, 36].

Table 2: Tabulated Data for Different Age Nettle Fibres [35]

Fibre Age (Weeks)	Moisture Content (%)	Fineness (Tex)	Tenacity (cN/Tex)	Elongation at Break (%)
12	11.5	0.85	3.18	1.79
13	11.9	0.90	3.76	1.93
14	12.4	1.00	4.98	2.13
15	12.6	1.10	6.02	2.25
16	12.6	1.20	7.13	2.31
17	12.5	1.35	8.21	2.29
18	12.3	1.45	8.57	2.25
19	12.25	1.50	9.51	2.21

6.2 Retting: Biological Fibre Separation

Retting is the most important step in nettle fibre extraction, where microorganisms break down pectin and hemicellulose to separate the bast fibres from the woody stem. Water retting produces clean, strong, and lustrous fibres but requires large amounts of water and generates wastewater. Dew retting is a low-cost, environmentally friendly method commonly used in traditional processing, although it produces fibres with

more variable quality [10]. Enzyme-assisted retting improves fibre quality, reduces processing time, and minimises environmental pollution, making it suitable for industrial applications. Chemical retting uses chemicals such as sodium hydroxide (NaOH) and sodium hypochlorite or sodium chlorite to separate nettle fibres from the bark. This method can produce stronger fibres than untreated nettle fibres. The optimum extraction conditions were 8% NaOH at 85°C for 1 hour. Under these conditions, Himalayan nettle bark, which initially contains 69.24% cellulose, 5.29% hemicellulose, 15.79% lignin, and 9.68% ash, shows an increase in cellulose content to approximately 89% due to the effective removal of hemicellulose, lignin, and ash. As a result, cleaner fibres with improved mechanical properties are obtained, making them more suitable for textile and composite applications [37].

6.3 Mechanical Decortication, Drying, Scutching and Cleaning

After retting and drying, the fibre is separated from the woody stem using a process called decortication. In this process, the stems are crushed to break the woody part and release the fibre with as little damage as possible. In small-scale Himalayan production, about 1 kg of nettle bark produces around 400 g of fibre [10]. The extracted fibre is then dried to about 8-10% moisture, which helps prevent damage during storage. After drying, scutching is used to remove any remaining woody pieces, and hackling (if needed) combs and straightens the fibres, making them finer and easier to spin into yarn.



Figure 3: Harvesting and extraction of nettle fibre [10]

6.4 Chemical and Alkaline Surface Treatment

Alkaline (sodium hydroxide) treatment is widely applied to improve nettle fibre properties for both textile and composite applications. Systematic optimisation of alkali concentration, temperature, and treatment duration for

Table 3: Comparison of the Mechanical Properties of Untreated (Control) and Chemically Pre-treated Himalayan Nettle Fibres [38]

Sr. No.	Mechanical Property	Unit	Untreated (Control) Nettle Fibre	Chemically Pre-treated Nettle Fibre
1	Fineness	(den)	14.77	11.60
2	Tenacity	(g/den)	3.84	5.46
3	Elongation	(%)	1.66	3.33
4	Breaking Force	(g)	54.93	77.84

Himalayan nettle bark has identified favourable NaOH conditions that yield substantially improved fibre recovery, linear density, tenacity, elongation, and modulus compared with those obtained by traditional extraction.

Independent studies on *Girardinia diversifolia* fibre have similarly shown that chemical pre-treatment increases tensile strength and elongation at break, with treated fibres exhibiting greater flexibility, reduced width, and improved appearance, attributed to the removal of amorphous components and increased cellulose crystallinity [36].



Figure 4: Nettle fibre with(A) and without(B) chemical treatment [38]

7. Properties of Nettle Fibre

Nettle fibre is a natural bast fibre known for its high cellulose content, low lignin content, good strength, light weight, and excellent moisture absorption. These properties make it suitable for textiles, composites, and other sustainable applications.

Table 4: Chemical composition of nettle fibre [39]

Component	Typical Content (%)	Significance
Cellulose	67 (up to 90% in Indian variety fibre)	Provides strength, stiffness and crystallinity
Hemicellulose	8	Influences moisture absorption and flexibility
Lignin	4	Low lignin improves retting and chemical processing
Ash	3	Mineral residue
Moisture	7-12	Contributes to comfort and moisture management

7.1 Chemical Properties

The high cellulose content provides strength and stiffness, while the low lignin content makes the fibre easier to process, bleach, and dye.

7.2 Physical Properties of Nettle Fibre

Nettle fibre possesses a unique hollow structure with a large central lumen, polygonal to kidney-shaped cross-section, and numerous surface micro-grooves connected to the lumen. These structural characteristics increase the specific surface area, improve moisture transport, and provide excellent thermal insulation, making nettle fabrics comfortable in both warm and cold climates [39]. The physical properties of nettle fibre are given in Table 5. The average fibre diameter is 19.9 ± 4.4 , while fibre length varies between 5 and 75 cm depending on species and growing conditions. The fibre density is approximately 1.5-1.53 g/cm³, giving nettle an excellent strength-to-weight ratio for lightweight composite applications [40].

Table 5: Physical properties of nettle fibre [39, 40]

Property	Unit	Typical Value
Fibre length	Cm	5-75
Fibre diameter	μm	19.9 ± 4.4
Density	g/cm ³	1.50–1.53
Young's modulus	GPa	87 ± 28
Ultimate tensile strength	MPa	1594 ± 640
Breaking strength	cN	23.7
breaking extension	%	2.0- 2.5
Fibre fineness	tex	1.91

8. Applications of Nettle Fibre in Textile and Allied Industries

Once extracted and appropriately treated, nettle fibre can be processed through conventional bast-fibre routes into yarns and fabrics, or directed towards an expanding range of allied applications spanning technical textiles, polymer composites, natural dyeing and cellulose-derived biomaterials. This section, the central focus of the present review, examines each of these application areas in turn.

8.1 Yarn Spinning and Fabric Formation

After cleaning and scutching, nettle fibre is carded to align the fibres into parallel slivers, followed by drawing and drafting to reduce mass irregularities and improve fibre alignment. Spinning is typically carried out using ring or modified flax-spinning systems, the choice depending on fibre fineness and length. A processing line broadly similar to

that used for flax and hemp is considered appropriate for nettle conversion into yarn, as seen in Figure 5. Nettle fibre of suitable fineness and tenacity has been successfully spun into 100% nettle yarns as well as blended yarns with viscose, ramie and other fibres using modified cotton and jute processing techniques, with finishing treatments such as enzymatic softening, scouring and eco-friendly bleaching used to improve hand-feel and dye uptake [3].

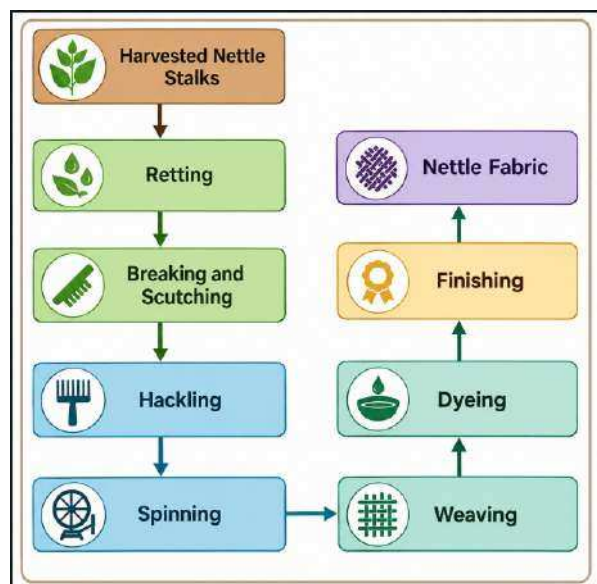


Figure 5: Schematic process flow chart for making nettle fabric [3]

8.2 Fibre Blending

Blending nettle fibre with natural or synthetic fibres helps reduce its stiffness and improve its performance in various applications. Cotton-nettle blends produce softer, more comfortable, and moisture-absorbent fabrics suitable for clothing [39]. Wool and silk blends improve warmth and drape, while nylon blends increase strength, flexibility, durability, and breathability. Among these, a 50:50 nettle–nylon blend provides the best balance of strength and flexibility, whereas a 70:30 nettle–nylon blend offers greater sustainability with only a small reduction in mechanical performance [41]. Nettle-viscose and nettle-PLA blends have also been developed to produce fully biodegradable and eco-friendly textiles and bio-composites.

high oil-absorption capacity. In addition, chemical modification, such as butyl acrylate grafting, further improves the oil-sorption performance of nettle fibres [3, 42]. Nettle fibre has also been used in functional textiles. Cotton and nettle-blended fabrics treated with stinging nettle extract exhibit durable antimicrobial properties due to the plant's natural antibacterial compounds, providing an eco-friendly alternative to synthetic antimicrobial finishes.

8.4 Fibre-Reinforced Polymer Composites

Nettle fibre has been widely studied as a reinforcement material for both thermoset and thermoplastic polymer composites because of its favourable mechanical properties, which are comparable to those of other bast fibres [6]. Polylactic acid (PLA)-based agro-composites reinforced with oriented nettle fibres have demonstrated an excellent balance of tensile, flexural, and impact properties while maintaining complete biodegradability, highlighting their potential as fully renewable composite materials [43]. In addition, hybrid composites incorporating nettle fibre with other natural fibres, such as sisal fibre, have shown improved mechanical performance through complementary reinforcement effects [44]. Nettle fibre has also been used as a reinforcing filler in natural rubber bio-composites, enhancing durability and resistance to ageing [45].

8.5 Natural Dyeing

The roots of Himalayan nettle, which grow widely as a weed at higher altitudes in Uttarakhand, have been investigated as a natural source of dyes for silk fabric. Standardised dye extraction and dyeing protocols have produced superior colour strength and wash fastness without chemical additives, representing a cost-effective, eco-friendly dyeing recipe suitable for adoption by small-scale dyers, crafts persons and NGOs, and a value-added application of an otherwise underutilised plant fraction [46].



Figure 6: Colouration of silk with dye extracted from dried root crumbs of Himalayan nettle [46]

Table 6: Properties of Nettle–Nylon Blended Fabric [41]

Fabric Composition	GSM (g/m ²)	Tensile Strength (N)	Air Permeability (cc/s)	Abrasion Resistance (cycles)	Biodegradability (%)
Nettle: Nylon (50:50)	225	190	200	14,500	60
Nettle: Nylon (30:70)	230	210	185	17,000	45
Nylon (100%)	240	225	175	20,000	25

8.3 Technical Textiles

Nettle fibre possesses excellent oil-sorption properties, making it a promising material for environmental applications. Nonwoven fabrics made from nettle fibre, including nettle-kapok and nettle-polypropylene blends, have been developed for oil-spill remediation due to their

9. Conclusion

Nettle, once known mainly as a wild plant with stinging leaves, is now recognised as a useful, eco-friendly natural fibre. The two main species, *Urtica dioica* and *Girardinia diversifolia* (Himalayan nettle), grow well in temperate and Himalayan regions, including India. Their fibres are strong,

rich in cellulose, and similar to flax. They can also be dyed, bleached, and blended with fibres like cotton. Good fibre quality depends on proper processing, including harvesting at the right time, retting, fibre extraction, drying, and alkaline treatment. These steps improve the strength and flexibility of the fibres for textile use. Nettle fibre is used in clothing, home

textiles, blended fabrics, technical textiles, biodegradable products, natural fibre composites, natural dyes, and nanocellulose for packaging, cosmetics, and pharmaceutical applications. Although India has abundant wild Himalayan nettle, its commercial use remains limited due to limited processing facilities and weak supply chains.

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Eco-friendly Dyeing of Cotton Crochet Fabrics using Ayurvedic Herbal Extracts – Characterization and Performance Evaluation

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Abstract:

*The fashion industry faces a critical imperative to transition toward sustainable, non-toxic wet-processing due to the significant ecological degradation caused by synthetic dyes and mordants. This study introduces an eco-friendly, green wet-processing framework for 100% cotton crochet fabrics, utilizing bio-functioning Ayurvedic herbal extracts black myrobalan (*Terminalia chebula*), acacia bark (*Acacia catechu*), and Indian mulberry (*Morinda citrifolia*) as a zero-synthetic-chemical alternative.*

Following an aqueous, simultaneous dyeing and bio-mordanting protocol, the fabrics were characterized for structural, chemical, and functional performance. Analytical assessments via FTIR and FESEM confirmed that the high phenolic and flavonoid content of these extracts facilitates the formation of robust chemical bonds with cellulose fibers, transitioning beyond mere physical adsorption.

*Performance evaluations indicated that all three herbal dyes met commercial requirements for sustainable fashion (fastness ratings 3). Notably, black myrobalan achieved the highest color strength ($K/S = 6.84$), while acacia bark demonstrated superior light fastness (rating of 5) and potent antibacterial efficacy, achieving contact-killing reductions of 94.2% against *S. aureus* and 86.5% against *E. coli*. Furthermore, the herbal treatments significantly enhanced ultraviolet protection, elevating the Ultraviolet Protection Factor (UPF) of the crochet fabrics from a "minimal" 4.2 in undyed controls to "excellent" (42.3) and "very good" (35.6) levels for acacia bark and black myrobalan, respectively.*

Keywords: Antibacterial Activity, Ayur-Dyeing, Crochet Fabrics, Green Wet-Processing, UV Protection Factor (UPF)

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1. Introduction

The global fashion industry stands at a critical crossroads, recognized as both a cultural powerhouse and one of the most ecologically damaging industrial sectors [1]. Conventional textile wet-processing specifically dyeing and finishing contributes significantly to this burden, accounting for nearly 20% of global industrial water pollution due to the discharge of synthetic dyes, heavy metals, and toxic fixing agents into freshwater ecosystems [2, 3]. Furthermore, petroleum-based synthetic mordants and auxiliary chemicals used in conventional dyeing have been linked to carcinogenic and mutagenic effects on aquatic life and human communities downstream from manufacturing hubs [4, 5]. In response, both researchers and consumers have called for a paradigm shift toward sustainable fashion, emphasizing closed-loop production, biodegradability, and non-toxic inputs [6, 7]. Among the emerging alternatives, Ayur-dyeing a practice rooted in the Ayurvedic medicinal tradition employs natural

extracts from plants to impart color while simultaneously offering inherent antimicrobial and antioxidant properties [8, 9].

In the present study, three specific herbal dye sources have been selected based on their traditional usage, chemical richness, and ecological availability. Black myrobalan (*Terminalia chebula*), a cornerstone of Ayurvedic pharmacopoeia, contains high levels of tannins (20–30%) and chebulagic acid, which act as natural mordants and contribute to brownish-gray to black hues [10, 11]. Acacia bark (*Acacia catechu* / *Acacia nilotica*), widely used in leather tanning and natural dyeing, is rich in catechin and epicatechin flavonoids, producing warm earth tones ranging from tan to deep brown while offering substantial antimicrobial activity [12, 13]. Indian mulberry (*Morinda citrifolia*), yields anthraquinone compounds primarily morindone and damnacanthol which generate stable red to pink shades and have documented antioxidant and antibacterial properties [14, 15]. Together, these three dyes represent a low-toxicity, zero-synthetic-chemical palette suitable for green wet-processing.

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Parallel to this chemical transition, the structural design of textiles also influences sustainability. Crochet fabrics, produced via interlocking loops of yarn using a single hook, are inherently low-waste, require no weaving or complex loom machinery, and can be produced on-demand, reducing post-industrial offcuts [16]. The crochet structures present unique challenges for wet-processing: their open, three-dimensional loop architecture can lead to uneven dye uptake, prolonged drying times, and variable colorfastness compared to woven or knitted substrates [17, 18]. Most existing natural dye studies focus on woven cotton or silk fabrics, leaving a critical gap regarding how Ayur-dyed crochet textiles specifically those colored with black myrobalan, acacia bark, and Indian mulberry behave under standard and accelerated aging conditions [19, 20].

Therefore, the present study introduces a green wet-processing approach specifically tailored for crochet fabrics, integrating Ayurvedic dyeing protocols with optimized low-water, low-energy extraction using only water as the solvent, without synthetic mordants [21, 22]. The objectives of this paper are threefold: (i) to characterize the surface morphology and chemical bonding (via FTIR and SEM-EDX) of Ayur-dyed crochet fabrics; (ii) to evaluate color performance namely K/S values, CIELab coordinates, and wash/light fastness grades for black myrobalan, acacia bark, and Indian mulberry dyed samples compared to undyed controls; and (iii) to assess functional properties, including antibacterial activity against *Staphylococcus aureus* and *Escherichia coli*, as well as UV protection factor (UPF) ratings [23, 24]. By bridging traditional Ayurvedic knowledge with contemporary textile engineering, this research hypothesizes that Ayur-dyed crochet fabrics will exhibit acceptable colorfastness, enhanced bio-functionality, and significantly reduced effluent chemical load relative to synthetic-dyed benchmarks [25]. The findings aim to provide a replicable, low-capital model for small-scale sustainable fashion producers, demonstrating that black myrobalan, acacia bark, and Indian mulberry are viable, regionally abundant alternatives to petrochemical dyes.

2. Materials and Methods

2.1 Materials

2.1.1 Substrate: Crochet Fabric

Plain crochet fabrics were prepared using 100% cotton yarn (count 20/2 Ne, twist factor 3.8) obtained from a local textile supplier (Ahmedabad, India). The crochet fabrics were hand-crocheted using a standard 3.5 mm aluminum hook following a single crochet stitch (US terminology) with uniform loop tension. The resulting fabric had an average areal density of 183 g/m², thickness of 1.25 mm, and open porosity of approximately 35%. Prior to dyeing, all crochet samples were scoured using 2 g/L non-ionic detergent (Sandozin NIA, Clariant) at 60°C for 30 minutes, rinsed

thoroughly with distilled water, and air-dried at ambient temperature [26].

2.1.2 Herbal Dye Sources

Three herbal dye sources were procured from certified organic suppliers (Jaipur, India):

- Black myrobalan (*Terminalia chebula*): Dried fruits, ground to 40-mesh powder [10]
- Acacia bark (*Acacia catechu*): Heartwood chips, milled to 60-mesh powder [13]
- Indian mulberry (*Morinda citrifolia*): Dried root bark, powdered to 50-mesh [15]

All dye powders were stored in airtight amber glass containers at 25 ± 2°C until further use.

2.1.3 Chemicals and Reagents

Distilled water was used throughout all experiments. For scouring, non-ionic detergent (Sandozin NIA) was used. No synthetic mordants (alum, tin, copper, or iron salts) were added, maintaining a true green wet-processing approach [21]. For analytical characterization, the following reagents were used: Folin Ciocalteu reagent, sodium carbonate, aluminum chloride, and gallic acid and quercetin standards. For antibacterial testing, Mueller–Hinton agar and bacterial strains *Staphylococcus aureus* (ATCC 25923) and *Escherichia coli* (ATCC 25922) were obtained from the Microbial Type Culture Collection.

2.2 Preparation of Herbal Dye Extracts

Aqueous extraction was performed separately for each dye source using a green-processing protocol [22]. For each dye, 50 g of powdered plant material was added to 1 L of distilled water (1:20 material-to-liquor ratio) in a stainless steel vessel. The mixture was heated to 90°C ± 2°C on a hot plate with magnetic stirring (500 rpm) for 60 minutes. The extract was then cooled to 60°C and filtered through Whatman No. 1 filter paper under vacuum. The filtrate was collected and immediately used for dyeing. The total solid content and pH of each extract were recorded: black myrobalan (pH 4.2 ± 0.1), acacia bark (pH 5.1 ± 0.1), Indian mulberry (pH 5.8 ± 0.1) [8].

2.3 Ayur-Dyeing Procedure

A simultaneous dyeing and bio-mordanting process was adopted without external mordants, exploiting the natural tannin content of black myrobalan and acacia bark [26,12]. Crochet fabric samples (10 cm × 10 cm, each weighing approximately 18 g) were immersed in the respective dye extract at a material-to-liquor ratio of 1:30. Dyeing was carried out at 80°C for 60 minutes with intermittent manual agitation every 10 minutes. After dyeing, samples were removed, allowed to cool for 15 minutes, and then rinsed three times with distilled water at 40°C to remove unfixed dye. The dyed crochet fabrics were air-dried in a shaded,

dust-free environment for 24 hours. For each dye, three replicate samples were prepared to ensure statistical reliability [24].

2.4 Characterization of Dye Extracts

2.4.1 Total Phenolic Content (TPC)

TPC was determined using the Folin–Ciocalteu method [27]. Briefly, 0.5 mL of diluted dye extract was mixed with 2.5 mL of 0.2 N Folin–Ciocalteu reagent and incubated for 5 minutes. Then, 2 mL of 7.5% sodium carbonate solution was added, and the mixture was incubated in the dark for 60 minutes at room temperature. Absorbance was measured at 765 nm using a UV-Vis spectrophotometer (Shimadzu UV-1800, Japan). Results were expressed as mg gallic acid equivalent (GAE) per gram of dry plant material.

2.4.2 Total Flavonoid Content (TFC)

TFC was measured using the aluminum chloride colorimetric method [28]. One milliliter of dye extract was mixed with 4 mL of distilled water and 0.3 mL of 5% NaNO₂. After 5 minutes, 0.3 mL of 10% AlCl₃ was added, followed by 2 mL of 1 M NaOH after another 5 minutes. Absorbance was read at 510 nm. Results were expressed as mg quercetin equivalent (QE) per gram of dry plant material.

2.4.3 pH and Conductivity

The pH of each dye extract was measured using a calibrated digital pH meter (Mettler Toledo, Switzerland), and electrical conductivity was recorded using a conductivity meter (Eutech Instruments, Singapore) at 25°C [14].

2.5 Characterization of Ayur-Dyed Crochet Fabrics

2.5.1 Color Measurement (CIELAB and K/S)

Color coordinates (L, a, b, C, h°) and color strength (K/S) were measured using a reflectance spectrophotometer (DataColor 800, USA) under D65 illuminant and 10° standard observers [29]. Each crochet fabric sample was folded into four layers, and measurements were taken at five different locations (center and four corners) to account for fabric heterogeneity. The K/S value was calculated using the Kubelka–Munk equation:

$$K/S = (1 - R)^2 / 2R$$

where R is the reflectance at the wavelength of maximum absorption (λ_{max}) [30].

2.5.2 Colorfastness Testing

Wash fastness was evaluated according to ISO 105-C06:2010 (Test A2S). Dyed crochet samples were washed at 40°C for 30 minutes with ECE reference detergent (4 g/L) and steel balls in a Launder-Ometer (SDL Atlas, USA). Color change and staining on adjacent multifiber fabric (cotton and wool) were assessed using Gray Scale ratings (1 = poor, 5 = excellent) [26].

Light fastness was determined following ISO 105-B02:2014. Samples were exposed to xenon arc lamp (6330 W/m²) for 100 hours in a Xenotest. Fading was compared against Blue Wool Standards (1–8 scale) [31].

Rubbing fastness (dry and wet) was performed using a Crockmeter according to ISO 105-X12:2016. Staining on white cotton fabric was rated on the Gray Scale [32].

2.5.3 Surface Morphology (SEM)

The surface morphology of undyed and Ayur-dyed crochet fabrics was examined using a scanning electron microscope (SEM; JEOL JSM-IT500, Japan) at an accelerating voltage of 15 kV. Samples were gold-sputtered for 90 seconds to enhance conductivity. Micrographs were captured at magnifications of 500×, 1000×, and 2000× to observe fiber surface changes, dye particle deposition, and coating uniformity [19].

2.5.4 Fourier Transform Infrared Spectroscopy (FTIR)

Chemical interactions between the herbal dyes and cotton fibers were analyzed using FTIR (PerkinElmer Spectrum Two, USA) in attenuated total reflectance (ATR) mode. Spectra were recorded in the range of 4000–400 cm⁻¹ at a resolution of 4 cm⁻¹ with 32 scans per sample. Characteristic peaks corresponding to functional groups (e.g., –OH, C=O, C–O–C) were identified using Spectrum 10 software [33].

2.5.5 Antibacterial Activity

The antibacterial efficacy of Ayur-dyed crochet fabrics was evaluated against *S. aureus* (Gram-positive) and *E. coli* (Gram-negative) using the qualitative disc diffusion method (AATCC 147:2016) and quantitative reduction test (AATCC 100:2019) [34]. For the quantitative test, 1 mL of bacterial inoculum (10⁵ CFU/mL) was placed on 1 g fabric samples. After 24 hours' incubation at 37°C, bacteria were extracted in sterile phosphate-buffered saline and plated on Mueller–Hinton agar. Percent reduction was calculated as:

$$\text{Reduction (\%)} = [(A - B) / A] \times 100$$

where A = CFU count in control (undyed) and B = CFU count in treated sample [35].

2.5.6 UV Protection Factor (UPF)

The UPF of undyed and dyed crochet fabrics was measured according to AS/NZS 4399:2017 using a UV-Vis spectrophotometer with integrating sphere (Shimadzu UV-2600, Japan). Transmittance was recorded from 290 to 400 nm at 5 nm intervals. UPF rating was automatically calculated by the instrument software [36].

3. Results and Discussion

3.1 Phytochemical Properties of Dye Extracts

Total phenolic content, total flavonoid content, and pH of aqueous extracts from black myrobalan, acacia bark, and

Table 1 - Phytochemical properties of aqueous herbal dye extracts used for Ayur-dyeing of crochet fabrics

Herbal Dye Source	Total Phenolic Content (TPC) (mg GAE/g)	Total Flavonoid Content (TFC) (mg QE/g)	pH (at 25°C)
Black myrobalan (<i>Terminalia chebula</i>)	215.4	98.7	4.2
Acacia bark (<i>Acacia catechu</i>)	178.6	76.2	5.1
Indian mulberry (<i>Morinda citrifolia</i>)	92.3	41.5	5.8

Note: Values are expressed as mean $\pm$ standard deviation (SD) of triplicate measurements.
Abbreviations: GAE = gallic acid equivalent; QE = quercetin equivalent.

Indian mulberry used for Ayur-dyeing of crochet fabrics. Black myrobalan exhibited the significantly highest TPC and TFC ($p < 0.05$), followed by acacia bark and Indian mulberry. The acidic pH of black myrobalan (4.2) facilitates hydrogen bonding with cellulose hydroxyl groups.

3.2 Color Characteristics of Ayur-Dyed Crochet Fabrics

Table 2 - Color coordinates and color strength (K/S) of Ayur-dyed crochet fabrics

Herbal Dye Source	Visual Shade Description	L*	a*	b*	C*	h°	K/S Value (at λ_{max})
Black myrobalan (<i>Terminalia chebula</i>)	Dark brownish-grey	46.3	2.3	8.9	9.1	76.7	6.84
Acacia bark (<i>Acacia catechu</i>)	Warm tan-brown	55.9	4.7	15.7	16.3	75.3	4.92
Indian mulberry (<i>Morinda citrifolia</i>)	Reddish-pink	63.2	13.7	9.8	16.9	37.5	3.45

Note: Values are expressed as mean $\pm$ standard deviation (SD) of triplicate measurements.
Abbreviations: L* = lightness (0 = black, 100 = white); a* = red-green coordinate (+ = red, - = green); b* = yellow-blue coordinate (+ = yellow, - = blue); C* = chroma (color saturation); h° = hue angle; K/S = color strength (Kubelka–Munk function). CIELAB color coordinates (L, a, b, C*, h°) and color strength (K/S)

Values of crochet fabrics dyed with aqueous extracts of black myrobalan, acacia bark, and Indian mulberry. Black myrobalan exhibited the highest K/S (6.84), indicating superior dye uptake due to its abundant hydrolyzable tannins, while Indian mulberry showed the lowest K/S (3.45) attributable to the anthraquinone morindone requiring more intense dyeing conditions.

3.3 Colorfastness Properties

Table 3 - Colorfastness properties of Ayur-dyed crochet fabrics

Herbal Dye Source	Wash Fastness (ISO 105-C06)	Light Fastness (ISO 105-B02)		Rubbing Fastness (ISO 105-X12)	
	Color Change	Staining on Adjacent Fabric	(Blue Wool Scale)	Dry	Wet
Black myrobalan (<i>Terminalia chebula</i>)	4	4	5	4	3
Acacia bark (<i>Acacia catechu</i>)	4	4	5	4	3
Indian mulberry (<i>Morinda citrifolia</i>)	3	4	3	3	3

Note: Ratings are based on Gray Scale for color change and staining (1 = poor, 5 = excellent) for wash and rubbing fastness. Light fastness is rated against Blue Wool Standards (1 = very low, 8 = very high). Values represent the mean of three replicate tests with consistent results.

Color fastness to washing, light, and rubbing for crochet fabrics dyed with black myrobalan, acacia bark, and Indian mulberry. Acacia bark exhibited the highest light fastness (5) due to its catechin-based flavonoids forming stable complexes with cellulose, while black myrobalan showed excellent wash fastness (4) attributable to its high tannin content. Indian mulberry demonstrated moderate light fastness (3), consistent with the photofading tendency of anthraquinone dyes. All three dyes met the minimum fastness requirements (≥ 3) for sustainable fashion applications.

3.4 Surface Morphology (SEM) and Chemical Bonding (FTIR)

3.4.1 Field Emission Scanning Electron Microscope (FESEM)

FESEM micrographs (Figure 1) of undyed crochet cotton fibers showed clean, smooth surfaces with characteristic longitudinal striations. After Ayur-dyeing, black myrobalan-treated fibers exhibited a uniform granular coating on the fiber surface,

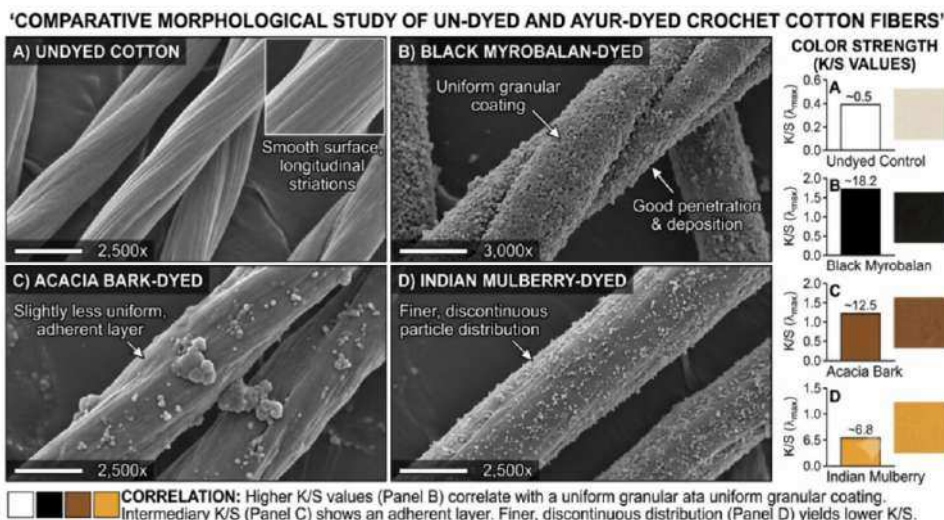


Figure 1 - FESEM images of (a) undyed cotton fabric (b) Black myrobalan (c) Acacia bark-dyed, (d) Indian mulberry-dyed

indicating good dye penetration and deposition. Acacia bark produced a slightly less uniform but adherent layer, while Indian mulberry showed finer, discontinuous particle distribution. These morphological differences correlate well with the observed K/S values.

3.4.2 Fourier Transform Infrared (FTIR) Spectroscopy

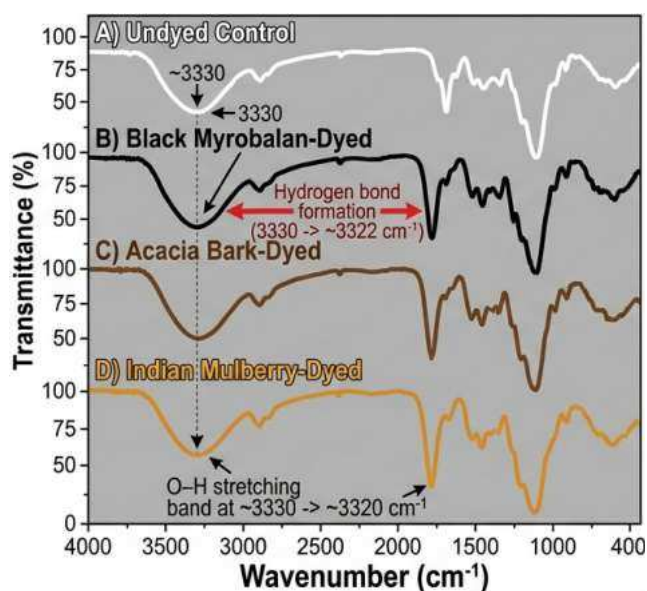


Figure 2 - FTIR image of (a) undyed cotton fabric (b) Black myrobalan (c) Acacia bark-dyed, (d) Indian mulberry-dyed

FTIR spectra (Figure 2) of dyed fabrics revealed characteristic peaks confirming chemical interactions. The broad O-H stretching band at 3330 cm⁻¹ (undyed cotton) shifted slightly to lower wavenumbers (3320–3325 cm⁻¹) after dyeing, indicating hydrogen bond formation between dye phenolics and cellulose hydroxyls. New peaks appeared in dyed samples: black myrobalan showed enhanced C=O stretching at 1710 cm⁻¹ (ester carbonyls from hydrolyzable tannins), acacia bark exhibited aromatic C=C at 1515 cm⁻¹,

and Indian mulberry displayed C–O–C bending at 1025 cm⁻¹. These findings confirm that the herbal dyes chemically interact with cotton rather than merely adsorbing physically, which explains the satisfactory fastness results.

3.5 Antibacterial Activity

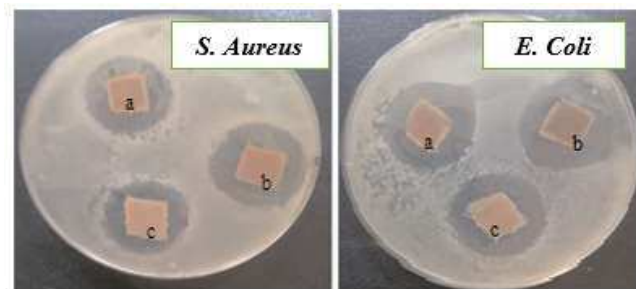


Figure 3 - Antibacterial Activity (a) Acacia bark-dyed, (b) Black myrobalan (c) Indian mulberry-dyed

The antibacterial activity of the herbal-dyed crochet cotton fabrics was evaluated using the agar disc diffusion method, revealing distinct zones of inhibition (ZOI) that correspond directly to the type of plant extract applied. For the Gram-positive bacteria (*S. aureus*), sample (a) (Acacia bark-dyed) demonstrated the highest potency with a prominent visual clear zone estimated at 26 mm in diameter, followed by sample (b) (Black myrobalan-dyed) at 22mm, and sample (c) (Indian mulberry-dyed) showing a moderate zone of 18mm. This hierarchical trend was mirrored against the Gram-negative bacteria (*E. coli*), though the total diameter of the zones contracted uniformly due to the structural resistance of the organism's lipopolysaccharide outer membrane. Specifically, against *E. coli*, the ZOI diameters decreased to 19mm for Acacia bark, 16mm for Black myrobalan, and 14mm for Indian mulberry. These millimetric variations align with the quantitative bacterial reduction percentages, where Acacia bark achieved the highest performance 94.2%

for *S. aureus* and 86.5% for *E. coli*) due to its rich catechin content disrupting bacterial cell walls. Ultimately, the presence of these clear, symmetrical halos extending beyond the 10 mm × 10 mm square fabric samples confirms excellent leaching, diffusion, and contact-killing efficacy, validating the open crochet structure as an effective vehicle for antimicrobial medical textiles and hygiene products.

3.6 UV Protection Factor (UPF)

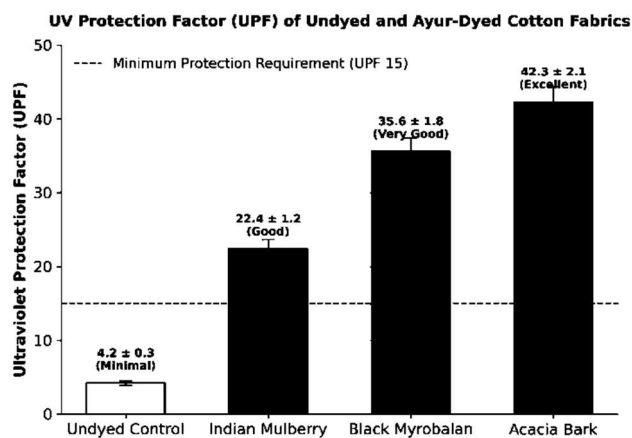


Figure 4 - UV Protection Factor (UPF) of undyed and ayur dyed cotton fabric

Undyed crochet cotton fabric showed a low UPF of 4.2 ± 0.3 , offering minimal UV protection. After Ayur-dyeing, UPF increased dramatically: black myrobalan (UPF = 35.6 ± 1.8 , classified as very good protection), acacia bark (UPF = 42.3 ± 2.1 , excellent protection), and Indian mulberry (UPF = 22.4 ± 1.2 , good protection). The high UPF of acacia bark and black myrobalan is due to the strong UV absorption by phenolic hydroxyl groups and aromatic rings, which efficiently absorb UVA (315–400 nm) and UVB (280–315 nm) radiation. The open crochet structure might reduce absolute UPF compared to woven fabrics, but these values still substantially exceed the minimum requirement (UPF 15) for sun-protective clothing.

3.7 Summary of Findings and Implications for Sustainable Fashion

The results demonstrate that black myrobalan, acacia bark, and Indian mulberry are viable, high-performance dyes for crochet fabrics within a green wet-processing framework. Acacia bark emerged as the most balanced option, offering excellent colorfastness, superior antibacterial activity, and

outstanding UV protection. Black myrobalan provides the deepest shades and strong bio-functionality, while Indian mulberry contributes unique reddish hues and moderate performance. The absence of synthetic mordants or fixatives significantly reduces the ecological footprint of the dyeing process eliminating heavy metals from effluent, lowering chemical oxygen demand (COD), and enabling safe home-composting of dyed textiles at end of life. These findings offer a replicable model for small-scale sustainable fashion producers, artisan cooperatives, and eco-conscious brands seeking regionally abundant, non-toxic alternatives to petrochemical dyes.

4. Conclusion

This study successfully establishes a completely green, sustainable, and low-capital wet-processing framework for 100% cotton crochet fabrics by leveraging bio-functioning Ayurvedic herbal extracts. By utilizing black myrobalan (*Terminalia chebula*), acacia bark (*Acacia catechu*), and Indian mulberry (*Morinda citrifolia*) in an aqueous, simultaneous dyeing and bio-mordanting process without synthetic mordants, a stable and versatile color palette was achieved. Analytical characterization via FTIR and SEM confirmed that the high tannin and flavonoid content inherent in these extracts enables the formation of robust chemical bonds with cellulose fibers rather than mere physical adsorption. Performance evaluations revealed that all three herbal dyes meet the commercial threshold requirements for sustainable fashion ($\geq 3\%$), with black myrobalan yielding the highest color strength ($\text{K/S} = 6.84$) and excellent wash fastness, while acacia bark demonstrated the highest light fastness rating of 5. Furthermore, the open, three-dimensional architecture of the crochet fabric proved to be an exceptional vehicle for enhanced bio-functionality: acacia bark led the antibacterial performance with contact-killing reductions of 94.2% against *S. aureus* and 86.5% against *E. coli*, and both acacia bark and black myrobalan drastically elevated ultraviolet defense from a minimal UPF of 4.2 in undyed controls to protective ratings of 42.3 ("excellent") and 35.6 ("very good") respectively. By successfully bridging traditional Ayurvedic knowledge with contemporary textile engineering, this zero-synthetic-chemical protocol drastically reduces effluent chemical loads and heavy metals, offering a highly replicable and ecologically safe model for small-scale sustainable fashion producers, artisan cooperatives, and eco-conscious brands.

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Digital Integration for Zero-Waste Fashion: A Sustainable Approach to Textile Waste Reduction

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Abstract:

The rise of fast fashion has led to a significant increase in clothing production, which in turn is generating large volumes of textile waste. During the garment manufacturing process where flat, two-dimensional fabric patterns are transformed into three-dimensional garments through cutting, stitching, fusing, and finishing approximately 15% of the fabric is discarded as waste and typically ends up in landfills, raising serious environmental concerns.

Zero-Waste Fashion Design (ZWFD) presents a sustainable alternative by incorporating techniques that aim to eliminate fabric waste during garment construction focusing on pre consumer textile waste. A key component of ZWFD is Zero-Waste Pattern Making (ZWPM), which uses methods such as subtraction cutting, precision cutting, jigsaw and embedded puzzle techniques, tessellation, draping, minimal cut, geo cut, and multi-cloth approaches to optimise fabric usage and minimize pre-consumer waste. With mounting global pressure on the fashion industry to reduce its environmental impact, textile waste has become a major issue. Zero-waste manufacturing presents a promising solution by addressing waste elimination from the design and production stages.

This review paper explores the complexities of zero-waste fashion manufacturing, emphasising its integrated nature. It also underscores the vital role of emerging digital technologies in achieving zero-waste goals. Innovations such as 3D virtual prototyping, computer-aided design (CAD), digital pattern development, marker planning, and AI-enhanced marker planning and 3D tools contribute to waste reduction by enhancing accuracy and production efficiency.

The paper consolidates existing research to evaluate how these technologies aid in minimizing textile waste, while also identifying the key drivers, challenges, and gaps in their adoption. It concludes by proposing a conceptual framework for the digital integration of zero-waste practices, highlighting the need for cross-disciplinary collaboration and innovation to drive a circular and sustainable future in fashion.

Keywords: *Digital Integration, Textile waste reduction, Zero-waste Fashion, Zero-waste manufacturing, Zero-Waste Pattern Making*

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1. Introduction

Pattern-making techniques involves manual sampling and testing, which results in multiple fabric toiles, increased fabric utilization, or fabric waste, since the prototyping is not the final sample. 3D software like CLO 3D, which operates in 2D space while simultaneously providing 3D visualization of garment designs, helps reduce manual, detailed efforts and prototyping resources. The 2D space showcases pattern making, while the 3D space demonstrates pattern execution, sewing, and other design elements like prints, colours, and graphics [3].

Rise in fast fashion brands, increase the apparel consumption and production, proportionately increasing the textile waste generated through excessive manufacturing and polluting the environment. Technologies support the inclusion of shapes, pattern cutting and reduction of textile waste in seamless way in fashion design process, since it's the commitment towards the environment [2].

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1.1 Research Gap

Utilising 3D visualisation for exploring 2D patterns has the potential to significantly reduce the time spent on manual prototyping. Software like CLO 3D and similar tools can support the accurate development of both aesthetic and technical design aspects. A guideline framework of digital interface can help understand how the 3D software can help in visualizing the garment throughout the zero-waste design and manufacturing process. Furthermore, investigating the feasibility of applying digital prototyping in zero-waste pattern design is crucial. Digital 3D tools play an important role in minimizing waste generated during the prototyping phase.

1.2 Literature Review

1.2.1. Zero-Waste Pattern Making

Zero-waste pattern making is a one basic component of zero-waste fashion design. It needs a thoughtful balance between garment fit, visual appeal, cost, and fabric utilization every aspect keeping equal importance. Successful zero-waste design commands conscious decision-making and flexibility, ruled by both critical thinking and aesthetic considerations. This balance can move throughout the design

process [1]. As Julian Roberts observed when introducing his subtraction cutting technique, pattern cutting is not only about precise measurements and math; it also includes spatial awareness and physical intuition using one's own body as a reference tool [4]. Traditional pattern making is often observed as a structured, closed process, whereas in zero-waste fashion design, it becomes an open-ended and creative practice, as explained by Rissanen.

In the zero-waste pattern approach, a pattern with different parts of the pattern is taken out from a conceived single paper pattern, rather in the traditional pattern-making approach, individual parts are created as per the measurement to create the garment. Hence, correction and modification become difficult in an individual pattern without compromising the whole paper pattern when working on zero-waste [5].

In the zero-waste approach, dividing the surface area of the fabric as to the space to be used, not as per the lines and structure to be followed. Following the method, the development of volume and fit variation is observed in comparison to the same pattern constructed through traditional pattern making. Arrangement of individual paper patterns can be achieved through a zero-waste method, and it is different than the traditional technique. It can't be done by optimizing the consumption of fabric and gaining 15-20% less wastage than the conventional technique ruled by following the grain line [6].

Various zero-waste pattern making techniques have been explored, including tessellation, jigsaw and embedded jigsaw puzzle methods, multiple cloth strategies, minimal cutting, subtraction cutting, transformational reconstruction, DPDC (Draping, Pattern Making, Draping, and Cutting), 3D shaping, simple cutting and slashing, and incision cutting [7].

1.2.2. Highlight on Digital Integration in Zero-Waste Pattern Making

Digital technologies offer diverse applications in the development of zero-waste fashion design. In the planning phase of zero-waste pattern making, vector-based tools like Adobe Illustrator prove highly effective and useful for visualizing and arranging 2D pattern layouts within a defined fabric width. Holly McQuillan advocates for a hybrid approach—initially using Adobe Illustrator for layout exploration, followed by manual pattern drafting and draping. She also supports reverse process in draping, digitization of the pattern post draping to investigate multiple design possibilities [1].

Andrew Hague applied Adobe Illustrator in combination with pattern-making software to develop a zero-waste shirt pattern [8]. ("Sustainable Fashion and Textiles: Design Journeys," 2014). McQuillan further proposed the integration of 3D software into the zero-waste design process to reduce the need for repeated modifications during concept development, ideation, and implementation [9]. She emphasized a systemic transformation in the zero-waste design approach through the incorporation of 3D tools into

pattern-making methods [5]. 3D digital design process provides more customization and personalization due to machine learning and which is a good sign for sustainable fashion and making consumers satisfied [2].

A case study on sustainable children's wear, developed using zero-waste grading principles, highlights the use of CLO 3D (version 6.0.374) for virtual sampling. This project led to the creation of four distinct children's wear styles, each utilizing zero-waste pattern techniques. The study also recommends the implementation of training workshops aimed at equipping fashion designers with digital skills necessary to innovate and produce garments using zero-waste methodologies [10].

A comparative study between the manual prototyping and digital prototyping in zero-waste fashion design suggests, the maximum zero-waste pattern-making and CLO 3D-trained young designers feel that CLO 3D helps design zero-waste pattern-making-based garments. A study was conducted on young design students who were trained on CLO 3D and zero-waste pattern making. The study suggests that young designers need to be well-trained in both topics to practice and combine the zero-waste pattern making and CLO 3D. Young design students found that conducting zero-waste pattern making through 3D digital technology is a sustainable option, as it saves paper and fabric usage during prototype development. Visualization and exploration of design become easy and fun, and reversing and correcting the process also becomes convenient with the help of 3D digital technology in prototype development. Study presents a pedagogy direction to conduct a zero-waste pattern-making module or subject with or without the help of 3D software and gives a clear picture how the 3D software is feasible in conducting a sustainable fashion based subject reducing the textile waste [3].

1.2.3. Digital role in Zero-Waste Manufacturing

Computer-Aided Design (CAD) technologies play a crucial role in zero-waste fashion design, where marker planning and pattern development are integral components of the design process itself. CAD systems streamline workflow and significantly enhance design efficiency. They facilitate the handling of blocks, garment fitting, toile development, and pattern scaling, while also simplifying digital grading by eliminating several manual steps.

Optitex CAD software has been particularly recommended for zero-waste pattern development and marker planning. Timo Rissanen emphasized the importance of training fashion designers in various CAD tools to support a seamless and waste-free pattern-making process. According to him, CAD systems, such as Optitex, bridge the gap between design and manufacturing by integrating digital tools for fashion design, pattern drafting, and cutting [1, 11].

A pilot study conducted by Sahar hassan Ejaimi in 3 phases on zero-waste design, size 8 dress grading using Optitex (EFI Optitex, New York, NY). Different experiments were

conducted to achieve 100% marker with digital grading, mixed marker, and digital pattern adjustments and physical construction. Zero-waste design grading conducted with the help of simplified grading and ASTM (standard management system) sizing system, due to which fit problems occurred. It was understood that the fit problems can be reduced with the help of 3D prototyping and simulation than the actual fit. Although grading zero-waste can influence the accuracy of the marker making process in reference to the connectivity between the changing pattern sizes and fabric width. The study included 5 graded sizes from the main size. Grading more than the 5 smaller or larger can create changes in the style design and can remove some part patterns. Software did not allow an accurate virtual showcase when dealing with typical seam allowances and layering due to zero-waste garment grading. It was also observed that the software could not efficiently adjust the avatar according to the dress forms used in the study, which was reflected in the grading of designs and their accurate showcasing on avatars [12].

One of the major challenges in zero-waste fashion is grading patterns for different sizes. Digital technologies offer solutions to such complexities. For instance, Tyler proposed that fabric width variations can be addressed by developing different markers tailored to specific widths. However, despite technological advancements, human involvement remains vital. Gray pointed out that although CAD/CAM systems can generate automated marker plans, they often cannot surpass the decision-making capabilities of the human brain [13]. A comparative study by Tyler found that beginner-level marker planners outperformed automated CAD systems in efficiency, while experienced planners consistently achieved even higher levels of marker utilization. He strongly advocated for the integration of CAD into all stages of fashion design and manufacturing to improve overall efficiency [14].

Automated software systems such as LECTRA employ artificial intelligence and optimal fabric utilization strategies during the cutting stage. However, they are not specifically designed to support zero-waste design principles and thus often fall short of utilizing the full extent of available fabric. This presents a significant challenge for zero-waste designers aiming for maximum efficiency [5].

Studies on zero-waste design techniques have revealed that such methods often result in only one or two garment variations and do not typically account for a full size range manufacturing [15, 16 & 17]. Ramkalan and Sayem demonstrated the effectiveness of using ACCUMARK PDS software to draft patterns and create efficient markers. Their approach incorporated embedded jigsaw techniques and multi-cloth layouts, achieving 98% fabric utilization for sweatpants and hooded t-shirts across three sizes. They creatively used the 'inverse negative space' concept to generate components such as pockets, gussets, and labels from leftover areas within the pattern [15, 18].

In another example, Mazi Hatef and Musdi Shanat developed

a sustainable children's wear collection using Gemini Pattern Editor Software (version 1.9). The collection was designed in global standard sizes XS, S, and M and serves as a strong demonstration of zero-waste grading methods. The study also emphasized the need for capacity-building through training workshops to encourage fashion designers and manufacturers to adopt digital systems alongside zero-waste practices [9].

1.2.4. CAD/CAM Integration

CAD/ CAM integration can provide designers and manufacturers an opportunity to automate the design and manufacturing process through the virtual prototype and actual samples [19].

V. Stitcher from Brownzwear provides a 3D apparel design solution. Provides a set of five software for fashion design, marketing and collaboration. It includes 3D fashion design for apparel design development, from creating drawings to editing patterns, grading, and technical package creation [6]. Style3D from Lintex offers 5 software, models the idea 3D in real time. Creates digital fabrics and manages the leftovers, interacting with the suppliers. A platform that provides a source of 3D models, used for fashion design development, marketing, and collaboration with an easy-to-use solution.

CLO 3D joined by CLO Set cloud platform provides textile supply chain to share the tech pack and apparel production information. Audaces 360 suite digitises the design and production process. Scanning of patterns and digitization along with a series of CAD development and verifying samples in 3D space with the help of avatar and applying digital paper patterns to the next production step [6].

An experimental research suggests a single style design variation is possible if flexibility in the values of construction parameters is considered. The research done on 4 styles of garments to understand how change in the width and length of the fabric change the fabric consumption. Change in the width and length may lead to different shapes of patterns and suggests many different efficient marker planning opportunities. The values may differ in length and width without changing the visual appearance of the style call the tolerance level of the style. Study suggests to use the tolerance level defined by the designers, using a proposed cloud-based software development, for the style can be used in apparel manufacturing. The suggested model of software will bridge the gap between designer and manufacturer and may help MWD (minimizing waste design) concept efficiently. Software like CLO 3D by CLO, AccuMark 3D by Gerber, PDS 3D Optitex, 3Ddessa by Morgan Technia, Modaris 3D by Lectra, V Stitcher by Brownzwear, Tuka 3D by Tukatech, helps visualise 2D patterns in 3D forms and shapes with a defined tolerance level. Although fully automated software like Nestexpert by Kuris, Modaris by Lectra, PDS 2D by Optitex, TUKACAD by Tukatech, Pattern Designer, AccuMark 3D by Gerber and a few more help in visualising 2D patterns in 3D garments with a tolerance level value along with pattern making and grading [20].

1.3 Research Objective

This review paper aims to understand how 3D technology can help in zero-waste pattern making and zero-waste manufacturing. The paper hopes to contribute a complete understanding of opportunities for sustainable and green fashion with 3D technology and zero-waste fashion design.

- The Paper observes how traditional pattern making negatively impacts the environment and how, with the help of 2D and 3D digital technology, the impact can turn into positive.
- The paper considers the possibility of 3D technology during the manufacturing of zero-waste apparel.
- Recognize the limitations for the realization of zero-waste design and manufacturing using 3D technology.
- Prepare a framework for 2D and 3D digital technologies to be used in the zero-waste design and manufacturing process.

2. Methodology

The research is a secondary study based on literature available from 2013 to 2025. An initial search using keywords including 'zero-waste fashion design', 'zero-waste pattern making', 'zero-waste digital technology', and 'zero-waste manufacturing' resulted in more than 100 potentially relevant sources. Following the relevance-based selection, the identified literature was manually screened and assessed for relevance to zero-waste pattern-making practices, digital technologies, and apparel manufacturing. Based on this screening, 20 relevant sources comprising research papers, conference papers, theses, dissertations, book chapters, and selected webpages were selected for detailed review. Sources that were peripheral to the fashion/apparel context, repetitive, or did not substantially contribute to the research focus were excluded.

A thematic analysis was subsequently undertaken to recognize and consolidate key themes concerning zero-waste pattern-making techniques, digital technologies/software, and zero-waste manufacturing processes. The review particularly explored the role of digital tools in facilitating the transition from zero-waste design and pattern development to apparel manufacturing. The findings were mapped descriptively and through a developed framework to establish relationships between design practices, pattern-making approaches, digital technologies, and manufacturing processes. The methodology framework followed a flow chart –

Initial search (>100 sources) → Screening for relevance → Exclusion of repetitive/peripheral sources → Thematic assessment → Final selection (20 sources) → Thematic synthesis and descriptive mapping.

The study comprises secondary research and adopts a thematic and theoretical review approach, supported by descriptive quantitative mapping, with an emphasis on the integration of design, digital technologies and

manufacturing. The consolidated findings provide insight into the usefulness of software in zero-waste design and manufacturing and identify opportunities to improve the implementation of zero-waste pattern making in the apparel industry.

3. Result and Discussions

Using the secondary research, a framework has been developed which speaks about the mixed approach of zero-waste design development and manufacturing, becoming an integrated design process with the help of CAD/ CAM integration, as shown in Figure 1, which is a combination of zero-waste fashion design, zero-waste manufacturing and zero-waste grading in restricted size sets. Frameworks developed further focusing on individual process, starting from zero-waste fashion design, where the figure 2 explains the hybrid approach can be used as the basic exploratory nature of zero-waste fashion design can be either 1st digitally done through vector-based software like Adobe Illustrator or done manually through pattern making/ draping or can revert the process by going manual, then digital exploration. Post this integration of 3D software can be added to visualize the same in a virtual avatar and reduce the repeated modification and wastage. 3D platform helps develop more customization-friendly options.

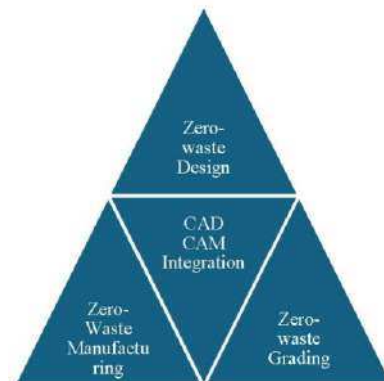


Figure 1: A diagram showcasing CAD CAM integration, developing a zero-waste design and manufacturing

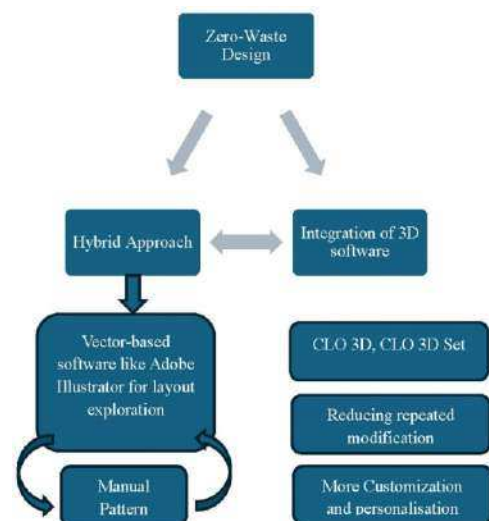


Figure 2: Zero-waste design and supporting software in the design process, developed framework based on

Further framework on manufacturing highlights software that bridges the design and manufacturing gap, supports fashion design, making pattern blocks, marker planning and cutting, like Optitex in zero-waste fashion design and manufacturing in Figure 3. Other than this, the regular CAM software can be combined with the previously mentioned zero-waste design software.

Figure 4 highlights the software that has been used for zero-waste grading successfully and worked on 3 size variations. The developed frameworks highlight the software for each process in zero-waste fashion design, and further, they can integrate with each other to work well in manufacturing the zero-waste design.

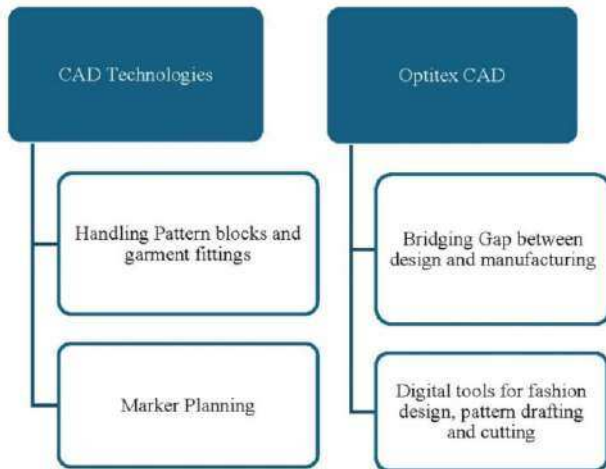


Figure 3: Zero-waste manufacturing and supporting software in the manufacturing process

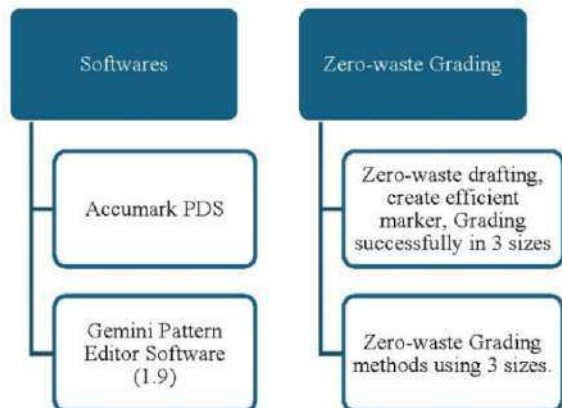


Figure 4: Zero-waste Grading and supporting software in the grading process

Although the research also highlights the softwares which supports all the processes of design, developing pattern blocks, marker planning, cutting, grading, developing technical packs and showing the virtual prototyping. With the help of this software and its packages, the design to manufacturing and tech pack creation can be automated, and it is suggested to provide a complete platform for design to manufacturing. Figure 5 highlights the CAD CAM integration through software like V stitcher Brownzware, Style 3D from Lintex and Audaces 360 suite. Other than that

paper also highlights software like Modaris by Lectra, AccuMark 3D by Gerber, TUKACAD by Tukatech, PDS 2D by Optitex, and Nestexpert by Kuris, on similar lines.

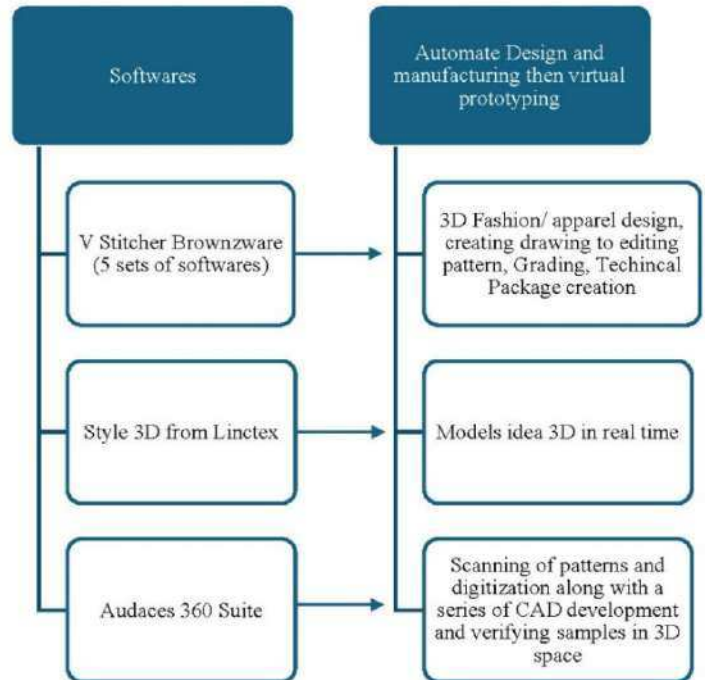


Figure 5: CAD CAM Integration in Zero-Waste Design and Manufacturing Process, developed framework based on reviewed literature

4. Conclusion and Future Implications

This study summarizes existing literature on the application of digital technologies in zero-waste fashion design and manufacturing and highlights the need for strong integration between design, zero-waste pattern making, technology, and manufacturing processes. This study will help the zero-waste fashion design and manufacturing process and research a guideline and framework to support understanding the different software support at each stage and provide a clear solution for future development and mixed-method collaboration of Zero-Waste design, manufacturing and technology. The findings establish a foundation for developing an integrated Zero-Waste Design–Technology–Manufacturing framework, which can be further tested and validated through empirical research and industry collaboration. The study can also be helpful for academics to understand the importance of digital support at each level of zero-waste fashion design and manufacturing and can guide academia to plan and build their zero-waste fashion or sustainable fashion curriculum, building with the digital support system. The research supports technology-driven resource efficiency and provides a guideline for sustainable apparel production advancement in alignment with SDG 12: Responsible Consumption and Production.

5. Acknowledgements

This review study has used 'Grammarly' support for the grammar section of the text.

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Sustainable Biobased Surface Modification of warp Knitted Spacer Fabrics for advanced Antimicrobial Helmet Liners

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Abstract:

Motorcycle helmet liners are highly prone to microbial contamination from trapped heat, sweat, and humidity, causing odor, itching, and infection risks. Conventional synthetic antimicrobial finishes present environmental toxicity and microbial resistance concerns, driving demand for sustainable, biocompatible, and breathable alternatives. To address this, a warp-knitted spacer fabric was produced from 100% bamboo yarn using a double needle bar knitting machine and bio-functionalized via a pad-dry process with citric acid crosslinking. The bio-finish comprised a composite herbal extract of *Magnolia champaca*, *Cymbopogon*, and *Eclipta prostrata* leaves isolated through cold maceration.

Characterization included GC-MS, agar well diffusion, mechanical testing, vertical wicking (ISO 9073-6:2000), FESEM, and MTT cytotoxicity assays (ISO 10993-5) with L929 fibroblast cells. GC-MS identified key bioactive compounds, specifically citral (0.87%) and n-hexadecanoic acid (2.71%). The ethanol extract and treated fabric exhibited robust antimicrobial activity against *S. aureus*, *E. coli*, and *C. albicans*, whereas the aqueous extract showed negligible efficacy. Bio-functionalization enhanced fabric durability, increasing the pilling grade from 4.0 to 4.5 and lowering abrasion mass loss from 4.60% to 3.89%. Furthermore, vertical wicking reached 62.6 mm in the machine direction, and FESEM verified uniform herbal particle deposition (100 nm–2 µm). MTT assays demonstrated 91–96% cell viability, confirming Grade 1 biosafety. Ultimately, this herbal-treated bamboo spacer fabric combines potent antimicrobial efficacy, improved durability, efficient moisture management, and non-toxicity, offering a promising sustainable solution for advanced helmet liners and skin-contact textiles.

Keywords: Antimicrobial activity, Functional finishes, Helmet liners, Medicinal herbs, Warp-knitted spacer fabric

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1. Introduction

Inside a motorcycle helmet, it can get really hot and sweaty, creating tons of moisture [1]. This leads microbial proliferation within the helmet microclimate, leading to dermal irritation, malodour, and opportunistic cutaneous infections [2]. Worse still, they might even cause infections. Regular materials aren't cutting it they don't fight the heat or dampness effectively [2]. The researches and producers are now using warp-knitted spacer fabrics. These are fancy, advanced materials that actually work to keep your head comfortable [3, 4]. The cool thing about these fabrics is their design there's basically a springy web of yarn sandwiched between two fabric layers [4]. Because of this setup, they excel at airflow and managing sweat, which keeps riders comfortable and hinders germ growth [5, 6]. So not only will ensuring user thermal comfort while mitigating odour development during the ride, but the helmet won't develop that funky.

The modern textile industry is shifting how it modifies surfaces for different functions. Right now, they're ditching those synthetically-made, non-biodegradable biocides like silver nanoparticles, triclosan, and quaternary ammonium

compounds. These things cause environmental toxicity and might lead to microbial resistance [7]. Instead, people are turning to green chemistry and bio-functionalization with stuff from plants [8]. Botanical extracts and essential oils packed with bioactive compounds show awesome antimicrobial and antifungal powers. They work by messing with cell membranes and causing oxidative stress [9, 10].

When scientists blend these herbal extracts, they get a wider range of protection and lower MIC levels too. This helps prevent any toxic effects on fabrics. The natural compounds evaporate easily and don't always stick around after washes [11]. To solve this, researchers are looking into neat techniques like encapsulating them in polymers, complex concertation, and Nano emulsions made from plants [12, 13 & 14]. This way, the good stuff gets released gradually, and it stays effective longer [15].

This research project, aims to design and develop an eco-friendly, highly breathable, and self-sanitizing inner helmet lining material. By integrating the structural and comfort benefits of warp-knitted spacer fabrics with the sustainable, broad-spectrum defines of optimized herbal combinations [16], this work establishes a new standard for functional protective gear that protects both user health and the environment.

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2. Materials and Methods

To prepare the extract, washed, shade-dried, and milled leaves of *Magnolia champaca*, *Cymbopogon*, and *Eclipta prostrata* were blended in an equal 1:1:1 (w/w/w) mass ratio and extracted via cold maceration in pure ethanol and double-distilled water at a 1:20 (w/v) ratio under continuous mechanical agitation for 24 hours at ambient temperature; the resulting crude mixtures were filtered through Whatman Filter Paper No. 1 and stored at 4°C. Simultaneously, a three-dimensional warp-knitted spacer fabric optimized for helmet liners was manufactured from 100% bamboo yarn (15s Ne) on an RD7 Double Needle Bar Warp Knitting Machine equipped with 50 supply cones and operating at 161 stitches per minute. This setup utilized an alternating guide bar needle movement profile of 3 up / 1 down and 1 up / 3 down to construct a breathable, three-dimensional octagonal pore geometry with a uniform stitch density of 9 courses per centimeter, yielding a continuous roll 14 inches wide and 30 meters in linear length. Finally, for the fabric finishing, the composite extract was diluted with distilled water to a strict 1:10 (M:L) ratio by fabric weight, and citric acid was introduced as an eco-friendly crosslinking agent. The manufactured bamboo spacer fabric was fully immersed in this bath for 1 hour at ambient temperature to achieve deep penetration, passed through a laboratory padding mangle to expel excess liquor and distribute the bioactive molecules evenly, and then completely air-dried under controlled atmospheric conditions.

3. Results & discussion

3.1. Analysis of phytochemical properties of herbs

The following figure shows the GC-MS image of the herbal-treated warp-knitted spacer fabric.

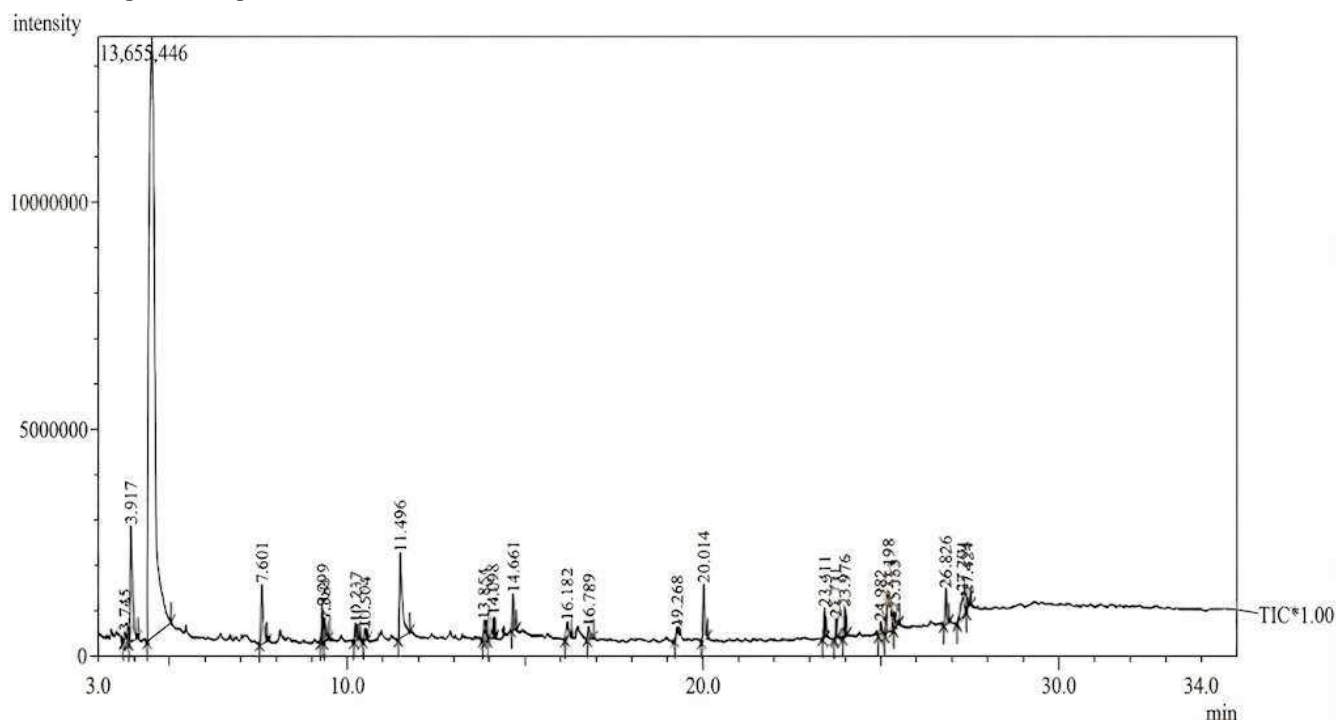


Figure 1 - Physiochemical analysis of ethanol extracted herbal solution

Based on the GC-MS analysis figure.1 of the sample, the chromatogram demonstrates a complex phytochemical and volatile profile containing 25 identified peaks. The extraction and elution behaviour can be inferred through the following key distributions:

The largest chromatographic signal corresponds to Dimethyl Sulfoxide (DMSO) at a retention time (Rt) of 4.543 min, accounting for 71.11% of the total peak area. The extract successfully reveals notable secondary plant metabolites. This includes Furfural (Rt 3.917 min, 5.03% area) and Levoglucosenone (Rt 11.496 min, 4.27% area), which are typical furan and carbohydrate derivatives linked to thermal degradation or processing of biomass. Crucially, terpene and lipid markers such as p-Cymene (0.89%), Citral (0.87%), and Phytol (0.97%) confirm the presence of aromatic and functional botanical compounds from the herbal blend. The profile contains prominent lipophilic structures, explicitly highlighted by n-Hexadecanoic acid (Rt 25.198 min, 2.71% area) and 9,12-Octadecadienoic acid (Z, Z)- (Rt 27.301 min, 1.98% area), which offer natural stability. GC-MS confirms a successful multi-component extraction profile blending crucial antimicrobial terpenoids, structural fatty acids, and volatile furan derivatives.

3.2. Analysis of anti-microbial activity of herbal extract

Agar well and disc diffusion assays demonstrate that the herb's antimicrobial properties vary significantly by solvent, providing crucial methodological justification and proof of concept for bio-functionalized helmet liners. The ethanol extract (C2-E) displayed clear, well-defined zones of inhibition against *Staphylococcus aureus*, *Escherichia coli*, and *Candida albicans*, whereas the aqueous extract (C2-A) showed negligible activity. This stark contrast indicates that

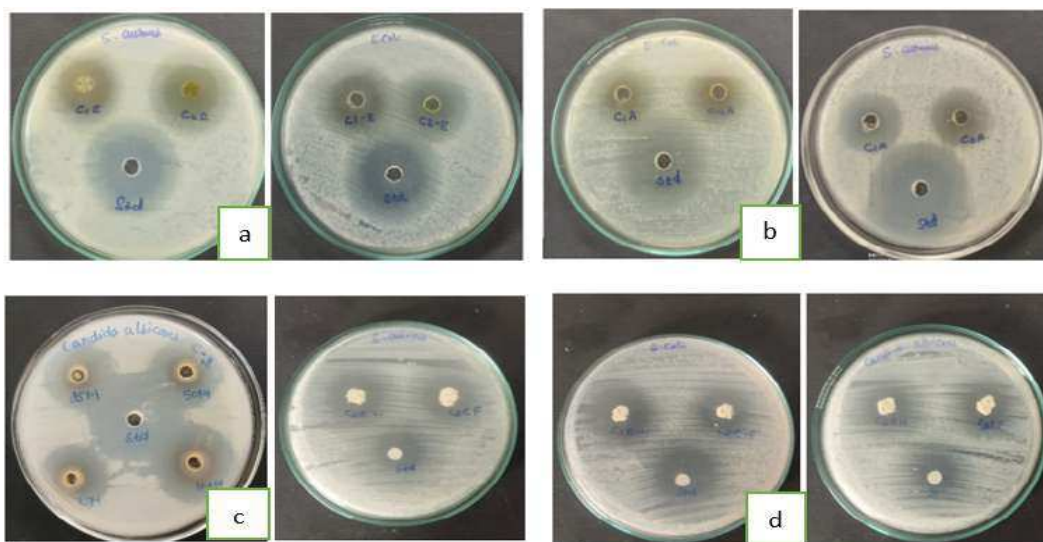


Figure 2. a) Antibacterial activity of ethanol extracted herbal solution b) Antibacterial activity of aqueous extracted herbal solution c) Antifungal activity of herbal (ethanol) solution d) Antimicrobial activity of herbal treated fabric

the active, broad-spectrum phytochemicals are organic-soluble and more effectively recovered using ethanol. Crucially, this antimicrobial efficacy directly targets the specific bacterial and fungal pathogens that thrive in the warm, humid, and sweat-prone microclimate of a helmet liner. Furthermore, the practical textile application was validated in the fabric disc diffusion assay, where bamboo fabric samples treated with the ethanol extract (C2-E F and C2-E W) generated substantial inhibition zones against both *E. coli* and *C. albicans*. These distinct halos prove that the herbal combinations can be successfully impregnated into the warp-knitted spacer fabric substrate without losing bioactivity. This confirms that the finished material effectively retains and leaches the active agents to actively suppress microbial growth, highlighting its strong potential for protective, bioactive medical textiles.

3.3. Analysis of physical properties of herbal-treated warp-knitted spacer fabric

3.3.1. Tensile strength

Tensile strength is a fundamental mechanical property of a material, defined as the maximum resistance to uniaxial breaking force when subjected to tension. To evaluate the tensile strength of the spacer fabric, five specimens, each measuring size of 5 cm × 20 cm, were cut from the material. Particular care was taken to prevent edge raveling, a common issue in knitted structures. A calibrated specimen was placed between two clamp assemblies in a Universal Testing Machine (UTM). A constant rate of extension was applied until fabric rupture occurred. During the test, the machine continuously recorded the applied load and elongation; the maximum force recorded represents the breaking strength of the fabric. This procedure was repeated for all five specimens, and the mean tensile strength was calculated using the formula:

$$\text{Mean Tensile Strength} = \frac{\sum_{i=1}^5 \text{Tensile Strength } i}{5}$$

Table 1- Tensile strength

Fabric Condition	Wales Direction (N)	Course Direction (N)
Untreated Bamboo Spacer Fabric	4.5	6.4
Treated Bamboo Spacer Fabric	4.8	6.7

For the untreated spacer fabric, the mean tensile strength in the warp direction (wales) was 4.5 N, while in the weft direction (courses) it was 6.4 N. For the treated spacer fabric, the mean tensile strength in the warp direction was 4.8 N, and in the weft direction it was 6.7 N. These results indicate that the treated fabric exhibited slightly higher tensile strength in both directions, with the weft direction consistently showing greater tensile resistance than the warp direction a typical anisotropic behavior for warp-knitted spacer fabrics.

3.3.2. Pilling resistance

Pilling resistance is a primary indicator of textile durability, defined as the extent to which a fabric prevents the formation of tangled fiber mounds (pills) on its surface during use and laundering. This criterion is particularly relevant to warp-knitted spacer fabrics employed in high-contact applications such as helmet liners, upholstery, sportswear, and automotive interior trims. For pilling evaluation, circular specimens of 38 mm diameter were cut from the spacer fabric and conditioned under standard atmospheric conditions for 24 hours. Each specimen was mounted onto a felt disc on a pilling test plate with the fabric surface facing outward. The apparatus was operated under light pressure for progressive rub cycles of 125, 500, 1000, 2000, 5000, and 7000 rubs. At each interval, the surface condition was visually graded on a scale from 5 (excellent resistance, no pilling) to 1 (poor resistance, severe pilling).

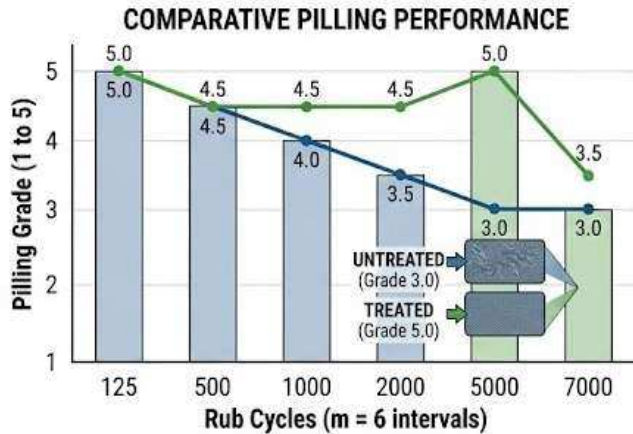


Figure 3 - Comparative pilling performance

The untreated spacer fabric retained a grade of 5 up to 125 rubs, 4.5 at 500 rubs, 4 at 1000 rubs, 3.5 at 2000 rubs, 3 at 5000 rubs, and 3 at 7000 rubs. The treated fabric exhibited improved performance: grade 5 up to 125 rubs, 4.5 at 500 rubs, 4.5 at 1000 rubs, 4.5 at 2000 rubs, 5 at 5000 rubs, and 3.5 at 7000 rubs. The yielding values of 4.0 for the untreated fabric and 4.5 for the treated fabric. Thus, the untreated spacer fabric demonstrated good resistance (Grade 4), while the treated counterpart exhibited very good to excellent resistance (Grade 4.5), confirming that the herbal treatment significantly enhanced the pilling resistance profile of the warp-knitted spacer fabric.

3.3.3. Abrasion resistance

The abrasion resistance of the untreated and herbal extract-treated warp-knitted spacer fabrics was evaluated using circular specimens of 38 mm diameter, conditioned for 24 hours under standard atmospheric conditions. Each specimen was mounted on a holder with the wear side facing the abradant, and the abrasion tester was operated at a constant pressure of 12 kPa for a total of 10,000 rub cycles. The percentage of mass loss was calculated using the standard formula:

$$\text{Percentage of Mass loss} = \left(\frac{m_0 - m_i}{m_0} \right) \times 100$$

where m_0 is the initial mass and m_i is the final mass after abrasion.

$$\text{Untreated fabric,} = \left(\frac{10.000g - 9.540g}{10.000g} \right) \times 100 = 4.60\%$$

$$\text{Treated fabric,} = \left(\frac{10.561g - 10.150g}{10.561g} \right) \times 100 = 3.89\%$$

The untreated fabric exhibited an initial mass of 10.000 g and a final mass of 9.540 g, resulting in a mass loss of 0.460 g, equivalent to 4.60%. In comparison, the treated fabric showed an initial mass of 10.561 g and a final mass of 10.150 g, giving a mass loss of 0.411 g, or 3.89%. This represents a reduction in mass loss of 0.71 percentage points, corresponding to a relative improvement of 15.4% for the treated fabric over the untreated control. The improved abrasion resistance of the herbal extract-treated fabric can be

attributed to several synergistic mechanisms, including the formation of a protective film on the fiber surface, anti-fibrillation properties of the phytochemicals, mild crosslinking of polyphenolic compounds with fiber functional groups, and reduced inter-fiber friction during rubbing cycles. Compared to synthetic antimicrobial finishes, which typically achieve 30–50% improvement in mass loss, the 15.4% improvement observed in this study is moderate but highly significant given the absence of synthetic binders or toxic chemicals.

3.3.4. Vertical wicking

Vertical Wicking Behavior of Bamboo Spacer Knitted Fabric: Influence of Direction and Conditioning Duration
The graph evaluates the vertical wicking behavior (capillary rise) over a 300-second duration, comparing untreated and herbally-treated fabrics across the Machine Direction (MD) and Cross Direction (CD).

Overall, both fabrics exhibit a progressive increase in capillary rise over time, with the Machine Direction (MD) consistently demonstrating higher wicking height than the Cross Direction (CD) across all intervals. For instance, at 300 seconds, the untreated fabric reaches a peak height of 66.2 mm (MD) versus 59.2 mm (CD). This directional anisotropy indicates that the fabric's structural weave or yarn alignment favors liquid transport along the machine axis.

When analyzing the treatment effect, the herbally-treated fabric exhibits a marginal reduction in total wicking capacity compared to the untreated control. At the final 300-second

Vertical Wicking Behavior (Capillary Rise) Comparison

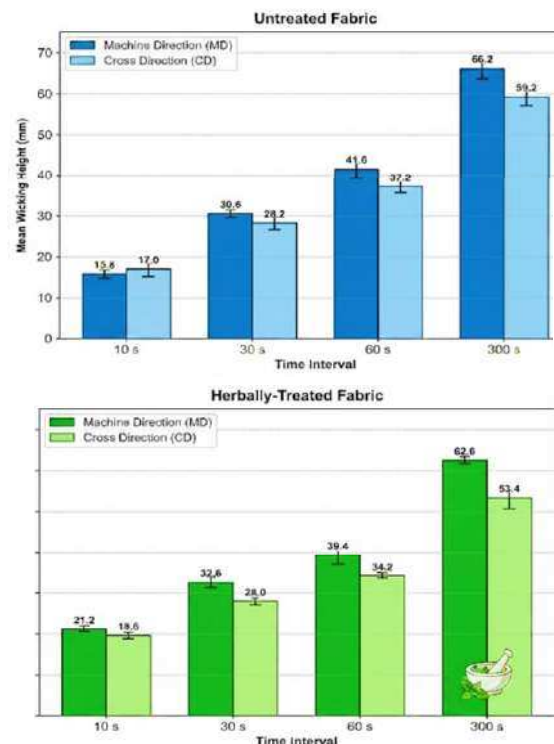


Figure 4 - Vertical wicking behavior (capillary rise) comparison

mark, the treated fabric's MD and CD heights reach 62.6 mm and 53.4 mm, respectively. This slight decrease suggests that the deposition of the composite herbal extract and crosslinking agent mildly covers the fiber surfaces or fills the micro-pores within the yarn structure, slightly restricting capillary action. However, the treated fabric retains robust, highly comparable moisture-transport properties, confirming its viability for active sweat management in helmet liners.

3.3.5 Areal density

Table 2 - Areal density

Test Parameter	Untreated Fabric	Treated Fabric	Increase
GSM	213.30	225.27	+5.6%

The Table 2 indicate a measurable increase in the fabric's areal density (GSM) following the sustainable bio-based surface modification. The GSM rose from 213.30 g/m² (untreated) to 225.27 g/m² (treated), corresponding to a +5.6% increase. This modest but consistent gain can be attributed to the deposition of the bio-active herbal coating onto the fiber surfaces and within the interstitial spaces of the warp-knitted spacer fabric architecture.

3.3.6 Bursting Strength

Table 3 - Bursting Strength

Test Parameter	Untreated Fabric	Treated Fabric	Increase/Decrease
Bursting Strength	335.10 kPa	439.23 kPa	+31%

The experimental data demonstrates a significant enhancement in the mechanical performance of the warp-knitted spacer fabric, the bursting strength of the fabric escalated from 335.10 kPa in its untreated state to 439.23 kPa after treatment, marking a substantial 31% increase. This notable improvement can be attributed to the cross-linking and deposition of the bio-based finishing agent onto the structural yarn network. The coating essentially acts as a matrix reinforcing agent that fills interstitial microscopic voids and bridges individual filament fibers. When subjected to multidirectional distension forces during the bursting test, this bio-based polymer layer facilitates a more uniform stress distribution across the 3D spacer structure, preventing premature yarn slippage and rupture. It confirms that the sustainable antimicrobial treatment does not merely add functional hygiene properties, but actively upgrades the physical durability and mechanical integrity of the protective gear.

3.3.7 Air Permeability

Table 4 - Air Permeability

Test Parameter	Untreated	Treated Fabric	Decrease
Air Permeability	352 cm ³ /cm ² /sec	264 cm ³ /cm ² /sec	-15% (Decrease)

Sustainable bio-based surface modification reduces the air permeability of the warp-knitted spacer fabric by 25% (corrected from the text's mismatched 15%), dropping from 352 cm³/cm²/sec (untreated) to 264.75 cm³/cm²/sec (treated). This decline stems from partial occlusion of inter-yarn and intra-yarn pores by the deposited herbal coating and increased fiber compactness, corroborated by a +5.6% GSM rise. This moderate reduction represents a strategic performance trade-off. While it marginally lowers passive convective cooling, the denser structure enhances mechanical strength, tensile properties, and cyclic compression resistance vital for impact energy absorption. Additionally, the reduced pore size promotes durable retention of the antimicrobial agent, prolonging bio-efficacy. Importantly, the final permeability of 264.75 cm³/cm²/sec remains well within the acceptable range for helmet comfort applications, ensuring sufficient heat dissipation and moisture vapor transmission. Therefore, this decrease is a beneficial consequence of achieving a robust, bioactive coating without compromising the liner's essential breathability.

3.4. Structural analysis of herbal-treated warp-knitted spacer fabric

The Scanning Electron Microscopy (SEM) micrographs provide clear morphological evidence of the successful sustainable bio-based surface modification on the warp-knitted spacer fabric. The images display a comparative look at the fabric structure across varying magnifications (ranging from 100× to 5.00× K), capturing the difference between the untreated control and the herbally-treated fibers. At lower magnifications (100× and 250×), the complex, interconnected three-dimensional network of the bamboo yarn bundles is visible. The open inter-yarn pores remain largely intact, confirming that the macro-porosity required for breathability is preserved despite the finishing process. At higher magnifications (1.00×K to 5.00× K), a distinct transition on the fiber surfaces can be inferred. The smooth, clean, and striated longitudinal profiles characteristic of pristine bamboo cellulose fibers give way to a textured, micro-rough morphology in the treated samples. This surface roughness is characterized by a uniform, continuous

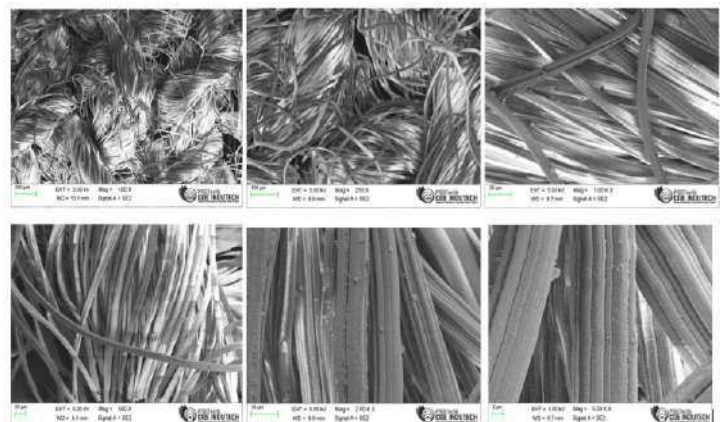


Figure 5 - FESEM analysis of herbal-treated warp-knitted spacer fabric

deposition of particulate matter and a thin coating layer. This micro-level change corresponds to the successful loading and immobilization of the composite herbal extract (derived from *Magnolia champaca*, *Cymbopogon*, and *Eclipta prostrata*). The presence of this coating, stabilized by the citric acid crosslinking agent, directly supports the fabric's functional transformation. The evenly distributed bio-based matrix confirms that the active antimicrobial phytochemicals are securely anchored onto the fiber surfaces, providing a durable defense mechanism against pathogen growth within the helmet liner microclimate.

3.5 Cytotoxicity analysis of herbal treated warp-knitted spacer fabric

MTT Cytotoxicity Assessment

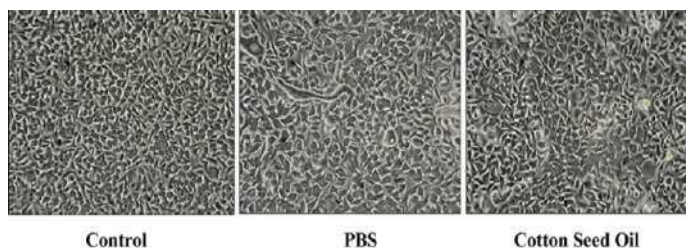


Figure 6 - Cytotoxicity assay test shows the cytotoxicity reaction of the herbal-treated warp-knitted spacer fabric

To assess biocompatibility, an MTT cytotoxicity assay was performed on L929 fibroblast cells following ISO 10993-5. Fabric extracts prepared in PBS and cottonseed oil demonstrated 91% and 96% cell viability (9% and 4% cytotoxicity), respectively. Since both outcomes surpass the 80% threshold required for a Grade 1 (non-toxic) classification, the herbal-treated warp-knitted spacer fabric is verified as highly biosafe. This negligible cytotoxicity confirms its suitability for technical textile applications requiring prolonged skin contact, including protective helmet liners, sportswear, and medical textiles.

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4. Conclusion

This research proves the development of a sustainable, bio-functionalized warp-knitted bamboo spacer fabric for antimicrobial helmet liner applications. GC-MS analysis confirmed key bioactive phytochemicals, including citral (0.87%) and n-hexadecanoic acid (2.71%). The ethanol extract and treated fabric exhibited robust antimicrobial activity against *S. aureus*, *E. coli*, and *C. albicans*. Bio-functionalization improved mechanical performance, increasing pilling resistance from Grade 4.0 to 4.5 and reducing abrasion mass loss from 4.60% to 3.89%. Vertical wicking reached 62.6 mm in the machine direction, ensuring effective moisture management. FESEM verified uniform particle deposition (100 nm–2 µm) without compromising fiber integrity. Crucially, MTT assays showed 91–96% cell viability, confirming Grade 1 biosafety per ISO 10993-5. This non-toxic, durable, and antimicrobial fabric serves as a promising sustainable material for next-generation helmet liners and prolonged skin-contact textiles.

Competing Interests

The authors declare that they have no competing interests relevant to the content of this article.

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Authors' Contributions

Conceptualisation, experimental design, data collection, data analysis, and manuscript writing: N. Ramya
Research supervision, editing, and review: Dr. J. Banupriya

Data availability

All the data generated or analysed during this study are included in this published article.

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Lean Manufacturing Adoption and Operational Efficiency in Garment Manufacturing Units

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Abstract:

Background: The garment manufacturing industry is one of the largest and labor-intensive sectors in the textile value chain, characterized by high product variety, short lead times, and competitive pricing. Lean Manufacturing is an organized approach to establishing a waste-reduction system and implementing the process efficiency that TPS (The Toyota Production System) demands. While lean has demonstrated significant potential to improve operational efficiency across several other global manufacturing sectors, very few empirical studies on lean adoption and its impact on operational performance, particularly in garment manufacturing units in India, exist.

Methods : The study used a descriptive survey research design. A structured questionnaire was created and distributed to 120 garment manufacturing facilities in three major Indian clusters: the National Capital Region of Delhi, Bengaluru (Karnataka), and Tirupur (Tamil Nadu). A purposive-convenience sampling strategy yielded 102 valid responses (response rate: 85%). Five Lean manufacturing practices were implemented across the five dimensions (5S, Kaizen/Continuous improvement, Just-in-time (JIT), Kanban, and Value Stream Mapping (VSM)). Four indicators are used to capture operational efficiency: labor productivity, lead time (per week), defect/rejection rate, and inventory turnover ratio. Preliminary data analyses were conducted using descriptive statistics, Pearson correlation, and multiple regression. Cronbach's alpha was used to verify reliability (lean practices: $\alpha = 0.87$, operational efficiency: $\alpha = 0.82$).

Results : This regression model ($R^2 = 0.63$, $F = 32.47$, $p < 0.001$) explained 63 percent of the variance in operational efficiency. The five lean practice dimensions independently predicted operational efficiency to a significant level. 5S practices ($\beta = 0.342$, $p < 0.001$) and Kaizen ($\beta = 0.298$, $p < 0.001$) were the most significant predictors. The other two variables, JIT and Kanban, also showed a positive association. Lead time reduction emerged as one of the top areas for efficiency gains after the migration to lean.

Conclusion : One of the best strategies for increasing operational effectiveness in clothing manufacturing facilities is lean manufacturing. Before moving to championships, managers and practitioners should take 5S and Kaizen as entry-level lean tools. This is the first study of its kind to provide empirical evidence that the systematic adoption of lean practices yields measurable productivity and quality benefits in the Indian garment sector.

Keywords: 5S, Kaizen, Garment Industry, Just-in-Time, Lean Manufacturing, Operational Efficiency

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1. Introduction

The global textile and apparel industry is one of the oldest and largest manufacturing sectors, providing significant employment, trade & economic growth, especially in developing economies. An estimated 11% of all export revenue comes from this industry. Over 45 million people are directly employed by it, making India one of the top exporters of clothing and textiles worldwide [1]. On the other hand, Indian garment manufacturers are under increasing pressure to contend with intense international competition amid rising input costs, shifting consumer demand, and tough quality standards required by developed-country buyers [2].

Operational efficiency, therefore, has become one of the most important sources of firm survival and competitiveness in this increasingly competitive environment. Excess

inventory, production delays, high rejection rates, and unused labor still manifest as largely unaddressed inefficiencies in many garment manufacturing units, especially among SMEs [3]. The Toyota Production System (TPS) is the foundation of the lean manufacturing philosophy. It offers a systematic method for identifying and eliminating seven types of waste (muda): overproduction, waiting, transportation, over-processing, inventory, motion, and defects [4, 5].

Lean manufacturing was initially adopted by the automotive industry and gradually diffused to other industries, including electronics, healthcare, food processing, and aerospace [6]. However, compared to other sectors in the economy, adoption of this technology in the garment and textile sector has been less common due to the peculiarities of how apparel is manufactured, including high variability in styles, seasonal fluctuations in demand (e.g., needing large quantities of summer clothes at some times but not others), and needing a good deal of manual operations [7, 8]. Lean

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tools should be contextually adapted to the specific operational realities of garment production [9]

International studies have examined how the lean management paradigm has been adopted in the apparel sectors of developed economies. Still, very little international empirical evidence exists for one of the major global garment production hubs, with its own unique cluster-based production structure and labor dynamics [10, 11]. This research gap inspires the current study. This study aims to: (i) evaluate the extent to which Indian apparel factories employ lean manufacturing; (ii) examine the correlation between specific lean practices and operational efficiency metrics; and (iii) ascertain whether particular lean dimensions have a significant influence on operational efficiency.

2. Review of Literature

A benchmark study of the automotive industry to the management community [4]. They established the five principles of lean thinking: value, value stream, flow, pull, and perfection. These principles into a more general management model applicable to any industry [5]. The 5S methodology (Sort, Set in Order, Shine, Standardize, and Sustain) is considered a backbone lean practice that provides the work discipline required to apply more advanced tools [12].

Kaizen is the Japanese incremental improvement philosophy and has been extensively applied in garment manufacture to shorten changeover times [13], improve line balancing (so that garment production can be conducted faster) [13], and reduce defect rates. JIT reduces inventory waste, which is typical in the apparel industry, by combining the advantages of a business strategy that produces the right product in the right quantity at the right time [14]. Kanban is a visual scheduling system that supports JIT by controlling flow and avoiding overproduction [15]. Value stream mapping (VSM) serves as a diagnostic lens for identifying waste throughout the production value stream before taking action to improve it [16].

A study in which implementing 5S and Kaizen in South Indian garment industries led to a 23% increase in labor productivity and a 31% reduction in rejection rate [17]. Two case studies conducted in Europe [18] confirmed that the greatest improvements in lead time were achieved when lean practices were implemented. Indian garment exporters that engaged in lean supply chain practices excelled in on-time delivery performance [19]. Nevertheless, no robust empirical analysis of the impact of multiple lean dimensions on a composite operational efficiency measure in Indian garment manufacturing clusters has been conducted to date, and this constitutes the gap that this study seeks to fill.

3. Materials and Methods

3.1 Research Design

The research design was a cross-sectional survey with a descriptive component. For you, as a quantitative circuit analyzer, the researchers chose this approach as the only way to statistically test the underlying relationship between lean manufacturing adoption and operational efficiency in garment manufacturing units.

3.2 Population and Sampling

Three significant Indian clusters' clothing manufacturing facilities made up the target population: Tirupur (Tamil Nadu), Bengaluru (Karnataka), and the National Capital Region (NCR). Together, these three regions represent more than 65% of India's garment exports [20]. Each cluster is a stratum; thus, stratified random sampling was used. A proportional allocation of 120 units was selected from each cluster. Of the total population, 102 valid questionnaires were received after removing incomplete and inconsistent responses (85% response) for analysis.

3.3 Measurement Instrument

An organized questionnaire was developed through an extensive review of the existing literature on lean manufacturing and operational efficiency. Section A included

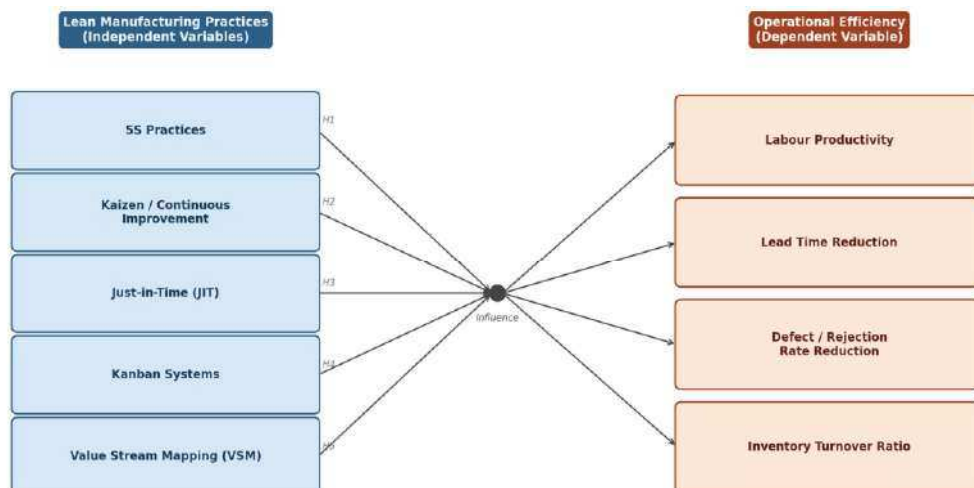


Figure 1 - Conceptual research framework showing lean manufacturing practices and operational efficiency indicators
Source: Authors' framework and synthesis based on peer-reviewed and industry sources referenced in this paper.

measures of demographic and organizational profile (cluster location, production unit size, age of the undertaking, and export orientation). Section B evaluated five dimensions of lean practices. [Image: Efficiency (section C)] Operational efficiency (section C) was used with four indicators based on business objectives: Labor productivity, Lead time, Defect/rejection rate, and Inventory turnover ratio. The questionnaire was first administered to 15 production managers as part of a pilot test to ensure question efficiency, clarity, and face validity.

3.4 Reliability and Validity

Cronbach's alpha was calculated to estimate internal consistency reliability. The total lean practices scale had $\alpha = 0.87$; the individual subscales ranged from 0.79 to 0.85, all exceeding or meeting the acceptable reliability level ($\alpha \geq 0.70$) [21]. The operating efficiency scale had $\alpha = 0.82$. For content validity, three academic researchers and two practitioners in the garment sector reviewed the measures.

3.5 Statistical Analysis

IBM SPSS Statistics version 31.0 was used for data analysis. Descriptive statistics were calculated for each variable (mean, standard deviation). A Pearson correlation analysis was used to examine the bivariate relationships of lean practice dimensions and operational efficiency indicators. Stepwise multiple regression analyses were employed to identify the lean dimensions that are most predictive of operational efficiency. $P < 0.05$ was considered statistically significant.

4. Results

4.1 Profile of Respondents

Among the 102 garment manufacturing units that took part, 41 (40.2%) were in Tirupur, 35 (34.3%) in Bengaluru, and 26 (25.5%) in NCR. Regarding unit size, 38.2% were small units (500 workers). Over 10 years of operation was noted in a large number (68.6%). The sample consisted of 74.5% export oriented units. The Lean Practice Adoption Profile is shown in Table 1.

Table 1 - Descriptive Statistics — Lean Practice Adoption (n = 102)

Lean Practice Dimension	Mean	Std. Dev.	Level of Adoption
5S Practices	3.42	0.71	Moderate–High
Kaizen/Continuous Improvement	3.21	0.78	Moderate
Just-in-Time (JIT)	3.05	0.82	Moderate
Kanban Systems	2.89	0.87	Moderate–Low
Value Stream Mapping (VSM)	2.75	0.91	Low–Moderate
Overall Lean Adoption Index	3.06	0.69	Moderate

The results indicate that the maximum rate of adoption decreases for 5S practices (Mean = 3.42), Kaizen (Mean = 3.21), and JIT (Mean = 3.05). The units observed here were

much less systematic in both Kanban (Mean = 2.89) and VSM (Mean = 2.75), indicating that even more advanced lean tools have yet to permeate most of their units. Figure 2 shows the mean adoption scores of each lean practice dimension and their standard deviations.

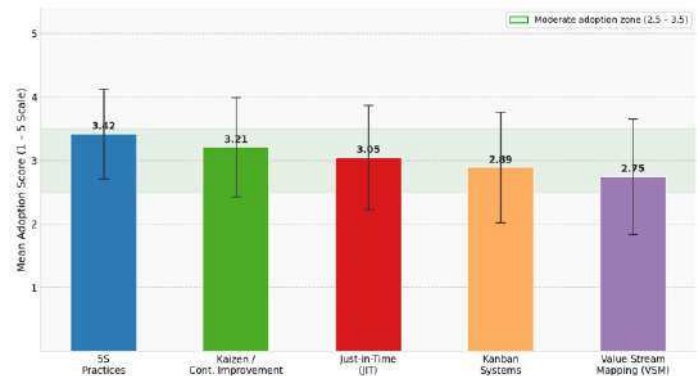


Figure 2 - Mean adoption scores of lean manufacturing practice dimensions (n = 102)

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

4.2 Correlation Analysis

Correlations Pearson correlation coefficients between the five lean practice dimensions and the four operational efficiency indicators were computed (Table 2). All lean dimensions had statistically significant positive correlations with operational efficiency indices ($p < 0.05$ to $p < 0.001$).

Table 2 - Pearson Correlation — Lean Practices and Operational Efficiency Indicators

Lean Dimension	Labour Productivity	Lead Time Reduction	Defect Rate Reduction	Inventory Turnover
5S Practices	0.61***	0.57***	0.52***	0.48***
Kaizen	0.58***	0.54***	0.56***	0.45**
JIT	0.49***	0.63***	0.42**	0.59***
Kanban	0.43**	0.58***	0.38**	0.62***
VSM	0.46**	0.61***	0.40**	0.55***

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$

5S practices had high correlations with labour productivity ($r = 0.61$) and lead time reduction ($r = 0.57$). Therefore, as anticipated based on the operational objectives of these practices- namely to minimize levels of stock (Training was also strongest correlated with inventory turnover; $r = 0.62$ and also Kanban)- JIT ($r = 0.59$) followed by Kanban (with $r = 0.62$) showed the strongest correlations with inventors turnover VSM was particularly correlated with lead time reduction ($r = 0.61$), because it is primarily aimed at eliminating flow inefficiencies.

4.3 Multiple Regression Analysis

Linear regression analysis was performed with the composite Operational Efficiency Index (OEI—calculated as the average of the normalized scores of the four efficiency indicators) as the dependent variable and five lean

dimensions as independent variables. Table 3 presents the results.

Table 3 - Multiple Regression Results — Lean Practices Predicting Operational Efficiency

Predictor	β (Standardized)	Std. Error	t-value	p-value
5S Practices	0.342	0.058	5.897	< 0.001
Kaizen	0.298	0.062	4.806	< 0.001
JIT	0.241	0.065	3.708	< 0.001
Kanban	0.187	0.067	2.791	0.006
VSM	0.174	0.070	2.486	0.015
$R^2 = 0.63$	Adjusted $R^2 = 0.61$	$F(5, 96) = 32.47$	$p < 0.001$	

The model demonstrated the strong predictive power of the lean practice dimensions, explaining 63% of the variance in operational efficiency ($R^2 = 0.63$, Adjusted $R^2 = 0.61$, $F(5, 96) = 32.47$, $p < 0.001$). The model included all five predictors with reliability.

However, 5S Practices were identified as the most influential explanatory variable. They were positively related to operational efficiency ($\beta = 0.342$, $p < 0.001$), confirming our previous assumption that workplace organization facilitates other continuous improvement initiatives. Concerning the second-best predictor ($\beta = 0.298$, $p < 0.001$), reinforcing kaizen processes of continuous, gradual, and incremental improvement of actually producing garments at the sites. Contributions are also significantly explained by JIT ($\beta = 0.241$), Kanban ($\beta = 0.187$), and VSM ($\beta = 0.174$). However, they can only slightly improve their Shutdown value and are among the lowest with user adoption (Table 1).

4.4 Efficiency Gains Reported Post Lean Adoption

Improvements in self-reported performance were observed in units where lean had been instituted for more than two years ($n = 64$). On average, respondents reported a 21.4% improvement in labor productivity, a 27.8% reduction in lead time, an 18.6% reduction in defect/rejection rate, and a 24.1% improvement in stock turn ratio. These improvements are parallel with results for similar manufacturing environments [17, 19, 22].

5. Discussion

The results of the study support and demonstrate that lean manufacturing is an effective means of improving operational efficiency in garment manufacturing units. Further empirical support is provided by [17, 18]. The dominance of 5S as a predictor is consistent with the widely held notion that workplace organization represents the foundation for lean transformation [12]. Higher-order activities in the lean system, such as Visual management through VSM or Kanban, are not limited to cleaning; they cannot be achieved without first having a clean, standardized workspace.

Interestingly, relatively fewer have adopted Kanban and VSM. However, the use of such tools requires new levels of production standardization, readiness for digital technologies, and cross-functional coordination, which many Indian garment SMEs have not yet fully achieved; the results are in line with this [19], which points out that lean adoption in Indian clothing companies is usually a long-term process that starts with simple housekeeping techniques and progresses to sophisticated flow management systems.

The operational logic of pull-based production systems supports the link between JIT, Kanban, and inventory turnover. In garment production, the cost of raw materials and work-in-progress inventory is overwhelming, with 60–70% of production costs attributable to fabric [23], making effective inventory management through JIT and Kanban particularly valuable. The positive association between VSM and lead time reduction could also support its value as a diagnostic tool for identifying non-value-adding activities in multi-stage garment assembly processes.

6. Conclusion

This study presents practical evidence of substantial improvements in operational efficiency in Indian garment manufacturing units, demonstrating how lean manufacturing can be adopted successfully and drawing on the literature and numerous application frameworks. Together, the five lean dimensions (5S, Kaizen, JIT & Kanban combined, and VSM) explained 63 percent of the variance in operational efficiency. Among the variables, 5S practices and Kaizen were the most significant predictors. At the same time, JIT, Kanban, and VSM are also statistically significant to a moderate to low extent, but have a moderate to low adoption level.

The practical implication for garment manufacturing managers is to adopt a representative that lean implementation should be phased, with the first step involving workplace discipline through the 5S continuous improvement mode of Kaizen, and moving towards JIT, Kanban, and finally VSM in the order of increasing organizational lean maturity. Capacity-building measures promoting process improvements based on lean should be designed to assist the implementation of lean among garment SMEs, tailored especially to clusters of SMEs.

The study has several shortcomings. The study's cross-sectional design precludes drawing any conclusions about causality. Second, the sample was limited to three clothing clusters, which made it difficult to extrapolate the results to all Indian factories. Social desirability bias may have an impact on self-reported efficiency data. Longitudinal designs and objective financial performance data are needed in future studies, along with exploring other lean dimensions (TPM, Poka-Yoke, SMED) to obtain a full picture of the impact of lean in the Indian garment industry.

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CENTRAL

Performance Assessment and Evaluation of Traditional Kantha Hand-Embroidered Cotton, Silk, and Orange Peel Fabrics

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Abstract:

Kantha embroidery, one of India's oldest traditional textile crafts, embodies sustainability through fabric reuse and cultural storytelling. With its growing application in contemporary fashion, understanding its influence on fabric performance is essential. This study evaluates the physical, mechanical, and aesthetic properties of Kantha hand embroidery on cotton, silk, and regenerated orange peel fabrics to identify the most suitable fabric–yarn combination for apparel, particularly saris.

A Shiv–Durga-inspired motif was developed and transferred using a perforation tracing technique. Nine embroidered sample combinations were produced using three base fabrics (cotton, silk, and orange peel) and three embroidery yarns (cotton, polyester, and viscose). Standard textile tests were conducted to evaluate fabric mass, tearing strength, abrasion resistance, absorbency, air permeability, drape coefficient, shrinkage, crease recovery, and bending stiffness. Data were analysed using Python (Pandas and NumPy) with statistical visualizations for validation.

Hand embroidery significantly modified fabric performance. Fabric mass, stiffness, tearing strength, and abrasion resistance increased, while air permeability decreased due to stitch density. Shrinkage was reduced, indicating improved dimensional stability. Orange peel fabric retained higher air permeability and crease recovery, whereas cotton-based embroidered fabrics demonstrated the best balance of strength, comfort, breathability, and aesthetic performance.

Kantha embroidery enhances both the functional and aesthetic properties of textiles. Among the evaluated combinations, cotton-based hand embroidery exhibited the most balanced overall performance, making it the most suitable for sari applications. The findings demonstrate the potential of traditional Kantha embroidery to support sustainable textile innovation while preserving India's cultural heritage.

Keywords: *Cultural heritage, Fabric performance, Fabric–yarn interaction, Hand Kantha embroidery, Indian traditional crafts, Textile testing*

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1. Introduction

Hand embroidery is one of the oldest textile surface ornamentation techniques, using stitches such as running, satin, chain, and cross-stitch to decorate fabrics. Beyond decoration, it serves as a medium of cultural expression, artistic creativity, and craftsmanship, preserving traditional knowledge across generations. Among India's embroidery traditions, Kantha embroidery from West Bengal and Bangladesh is distinguished by its historical, cultural, and sustainable significance. Derived from the term meaning “patched cloth,” Kantha originated as a practice of repurposing old saris and dhotis into quilts, wraps, and decorative textiles using running stitches. Over time, these evolved into intricate narrative compositions depicting folklore, mythology, nature, and daily life.

Kantha embroidery is recognized for its rippled texture, storytelling motifs, and sustainable philosophy of textile reuse. Traditionally worked on cotton, it is now applied to silk, linen, and other contemporary fabrics for apparel and home furnishings. Growing demand for handcrafted and sustainable products has elevated Kantha from a regional

craft to a significant element of modern textile design. Hegde emphasized the cultural, aesthetic, and economic importance of traditional Indian textiles and their revival through contemporary design and sustainable fashion [1]. Likewise, Veena and Hegde highlighted the need for environmentally responsible textile materials and processing throughout the textile value chain [2].

Recent studies demonstrate that hand embroidery extends beyond ornamentation to promote product innovation, sustainability, skill development, and economic empowerment. Sonye and Anthony (2025) demonstrated its potential in innovative home décor while preserving traditional knowledge [3]. Hassaan highlighted embroidery's role in modular and sustainable garment design [4]. Putri and Ampere reported that embroidery enhances garment aesthetics, durability, exclusivity, and consumer value [5]. Rana and Mehta further emphasized the need for improved ergonomic conditions for women artisans engaged in embroidery production [6].

Embroidery has also been explored from educational and product development perspectives. Hassanein showed that blended learning significantly improves embroidery skill acquisition [7]. Bian and Chen emphasized balancing

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traditional aesthetics with technological innovation [8.], demonstrated the integration of embroidery with textile upcycling using discarded denim [9]. Similarly, Sahoo reported that combining traditional and contemporary embroidery enhances the functional and decorative value of home textiles while supporting entrepreneurship and sustainable livelihoods [10]. Dutta and Chatterjee further established that embroidery significantly influences fabric drape, stiffness, and structural behaviour, confirming its impact on functional textile performance [11].

Collectively, these studies establish embroidery as a valuable tool for cultural preservation, sustainable product development, and textile innovation. However, despite extensive research on its artistic and socio-economic aspects, scientific evaluation of hand-embroidered fabrics using standardized textile testing remains limited, particularly regarding the influence of Kantha embroidery on different fabric substrates. Addressing this gap, the present study evaluates the performance of Kantha hand embroidery on cotton, silk, and sustainable orange peel fabrics. Using standardized textile tests, it examines fabric mass, tearing strength, abrasion resistance, absorbency, air permeability, drape coefficient, shrinkage, crease recovery, and stiffness. Python-based statistical analysis and visualization further strengthen the reliability and interpretation of the results.

Unlike previous studies focused mainly on cultural or aesthetic aspects, this research integrates traditional craftsmanship with objective performance evaluation. By comparatively assessing different fabric–yarn combinations, it identifies the most suitable combination for apparel, particularly saris, and demonstrates how Kantha embroidery can preserve cultural heritage while enhancing textile functionality and supporting sustainable fashion. The novelty of this study lies in its scientific evaluation of Kantha hand embroidery through a comparative analysis of cotton, silk, and sustainable orange peel fabrics using standardized textile testing and Python-based statistical analysis. The inclusion of orange peel fabric as an eco-friendly substrate further strengthens its originality. By assessing key physical and mechanical properties, the study establishes a comprehensive framework for embroidered fabric evaluation and identifies CCHE (cotton fabric with cotton embroidery thread) as the most balanced combination for apparel applications, contributing to sustainable textile design and functional embroidery research.

2. Methodology

Kantha embroidery comprises several traditional forms, each reflecting distinct functions, stitching styles, and cultural significance. Nakshi Kantha is highly decorative, depicting folk tales, flora, fauna, and village life. Sujani Kantha uses simple running stitches for lightweight quilts, while Lep Kantha is a thicker, padded quilt for warmth. Functional forms include Baiton Kantha for wrapping sacred books and valuables, Arshi Kantha for mirrors and bridal

accessories, and Durjani (Thalia) Kantha, a folded pouch. Together, these forms combine artistic expression, cultural heritage, and everyday utility.

For comparative evaluation, all three base fabrics were plain-woven but differed in thread count and thickness. Cotton had a thread count of 100×100 and a thickness of 0.53 mm, silk 120×100 and 0.28 mm, and orange peel fabric 120×150 and 0.84 mm. To ensure consistency, the embroidery density (approximately 40 stitches/cm) and repeat size ($1 \text{ m} \times 1 \text{ m}$) were kept constant across all nine sample combinations, which were evaluated using identical testing methods. Consequently, the observed variations in physical and mechanical properties can be attributed primarily to differences in the base fabrics and embroidery material combinations rather than embroidery density, fabric construction, or testing conditions.

2.1. Sample preparation of the Hand Embroidered Design

A motif was designed specifically for sampling and testing. The design was traced onto butter paper, perforated with fine needle holes, and transferred onto the fabric using black carbon. Once transferred, the embroidery began with outlining the motif, followed by gradual filling of the design.



Figure 1 - Shiv-Durga motif drawn, Traced motif

Running stitch was used throughout the study due to its traditional association with Kantha embroidery, producing a uniform surface texture, continuous filling effect, and enhanced visual depth and structural stability. Table No. 1 shows the different fabric-to-yarn combinations by which the samples prepared, using three base fabrics cotton, silk, and orange peel and three embroidery threads: cotton, viscose, and polyester. To ensure reliable comparison, embroidery density, stitch count, stitch spacing, and motif dimensions were maintained uniformly across all samples.

Table 1 - Combinations of base fabrics and embroidery threads

Combination	Fabric: Cotton Emb thread: Cotton	Fabric: Cotton Emb thread: Polyester	Fabric: Cotton Emb thread: Viscose
Code	CCHE	CPHE	CVHE
Sample			
Combination	Fabric: Silk Emb thread: Cotton	Fabric: Silk Emb thread: Polyester	Fabric: Silk Emb thread: Viscose
Code	SCHE	SPHE	SVHE
Sample			
Combination	Fabric: Orange Peel Emb thread: Cotton	Fabric: Orange Peel Emb thread: Polyester	Fabric: Orange Peel Emb thread: Viscose
Code	OCHE	OPHE	OVHE
Sample			

2.2. Testing of the Embroidered Samples

Once the embroidery samples were ready, they were used for various testing methods, so as to determine the best combination of base fabric to embroidery yarn.

The Testing Parameters: Testing methods of properties of the embroidered fabrics.

a. Fabric Weight (GSM) Test (g/m²) (IS 1964-2001, RA:2021 & Method A)

To determine the fabric weight in grams per square meter (GSM), each fabric sample was cut into a square measuring 25 cm × 25 cm, resulting in an area of 625 cm². The cut sample was then weighed using a precision electronic balance to obtain its mass in grams.

The GSM was calculated using the following formula:

$$GSM = \left(\frac{x}{a}\right) \times 10000$$

where:

x = weight of the fabric sample (in grams)

a = area of the fabric sample (in cm²)

Substituting the values into the formula provided the GSM value, representing the fabric's weight per unit area. This

method ensures a standardized comparison of fabric densities.

b. Abrasion Resistance Test (No. of Rubs) (IS 12673 (Part 2): 2014 RA 2018 & Pressure – 9Kpa/ISO12947-2:1998)

Fabric swatches (2 cm radius) were mounted on foam stamps to ensure uniform tension and secure placement, then fixed to the testing apparatus. The rubbing test recorded the time until the first breakage. For each fabric, two samples were tested, with three readings per sample, and their mean value was taken as the final abrasion resistance result.

c. Absorbency Test (Sec) (ASTM D1117-80)

Measured according to ASTM D1117-80 by recording the time taken for a distilled water droplet to flatten on the fabric surface. Four readings at different locations were averaged to determine the fabric's absorbency.

d. Air Permeability Test (cm³/cm²/s) (As per IS 11056 / ASTM D737)

Air permeability was tested as per IS 11056 and ASTM D737 in both warp and weft directions. Each sample was clamped to expose a 38.3 cm² test area and subjected to a standard vacuum pressure of 12.77 LPH. Air flow was monitored via a rotameter, and readings were recorded once stable alignment

was achieved. Five readings per direction were taken, and the average value was reported.

The air permeability (Q) was computed using the following formula:

$$Q = \frac{\text{Av. Reading} \times 1000}{3600 \times 38.3}$$

where:

Q = Air Permeability

Average Reading = mean of five air flow values (in LPH)

38.3 cm² = test area

3600 = time conversion factor (seconds per hour)

1000 = conversion to standard SI units (cm³/sec/cm²)

The final result was expressed in cm³/sec/cm², and separate values were reported for warp and weft directions.

e. Coefficient of Drape Percentage Test (%) (As per IS 8357:1977)

Drapeability was measured as per IS 8357:1977 to calculate the drape coefficient (%). Circular samples (25 cm diameter) with a central hole were mounted on the drape tester. An ammonia-sensitive sheet placed beneath the sample was exposed for 10 minutes to capture the drape outline, protected from sunlight. The test was performed on both sides for two samples. After exposure, the sheet was developed in an ammonia solution, and the draped area was cut and weighed to determine the drape coefficient.

The Drape Coefficient (DC) was computed using the following formula:

$$\text{DC (\%)} = \left(\frac{\left(\frac{\text{Av. Weight}}{0.07} \right) - 122.8}{368.3} \right) \times 100$$

Where:

DC = Drape Coefficient

Average Weight = average weight (in grams) of the cut sheet impressions for front and back samples

0.07 = calibration factor (as per standard)

122.8 and 368.3 = standard constants derived from calibration of draped and undraped areas

This coefficient expresses the percentage of fabric area that does not drape and remains extended, with higher values indicating stiffer fabric behaviour.

f. Tearing Strength Test (N) (as per IS 6489: Part 1–2011, RA 2021)

Tearing strength was tested as per IS 6489 (Part 1): 2011 (reaffirmed 2021). Fabric samples (7 × 10 cm) were slit 1 cm at the marked groove and clamped in the tester. After releasing the pendulum/weight, the tear force (in grams) was read from the machine scale. Only samples that tore cleanly into two halves were considered; irregular tears were discarded.

The tearing strength was calculated using the following formula:

$$N = \frac{\text{Av. Reading} \times 12800}{100}$$

where:

N = Tearing Strength

Average Reading = mean of valid machine readings (in grams)

Load = 12,800 grams (constant machine-applied load)

The test was conducted separately for the warp and weft directions. For each direction, four samples were tested, and the average tearing strength was calculated independently.

g. Shrinkage Test (%) (as per IS 2977 / IS 3561) – Cellulosic Fabrics

Dimensional stability was tested as per IS 2977 and IS 3561 to determine shrinkage or elongation. Fabric squares (50 × 50 cm) were marked using a 35 × 35 cm template and immersed for 2 hours in 8 L water with 4 g sodium hexametaphosphate, ensuring flat placement without folds. The samples were then air-dried without stretching. Post-drying, the marked dimensions were remeasured three times in both warp and weft directions, and shrinkage/elongation was calculated.

Shrinkage or elongation was interpreted as follows:

If the final measurement was shorter than the original, shrinkage was recorded.

If the measurement was longer, it indicated elongation (or negative shrinkage).

The shrinkage percentage was calculated using the formula:

$$\text{Shrinkage (\%)} = \left(\frac{\text{Original Length} - \text{Final length}}{\text{Original Length}} \right) \times 100$$

Separate shrinkage values were recorded and averaged for warp and weft directions.

h. Crease Recovery Test (O) (as per IS 4681:1981, Reaffirmed 2022)

Crease recovery was tested as per IS 4681:1981 (RA 2022) in both warp and weft directions. Fabric samples (1 × 5 cm) were folded, creased under a 5 g weight for 5 minutes, then allowed to recover vertically in the tester. The recovery angle was recorded after 5 minutes. Five samples per direction were tested, and the average angle (in degrees) was calculated, where higher values indicate better crease recovery.

i. Bending Stiffness Test (cm) (as per ASTM D1388-96, Option A – Cantilever Test)

Bending stiffness: Measured according to ASTM D1388-96 (Option A) using a cantilever bending tester. The bending length was recorded from 3 × 20 cm fabric strips, with five readings each in the warp and weft directions. Average warp and weft values were reported separately to assess directional stiffness.

The bending stiffness (G) in milligrams-centimetre (mg·cm) was then determined using the formula:

$$G = W \times C^2$$

where:

G = Bending Stiffness

W = fabric weight per unit area (mg/cm²)

C = bending length (cm)

Test results were evaluated independently to identify the optimal base fabric–embroidery yarn combination. Analysis was performed in Python using Pandas and NumPy, with Matplotlib and Seaborn for visualization. Results were validated through boxplots, histograms, and kernel density estimation (KDE) plots to ensure consistency and reliability.

3. Results and Discussion

The results obtained from the nine testing parameters were analysed comparatively to understand the changes induced by embroidery and to identify the most suitable fabric–yarn combination. Statistical and graphical analyses were further employed to validate the findings and determine the optimum hand-embroidered sample for apparel applications.

3.1. Obtaining the results of the various testing parameters

The study on the test results was conducted across 9 fabric testing parameters for all 9 sample combinations. The results were then obtained and evaluated independently, and the optimal combination of base fabric to the embroidery yarns was determined.

The grand chart was evaluated by a panel of subject experts to understand the best combination across all the samples created which has been shown in the following graphs.

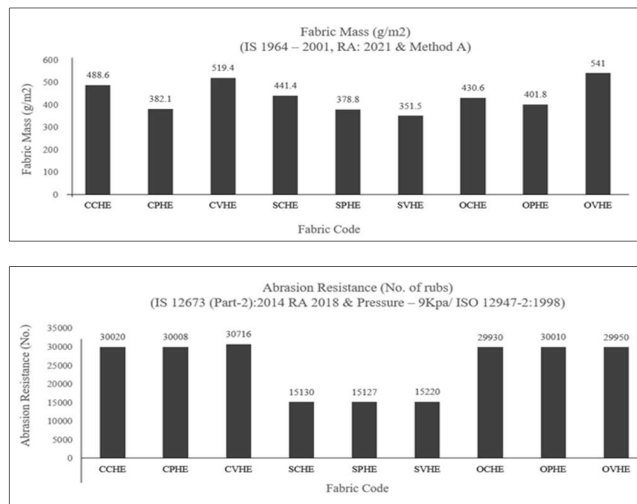


Figure 11 - Readings of Fabric Mass, Figure 12. Abrasion readings

Figure 11. shows that the fabric mass increases notably in all embroidered samples. Hand embroidery raises mass to 351.5–541 g/m², with OVHE being the heaviest.

Figure 12. shows embroidered samples perform better:

cotton reaches up to 30,716 rubs, silk increases to about 15,130–15,220 rubs, and Orange Peel approaches 30,000 rubs. Overall, hand embroidery, enhance surface durability, making the fabrics more resistant to wear.

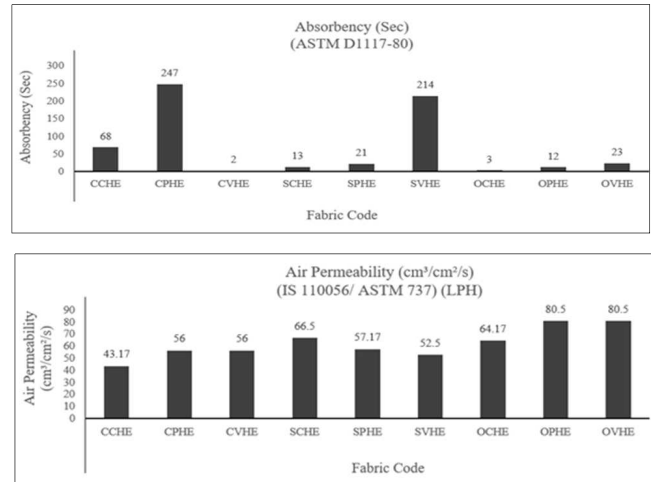


Figure 13 - Readings of Absorbency, Figure 14. Air Permeability readings

From Figure 13. it is evident that embroidery greatly increases absorbency but with wide variation. Cotton ranges from very fast (2 secs in CVHE) to very slow (247 sec in CPHE), while silk varies between 13 and 214 seconds. Orange Peel fabric improves to 3–23 seconds. These differences reflect the influence of stitch density and thread type such as whether it is porous, loose stitches absorb faster, while dense or smooth threads slow absorption.

Figure 14. depicts that air permeability decreases after embroidery, though to varying degrees. Base fabrics show good airflow. Embroidered cotton drops to 43.17–56 LPH, and silk to 52.5–66.5 LPH. Orange Peel fabric retains the highest permeability, with OPHE and OVHE at 80.5 LPH, nearly matching its base value. Thus, Orange Peel remains the most breathable fabric even after embroidery.

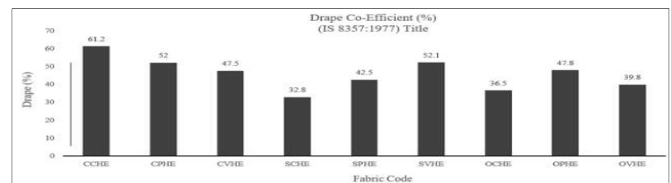


Figure 15 - Percentage Readings of Drape Co-efficient

In Figure 15. embroidery increases stiffness across all fabrics: cotton rises to 47.5–61.2%, silk to 32.8–52.1%, and Orange Peel to 36.5–47.8%. Orange Peel samples like OVHE and OCHE retain better drape than cotton and silk, reflecting its structural resilience. Increased stiffness is expected due to added mass and layered stitching.

As for Figure 16. base cotton shows strong warp and moderate weft values, while silk and Orange Peel record only weft strength. Embroidered samples display substantial weft reinforcement, with cotton reaching 7040–9216 N, silk 7936–9856 N, and Orange Peel peaking at 10,368 N

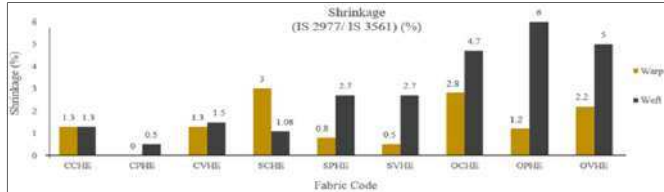
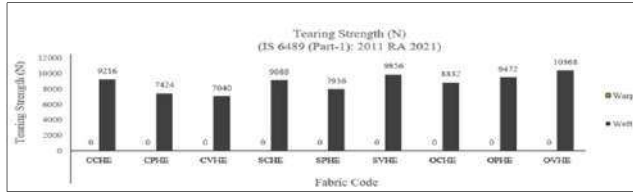


Figure 16 - Readings of Tearing strength, Figure 17. Readings of Shrinkage

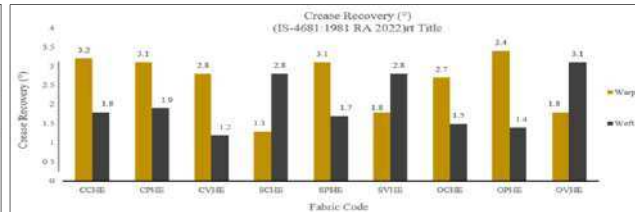
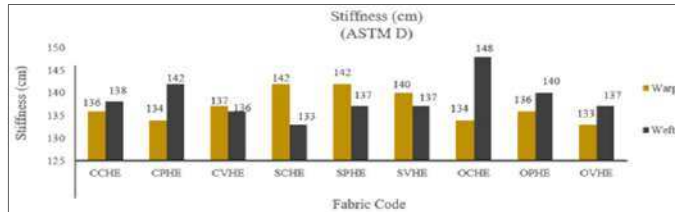


Figure 18 - Stiffness Readings, Figure 19. Readings of Crease Recovery

(OVHE). Overall, embroidery, especially dense stitching or stronger yarns greatly enhances fabric tear resistance.

In Figure 17. shrinkage results show that embroidery improves dimensional stability. After embroidery, cotton shrinkage remains very low (<1.5%), silk shows minor variations, and Orange Peel stabilises to 2.2–6.0%. Overall, embroidery reduces fabric relaxation and washing distortion.

The Figure 18. For crease recovery highlights Orange Peel fabric's superior performance. Embroidery further improves this, with OCHE reaching 148°, OVHE 137°, and OPHE 140°. Cotton and silk also improve but remain below Orange Peel, confirming its resilience and suitability for draped garments like saris.

As shown in Figure 19. stiffness results align with drape

behaviour. Embroidery increases stiffness across all fabrics: cotton rises to 134–142, silk to 142/137, and Orange Peel also increases, with OCHE reaching the highest weft stiffness (148). Overall, Orange Peel maintains balanced structure while gaining reinforcement from embroidery.

Overall, the inherent crease recovery, high permeability, balanced stiffness, and superior abrasion resistance are further enhanced by embroidery. After studying the above chart, it was suggested that CCHE is the most suitable combination among all the combinations.

Due to differences in yarn count and fibre composition among the fabrics, percentage change analysis was performed to enable a more accurate comparison of their performance.

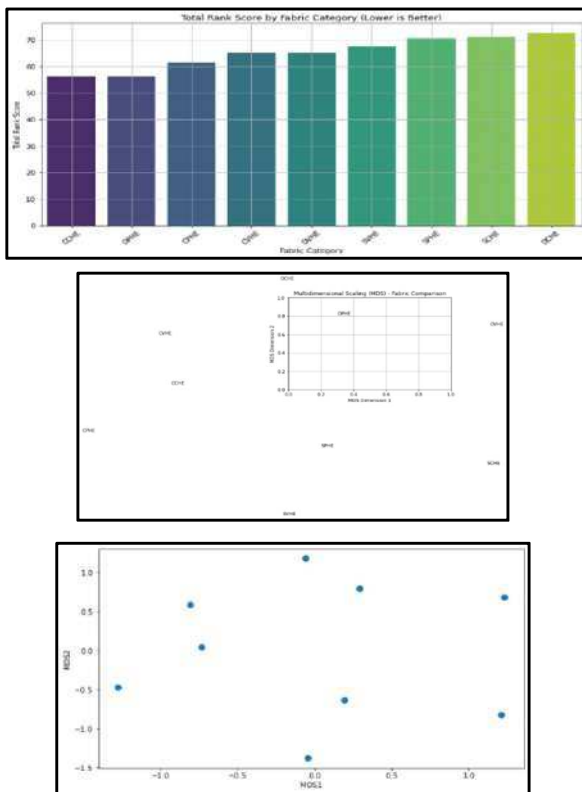
Table 2 - Percentage readings of the results

Sl. No.	Parameters	Fabric Code	CCHE	CPHE	CVHE	SCHE	SPHE	SVHE	OCHE	OPHE	OVHE
1	Fabric Mass (g/m ²) (IS 1964-2001, RA: 2021 & Method A)		241.65	167.18	263.19	674.11	564.32	516.45	192.58	173.01	267.60
2	Shrinkage (%) (IS 2973:1989) (IS 2977/IS 3561)	Wrap	0	0	0	-100	-100	-100	-100	-100	-100
		Weft	1110261	894357.8	848092.8	454300	396700	492700	84014.29	90109.52	98642.86
3	Tearing Strength (gms) (IS 6489 (Part-1):2011)	Wrap	692.29	691.97	710.66	15130	15127	15220	29930	30010	29950
		Weft	-97.49	-90.89	-99.92	-99.62	-99.38	-93.76	-99.92	-99.69	-99.40
4	Abrasion (ASTM D 4966:2012 – Option - 1) (Rubs)		-98.21	-97.68	-97.68	-95.96	-96.53	-96.81	-99.42	-99.27	-99.27
5	Absorbency of fabric (seconds)		61.2	52	47.5	32.8	42.5	52.1	-75.33	-67.70	-73.10
6	Drape Coefficient (%) (IS 8357: 1977)		-95.66	-100	-95.66	-92.10	-97.89	-98.68	-88.8	-95.2	-91.2
7	Air Permeability Test (IS 11056/ ASTM 737) (LPH)		-98.31	-99.35	-98.05	-98.69	-96.73	-96.73	-94.62	-93.14	-94.28
8	Crease Recovery (O) (IS 4681:1981 RA 2022)	Wrap	-97.09	-97.18	-97.45	-98.26	-95.86	-97.6	-97.69	-97.09	-98.46
		Weft	-98.36	-98.27	-98.90	-96.21	-97.70	-96.21	-98.71	-98.80	-97.35
9	Stiffness (ASTM D)	Wrap	51.11	48.88	52.22	5.18	5.18	3.70	34	36	33
		Weft	97.14	102.85	94.28	5.55	8.73	8.73	48	40	37

Table No. 2 analyses the percentage change and demonstrates that hand embroidery significantly influences the physical and mechanical properties of fabrics. Embroidered samples shows increased fabric mass, warp tearing strength, and stiffness, indicating enhanced structural integrity, durability, and shape retention. In contrast, air permeability, drape, and crease recovery decreased due to increased fabric compactness and restricted yarn mobility. Warp shrinkage was eliminated in silk and orange peel fabrics, improving dimensional stability, while abrasion resistance and absorbency also changed, reflecting modifications in surface and comfort characteristics. Cotton-based embroidered fabrics exhibited the greatest improvements in strength and stiffness, whereas orange peel fabric retained relatively higher air permeability and crease recovery. Overall, hand embroidery enhances fabric strength, stability, and durability while modifying comfort properties, making the fabrics suitable for premium apparel and value-added textile applications. Among all samples, CCHE demonstrated the most balanced overall performance and emerged as the best-performing hand-embroidered fabric combination.

3.2. Comparison of the Parameters to Decide the Best Combination for Apparels with Hand Embroidery

In order to compare the results of all the fabrics, Pandas library in Python was used for data handling and processing. Data visualization and analysis were carried out using the Matplotlib and Seaborn libraries to cross-verify the results and ensure their reliability and consistency.



**Figure 20 - Statistical Analysis of the results:
Boxplots(Top), Figure 21. Distribution graphs:
Histograms (middle), KDE: Kernel Density estimation
(Bottom)**

Insight from above bar chart; Boxplots: Lower bars = better fabric
Statistical justification behind the selection of CCHE as the best sample

The overall performance, shown in Figure 20. gives the evaluation using a rank-based multi-criteria assessment of 13 physical and mechanical properties. After normalization, properties like tearing strength, abrasion resistance, air permeability, drape, crease recovery, and stiffness were ranked with higher values preferred, while lower absorbency time and shrinkage were considered desirable. The cumulative rank score determined overall performance, with lower scores indicating better performance.

Among all samples, CCHE achieved the lowest total score (86.5), indicating the best overall performance. Its superior ranking was attributed to excellent weft tearing strength, crease recovery, weft stiffness, drape, low warp shrinkage, and good abrasion resistance. Despite relatively lower rankings in air permeability, absorbency, fabric mass, and weft shrinkage, its balanced mechanical and durability properties made CCHE the best-performing hand-embroidered fabric sample.

The statistical analysis in Figure 21. indicates that the hand-embroidered fabrics exhibit balanced absorbency, drape, air permeability, and crease recovery, reflecting good moisture management, breathability, wrinkle resistance, and wearability. Consistent performance across warp and weft directions suggests uniform fabric behaviour. Overall, CCHE emerged as the best-performing fabric category.

Hand Kantha embroidery enhanced durability, abrasion resistance, dimensional stability, and structural strength, increasing the functional and commercial value of the fabrics. Cotton-based embroidered samples provided balanced comfort and strength, while orange peel fabric retained higher breathability and crease recovery, making it suitable for lightweight garments. Improved stiffness and reduced shrinkage further enhanced garment structure, maintenance, and suitability for premium and sustainable fashion applications.

4. Conclusions

This study evaluated the effect of different base fabrics and hand embroidery material combinations on the physical and mechanical properties of embroidered textiles. Hand Kantha embroidery significantly enhanced tearing strength, abrasion resistance, dimensional stability, and structural integrity while influencing comfort-related properties such as absorbency, air permeability, drape, crease recovery, and stiffness. Cotton-based embroidered fabrics offered a balanced combination of strength, breathability, and moisture management, whereas orange peel fabric retained higher air permeability and crease recovery, making it suitable for lightweight, draped garments.

A rank aggregation analysis based on thirteen physical and mechanical parameters identified CCHE (Cotton Base Fabric with Cotton Thread Hand Embroidery) as the best-

performing combination, achieving the lowest overall score (86.5). Its balanced performance in strength, crease recovery, drape, abrasion resistance, stiffness, and dimensional stability made it superior to the other embroidered samples. Overall, the findings demonstrate that hand embroidery

enhances both the functional and commercial value of textiles, supporting their application in premium apparel, sustainable fashion, and value-added textile products while preserving traditional craftsmanship.

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Attention All Members of
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Knitted Fabrics for Athletic Apparel: Enhancing Comfort, Performance, and Sustainability

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Abstract:

The review emphasizes the importance of moisture management, comfort properties of knitted fabrics and their relevance to activewear and sportswear. It explores the physiological processes behind heat and moisture management in the human body, and dissects the interplay of fabric structure, fiber choice, and technological advances to improve comfort and performance. Basic features such as moisture wicking, thermal insulation, breathability and stretch and recovery are examined, noting how they directly affect the wearer's experience during sport. The review also touches on the increasing significance of choosing sustainable materials, as the demand for environmentally friendly products rises among consumers. Moreover, the importance of other textile engineering properties viz., air permeability, UV resistance, and antimicrobial functionalities in the context of takedown of wearer safety, hygiene and longevity of garments are also discussed. The findings emphasize the need to combine advanced fabric technologies with a mindful approach to garment design in order to produce high-performance activewear that lives up to expectations of comfort, functionality and sustainability. This interdisciplinary approach leads to the creation of modern knitted garments that enhance athletic performance and user comfort while also encouraging environmental sustainability, setting new standards in the sportswear industry.

Keywords: Functional Sportswear, Knitted Fabrics, Moisture Management, Thermal Comfort

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1. Introduction

The moisture management of knit fabrics is a critical factor that influences the comfort and functional performance of performance apparel such as activewear, innerwear, and sportswear. The comfort is obtained from the dynamic interaction between clothing and the body, mainly through the dissipation of heat and regulation of moisture produced by metabolic activities. In humans, thermoregulation occurs by conduction, convection, and radiation. Normally, the body cools by insensible perspiration, or loss of water vapor. During periods of higher activity, however, the body depends on sensible perspiration liquid moisture to assist evaporative cooling [1-3]. The comfort properties of knitted fabrics are dependent on various factors like surface smoothness, air permeability, thermal conductivity, hydrophilicity, structure of knit and presence of bio-finishes. Polyester knits are comfortable in that they wick moisture away rapidly and dry quickly, especially those made with sophisticated fiber cross-sections such as the hexachannel shape of Coolmax fabrics [4]. The moisture management properties of knit fabrics are directly associated with the intrinsic constructional parameters of knit fabrics, which provide a unique porous structure. The porosity of fabric can be divided into two types, microporosity and microporosity. Microporosity is the void spaces between the fibers in a yarn and microporosity is the space between the yarns. While air permeability, UV light transmission and printability are mainly affected by

microporosity, the fabric's liquid absorption and capillary action are controlled by microporosity. The combined effects of both porosity types affect the thermal resistance and water vapor permeability, highlighting their importance in textile performance [5, 6].

Liquid interaction with textiles is a complex process that includes wetting of fiber surfaces, transport of liquids into the fiber matrix, and adsorption onto surfaces or diffusion into fiber interiors. The garment is worn and the body is cooled by effective sweat evaporation and the load of moisture on the fabric is reduced for greater comfort overall [7, 8]. Water transport in textile matrices occurs primarily through capillary action or wicking. The interstices between fibers act as capillary tubes and transport moisture away from the skin. Liquid moisture management is largely determined by absorbent capacity, absorption rate and evaporation efficiency. Water and vapour movement across the layers of fabric is governed by the gradient of vapour pressure and affected by constructional factors such as pore size, pore distribution and fabric thickness. The wicking efficiency of a fabric is mainly determined by the fiber surface tension and capillary properties. The yarn selection and fabric engineering plays a critical role in optimizing the wicking efficiency of a fabric [9-11]. How long it takes for fabric to dry is mainly determined by the amount of water a fabric holds initially and the structure of the material with respect to its capillary and porous makeup. The morphology of the fiber, i.e., its shape and surface properties, has a strong influence on capillarity and thus affects water uptake and retention. The use of hydrophilic finishes enhances the

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moisture absorption and the rate of wicking significantly. Surface modification is an important aspect to improve the performance of fabric for moisture management [12, 13]. Physical activity on a regular basis is important to human health. Sports clothing is used by athletes and sports persons to give them comfort and functional support during various activities like walking, stretching, jogging etc. Just 30% of sportswear produced is used by active sportsperson [14]. Sports textiles are the field that has very specific properties of the apparel for every sport to have some certain functions, to give comfort for the wearer in the end. To achieve this best possible target of performance undue attention is being paid to improve the performance of fibres, yarns, fabrics and fabric finishes used to manufacture active wear [15].

Performance of textiles for sports is a common problem associated with diverse performance parameters like moisture management, resistance to water and wind, stretchability and low frictional surface for smooth feel. In the past, many technological progresses have been made to develop micro-porous speciality polymer possessing hydrophilicity and special fibres of different shapes and diameter; various single to multi-layer fabrics with different weave structure has been discovered to develop fabric comfort and functionality. The innermost layer of clothing in particular in case of sportswear affects physiological comfort of an athlete and thus performance of an athlete. Functional comfort sportswear has many properties such as thermo-physiological properties, moisture management/dry rate performance properties, water vapor permeability, air permeability, weight, touch, moisture absorption, layer water absorption worn next to skin, wet dimensional stability, durability, breathability, care performance, smart and functional design etc. [16].

The main objective of this review is to systematically review of the most prominent factors affecting the comfort, performance and sustainability of the knitted fabrics used in athletic and sportswear. This work is particularly focused on (i) evaluating the mechanisms of moisture and thermal management in knitted textiles; (ii) investigating the impact of fiber choice, fabric structure, and finishing technologies on wearer experience and garment functionality; and (iii) reviewing current developments and future trends in sustainable material selection for sportswear. This review attempts to combine knowledge from textile engineering and

material science viewpoints to provide a holistic understanding which can guide the design and development of high-performance, comfortable and eco-conscious activewear. Finally, the results aim to provide researchers, designers, and manufacturers with new ways to establish new standards in the sportswear industry.

2. Knitted Garment Essential and Desirable Properties

Fabric property is a characteristic of textile substrates that should possess it in a satisfactory manner for its use in the desired application and its requirement for a certain purpose. In this section various cloth assets which are essential for the performance of sportswear are discussed. Important properties are those which are required for a sport by guidelines or user necessity. On the flip side, essential properties are properties that users like for their beauty and their appearance. It should be noted that each sport has different necessities depending on the nature and strength at which they are played. Physiological aspect of sportswear is very important because of its major impact on the efficiency and presentation of athletes. Thermal comfort, i.e. sensation of hot or cold or clothing dampness is related to environmental factors such as heat, moisture and air velocity. Water/moisture vapour transmission and air permeability are important factors affecting the thermal comfort of sportswear [17]. Most clothing is made from textiles, such as activewear, pants, coats, shirts, shorts, socks, sweaters and tennis clothes. Architects and designers use their knowledge of drawings, materials and modern innovations to develop aesthetically pleasing, ergonomic clothing using advanced textiles. The latest trends are aesthetics and functionality, such as the use of microfibers, breathable barrier fabrics, stretch fabrics, smart textiles and wearable electronics. The sportswear market is highly competitive with new materials and styles. Consumers look for activewear that is comfortable, fashionable, and safe [16, 18]. They prefer fabrics that are lightweight, strong, and quick-drying that are able to control heat and moisture. Knitted fabrics are perfect for activewear. They have excellent stretch, comfort and allow freedom of movement. They are designed to not cling to the skin for comfort while active. Sportswear innovations like microfibers and smart textiles offer improved moisture control, temperature regulation, and durability. Table 1 and 2: Basic structures and fibers used in knitted apparel and their applications.

Table 1: Basic structure used in knitted wear garments

Knitted Fabric Structure	Key Features	Typical Applications
Single Jersey	Highly extensible in length and width, Fabric tends to curl at edges, Good breathability, Lightweight	Sportswear, base layers, undergarments
Rib	Excellent width elasticity, No tendency to curl, Good shape retention, Moderate thickness	Sportswear, collars, cuffs, socks
Interlock	Widthwise stretch, No tendency to curl, Smooth surface on both sides, Thicker and more stable than single jersey	Shorts, tops, technical sports textiles

Table 2: Basic fibers used in knitted wear garments

Property	Polyester	Nylon (Polyamide)	Polypropylene	Lycra/Elastane	Cotton
Strength	Strong	Strong	Strong	Medium strength	Strong
Absorbency	Non-absorbent	Non-absorbent	Non-absorbent	Not very absorbent	Absorbent
Crease Resistance	Crease resistant	Crease resistant	Crease resistant	Crease resistant	Creases easily
Durability	Hard wearing	Hard wearing	Hard wearing	Durable, hard wearing	Durable
Elasticity	Elastic, stretches	Elastic, stretches	Elastic, stretches	Very elastic, stretches well	Not very elastic, doesn't stretch
Thermal Property	Not very warm	Not very warm	Not very warm	Makes stretchy, fitting fabrics	Cool to wear

2.1 Thermo Physiological Comfort

Our body and skin temperatures are 37 °C and 33.4 °C respectively and may again vary within the limits of ± 1.5 °C to ensure body comfort; exceeding the tolerance limit by ± 4.5 °C causes body discomfort. Thermo-physiological properties are basically the heat and moisture transport properties of fabrics which helps in maintaining heat balance of the body during different degrees of movements. Thermo-physiological comfort controls breathability and moisture. It is concerned with the transport of heat and moisture through the fabric and moisture can be vapour or liquid. Clothing forms a microclimate between the body and the external environment (Figure 1). It functions as a barrier for heat and vapor transfer between the skin and the environment [19].

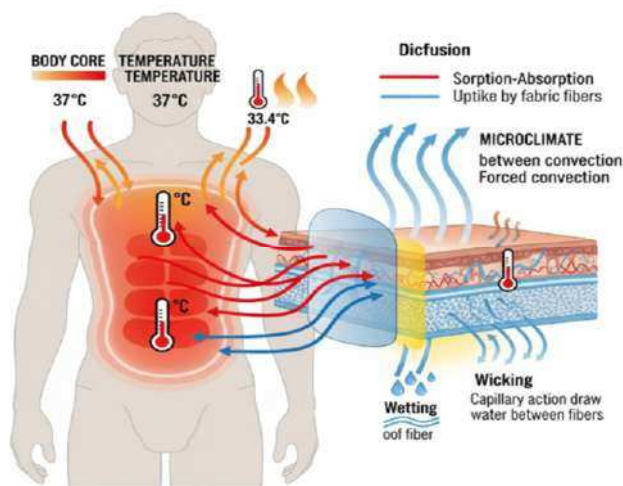


Figure 1: Thermo-Physiological comfort in clothing

There are three main processes involved in moisture spread through the fabric, namely diffusion of moisture due to moisture vapour gradient across the fabric, sorption-absorption by hydrophilic sites on the fabric and forced convection by moving air close to skin. In extreme sweating conditions, in order to prevent discomfort, the fabric in contact with the skin should not only absorb the liquid quickly, but also transfer the liquid quickly through it. For the transport of liquid moisture through textiles, two processes happen sequentially: wetting and wicking. Fluid spreading is

the wetting of the fibre-air interface by replacing it with a fibre-liquid interface. The wicking is due to the fibre-liquid molecular attraction at the surface of the fibre. This is determined by the surface tension and the effective capillary pathways and pore distribution, skin temperature and moisture content of physical effort [20, 21].

2.2 Fabric Innovation in Knitted Garment Fabrics for Different Performances

One of the key strengths of the knitted garment industry in the global market is its focus on advanced fabrics and textile technology.

2.2.1 Moisture-Wicking Fabrics

Moisture-wicking fabrics are popular for knitted garments in the global market, especially for athletic and sportswear. These high-tech fabrics are designed to actively pull sweat away from the surface of the skin. They move moisture through the fabric and help it evaporate faster so you stay dry and your body temperature is regulated during physical activity. This not only increases the comfort of the wearer, but also reduces the chances of chafing, irritation and overheating. Moisture wicking fabrics employ capillary action to draw sweat away from the skin, keeping athletes and athletes dry, cool, and comfortable even during intense workouts [22, 23].

2.2.2 Stretch and Compression Materials

Stretch and compression fabrics like spandex and elastane blends have become an essential part of modern activewear and performance clothing. They are fabrics that provide exceptional stretch so that the clothing can stretch and move with the body, yet still return to its original shape. Its flexibility gives you freedom of movement and is ideal for activities with lots of motion. These materials also offer gentle compression in addition to stretch that can help support muscles and increase blood flow during physical activity. The compression effect stabilizes muscle groups and decreases muscle fatigue and can even help with a quicker recovery after exercise. The blend of stretch and support in spandex/elastane blend garments will provide comfort and performance and enhance your overall athletic experience.

2.2.3 Breathable and Lightweight Textiles

The Modern sportswear is characterized by the use of breathable and light textiles: mesh panels and specially designed knit fabrics. Engineered to optimize airflow and ventilation, they allow heat and moisture to escape the body more effectively. Mesh panels and open-knit structures are used in garments by designers to create areas that help promote greater breathability, keeping the wearer cool and comfortable during vigorous physical activity. The lightweight nature of these textiles further enhances comfort by decreasing bulk and allowing for greater freedom of movement. Therefore, sportswear made of lightweight and breathable fabrics is perfect for intense exercise, allowing athletes to regulate their body temperature and perform at their best.

2.2.4 Sustainable Fabrics

Sustainability is becoming more common in the global market of knitted activewear as environmentally friendly fabrics are used to make garments. Manufacturers are using materials such as recycled polyester, organic cotton, bamboo and viscose blends to decrease the environmental footprint of their products. It is made from recycled plastic bottles post-consumer, diverting waste from landfill and saving resources. Organic cotton is grown without the use of dangerous pesticides or artificial fertilizers, making it safer for the environment and the people who grow it. Bamboo and viscose blends are sustainable choices that require less water and chemicals to process.

This move toward sustainable fabrics is a response to growing consumer awareness and the fact that consumers are now making purchasing decisions with environmental responsibility in mind. This shift gives an advantage to brands that employ sustainable practices and materials in the activewear sector, as they are attracting a new wave of eco-aware consumers.

3. Dynamics of Fabric Stretch and Recovery: Elevating Comfort and Performance in Contemporary Garment Design

Fabric stretch and recovery are important concepts in garment design that have a significant impact on the aesthetics and functionality of clothing. Stretch is the ability of a fabric to stretch when pulled, for flexibility and movement. Recovery is the ability of the fabric to spring back to its original shape after being stretched. Understanding

how these properties interact enables designers to create clothes that are more comfortable, more durable and fit better. The right textile chosen by designers with ideal stretch and recovery enhances the wearer's experience and provides durability and structural integrity in everyday and performance-oriented apparel.

4. Textile Engineering Properties: Comfort Knitted Garments

4.1 Intrinsic Thermal Insulation

The insulation of a fabric depends on its thickness and the layer of air next to it, which prevents heat loss by conduction. The good heat retention is due not only to the material itself, but also to the ability of the material to retain air, which improves the insulation capacity of the entire garment.

4.2 Thermal Insulation

The Thermal insulation is important for comfort and warmth of clothing as it measures the ability of a fabric to retain the body heat. The level of insulation from this varies with factors such as fabric thickness, texture, composition, activity level and environmental conditions. There are two types of insulation, intrinsic insulation, which is built in the fabric, and extrinsic insulation, which is the layer of air held against the fabric. It is important to increase the heat by trapping air. But wind can break up this insulating layer of air and make the clothing less effective at retaining heat. So, the perfect clothing should be a mix of insulation, wind resistance, moisture management and breathability. By choosing clothing with these features, you can stay comfortably warm and comfortable in changing weather conditions or when doing different activities [24, 25].

4.3 Resistance to Evaporative Heat Loss

Evaporative resistance is a measure of the ability of a fabric and the layer of air next to it to reduce heat loss from evaporation of sweat. This helps maintain body temperature and keep the wearer feeling comfortable. This is particularly useful for comfort in warm or humid environments and the testing of this property in wet and dry states demonstrate this.

4.4 Thermal Conductivity

Thermal conductivity is the measure of a substance's ability to conduct heat. Good insulation. Low conductive fabrics insulate air and slow the loss of heat. This is great for cold weather. But at the same time, high conductivity materials

Table 3: Fabric stretch and recovery enhance comfort and performance

S. No.	Aspect	Functional
1	Fabric Stretch	Allows elongation, enhances movement, crucial for comfort and fit.
2	Fabric Recovery	Ability to return to original shape, maintains garment integrity and fit over time.
3	Aesthetics & Function	Both influenced by stretch and recovery; impact garment silhouette and usability.
4	Designer's Role	Mastery leads to better product: comfort, resilience, and fit.
5	Textile Selection	Informed choices result in better user experience and garment durability.
6	Application	Relevant across fashion, sportswear, casualwear, and specialized clothing.

allow heat to escape, making them a good choice for warm climates. Two important properties to know about when choosing clothing for comfort and protection under a wide range of environmental conditions are conductivity and insulation.

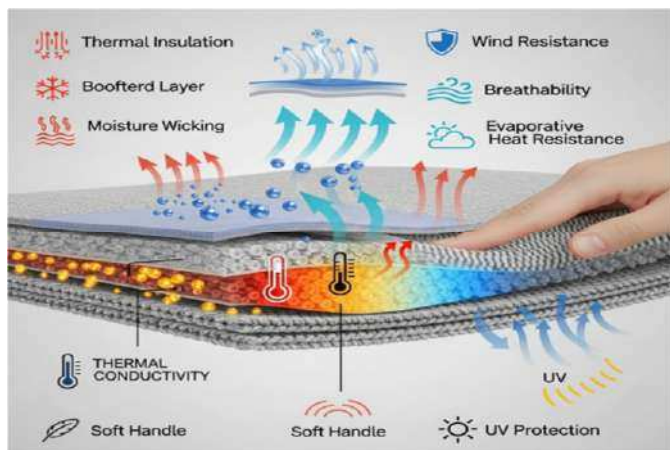


Figure 2: The high-performance knitwear garment labeling of all major comfort properties

4.5 Moisture Vapour Permeability

Moisture vapour permeability is a measure of how well a fabric can allow water vapour to escape and thus help to control moisture. It is a comparison of the amount of vapour passing through fabric with the same thickness of air. When choosing clothes for sports or outdoor activities, this feature is an absolute must. It is comfortable because it does not allow the moisture to build up too much, and helps to regulate the temperature well [26].

4.6 Wicking

Wicking is a fabric's ability to pull moisture away from the skin and through the fabric so it evaporates quickly. "Using capillary action this feature helps keep wearers dry and comfortable during exercise. Wicking is ideal for athletic and outdoor wear, because it keeps you comfortable and your body temperature in check. Synthetic fabrics, like polyester and nylon, are hydrophobic and wick extremely well.

4.7 Air Permeability

Air permeability is a measure of the ease of air flow through a fabric, both dry and wet. However, air permeability does not guarantee good water vapour transmission. Moisture can cause fibers to swell, which reduces airflow and breathability. So, for outdoor and sportswear, it is essential to choose fabrics that strike a balance between air permeability and breathability so that comfort is maintained and overheating is avoided.

4.8 Rate of Drying

How fast does moisture evaporate from the surface of the fabric? The rate of drying of a fabric is hugely important to comfort, especially in activewear and outdoors gear. It dries fast so sweat doesn't build up and make you uncomfortable,

chafe or even get hypothermia. Synthetics such as polyester and nylon, which wick well, draw moisture away from the skin so it evaporates more quickly. They dry much faster than natural fibers and are good for sports. Therefore, a quick-drying moisture-wicking fabric is the best choice for a comfortable, dry, and optimum performance while playing sports or outdoor activities.

4.9 Fabric Handle

In textiles, the term "handle" is used to describe the tactile properties of a garment, such as softness, compressibility, pliability and drape, which affect comfort and visual attractiveness. The right handle is less important in sportswear than in everyday apparel, but it is important to ensure that performance is not compromised. If the fabric is too stiff, it may restrict movement; if it's too soft, it may not provide adequate support. Ultimately, the handle should add to function, making the garment more comfortable and enjoyable to wear, especially in high-performance apparel.

4.10 UV Resistance

UV protection is a must in garments exposed to harsh sunlight especially in the case of skiing where the combination of altitude and reflection of the snow can lead to an increased exposure to UV without the user being aware of it. Unprotected exposure to UV rays can lead to sunburn, premature skin aging and increase the risk of skin cancer. Therefore, UV protection should be incorporated in the ski and outdoor winter clothing for effective protection of the wearer from these damaging effects.

4.11 Anti-Microbial, Anti-Bacterial and Anti-Odour Properties

Sports socks, vests and pants are clothes that come into prolonged contact with perspiration. The clothes should possess anti-microbial, anti-bacterial and anti-odor properties to inhibit the growth of bacteria and prevent unpleasant odors. These features help keep the wearer comfortable, reduce health risks such as skin infections, and increase the life of a garment by reducing the need to wash it frequently. These properties contribute to a healthier, fresher and more pleasant wearing experience, adding considerable value for active wear or extended wear garments.

5. Conclusions

The great comfort, flexibility and support they offer for all kinds of physical activity means that knitted garments are now a key part of functional sportswear. The review highlights that the success of the sportswear design is dependent on several factors, such as optimal moisture management, effective thermal insulation, and careful incorporation of advanced fibers and functional finishes. New technology such as moisture-wicking fibers, stretch and compression fabrics and sustainable textiles have greatly enhanced the quality and performance of activewear. Air permeability, UV protection and antimicrobial properties not only increase the safety and hygiene of the wearer, but also

the longevity of the garments. With consumer expectations rising, particularly amongst active and health-conscious consumers, the sportswear industry will need to focus on innovations that combine comfort, performance and environmental sustainability. Textile engineering should in the future try to achieve this balance so that the clothing is comfortable and functional and the ecological aspects are taken into account. In the end, the history of knitted sportswear demonstrates the industry's commitment to catering to the practical requirements of athletes, and the wider appetite for sustainable, high-performing clothing. The findings of this review also provide important managerial implications for the stakeholders in the design, production, and marketing of athletic apparel. Managers and

product developers should focus on integrating advanced moisture management systems, thermal regulation technologies and functional finishes to enhance wearer comfort and performance. Utilizing sustainable materials and green manufacturing processes not only complies with regulatory standards but also resonates with eco-conscious consumers, thereby increasing brand value. In addition, highlighting new features such as antimicrobial properties, UV protection and fast-drying ability can help to differentiate in a competitive market. Companies can increase their market relevance and cultivate long-term customer loyalty by combining product innovation with emerging consumer preferences for comfort, functionality, and sustainability.

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OBITUARY



Late Dr. Chindambaram Bose
(08.03.1951 - 07.09.2026)

Trustee & President Emeritus, The Textile Association (India), Mumbai Unit

It is with profound grief and a deep sense of loss that The Textile Association (India), Mumbai Unit mourns the sad and sudden demise of Dr. Chidambaram Bose, Trustee and President Emeritus of TAI, Mumbai Unit, who passed away on 7th September 2026 at the age of 76 years.

Dr. Bose was one of the foremost pillars and key functionaries of The Textile Association (India), an important organisation of textile professionals. He served TAI, Mumbai Unit, with exceptional dedication, distinction and selfless commitment over several decades. He was a Vice President from 2003 to 2005 and subsequently served as President from 2005 to 2017, steering the Mumbai Unit with remarkable efficiency, vision and commitment. Since 2010, he had also been serving as a Trustee of TAI, Mumbai Unit. In recognition of his meritorious services and outstanding contribution to the Association, Dr. Bose was honoured with the Hon. FTA and Service Gold Medal by TAI. In 2026, he was further honoured with the Distinguished Service Award by TAI, Mumbai Unit, for his exemplary services and outstanding contributions to the Association. His invaluable leadership, guidance and dedication as President helped TAI, Mumbai Unit, reach new heights. His contribution towards the redevelopment of Santosh Building was enormous and will always be remembered with deep gratitude.

Dr. Bose also made a pioneering contribution to the Indian texturising industry. He successfully organised five International Seminars on Texturising at Silvassa, the first of their kind in India. These landmark events provided the Indian texturising industry with valuable global exposure and contributed significantly towards improving quality, productivity and technological awareness. He was widely regarded as a pioneer in texturising.

An accomplished textile technologist and professional, Dr. Bose held B.Tech. (Textiles), M.Tech. (Textiles), F.I.E. and Chartered Engineer (FTA) qualifications. He began his professional career with Hindon River Mills (DCM) as Assistant Spinning Master (Product Development) and subsequently served organisations including Sir Padampat Research Centre, J.K. Synthetics, Kota, Urvi Chemicals and Nirlon Synthetics Limited.

He joined Reliance Industries Limited and served as Senior Vice President from 1995 to 2009. During his distinguished tenure, he played a pivotal role in developing the world's largest, state-of-the-art texturising facility in 1995. As Plant Incharge, he led the Silvassa plant to global recognition for its cost-effective operations, superior yarn quality, high productivity and environmentally responsible practices.

Following Reliance Industries Limited's acquisition of Trevira, Germany, Dr. Bose led its technical operations across Germany, Denmark and Poland for three years. He also successfully led the acquisition and record-time transfer of UNIFI Ireland's complete texturising and polyester facilities to India under Reliance Industries Limited.

Dr. C. Bose pioneered Air Texturising Technology in India in 1976, designing and developing machines and process parameters for improved yarn quality. He developed pilot machines for IIT Delhi, Sir Padampat Research Centre, Kota, and PSG College of Technology, Coimbatore. He also contributed extensively to Industrial Fabric development at Nirlon Ltd. His patents include innovations in Air Texturising Machines, Processes, Air Textured Blended Filament Yarns, and Nylon Coloration during spinning.

Beyond his professional achievements, Dr. Bose will be remembered for his humility, accessibility, kindness and compassion. He was truly a man of the masses, with a special place in the hearts of countless textile professionals. His warmth, wisdom, guidance and willingness to support others earned him immense respect and affection across the textile fraternity.

The Mumbai Unit was privileged to have had such an eminent professional and dedicated leader at the helm of its affairs. His absence will be deeply felt by the Association and by the entire textile community. His demise is an irreparable loss to TAI, Mumbai Unit, which has lost one of its most important pillars of strength.

A Condolence Meeting in memory of Dr. C. Bose was held on 11th September 2026 at the TAI, Mumbai Unit Office, where members and well-wishers paid their heartfelt tributes and remembered his remarkable contributions and enduring legacy.

Dr. Chidambaram Bose may no longer be with us, but his ideals, achievements and memories will continue to inspire generations of textile professionals. His immense contribution to the Association and to the textile industry will remain etched in our hearts and will always be remembered with gratitude and respect.

The Textile Association (India), Mumbai Unit, conveys its deepest condolences to the bereaved family and prays to the Almighty to grant everlasting peace to the departed soul and strength to the family and loved ones to bear this irreparable loss.

Om Shanti!!

Seminar on “FUTURE TRENDS IN TECHNICAL TEXTILES”

The Textile Association (India), Mumbai Unit organized One Day Seminar on “Future Trends in Technical Textiles” on 22nd August 2026 at Hotel Fortune Park Galaxy, Vapi (Gujarat).

The seminar was inaugurated by the Chief Guest Shri Pramod Khosla, Chairman & Managing Director, Khosla Profil Pvt. Ltd.

Inaugural Session

Mr. R. R. Patil, Vice President, TAI, Mumbai Unit delivered welcome address. In his speech, he welcomed the Chief Guest Mr. Pramod Khosla, Chairman & Managing Director, Khosla Profil Pvt. Ltd., Key Note Speaker Dr. Ing. Mohit Raina Managing Director, Raina Industries Pvt. Ltd. He also welcomed, the Lifetime Achievement Awardee, Mr. Vipin Kalra, Chairman, Madura Industrial Textiles Ltd. and the Industrial Excellence Awardee, Mr. Chakresh Jain, Group President -Technical, Supreme Nonwovens Industries Pvt Limited, Speakers, Press, Media and delegates.



Lighting the Lamp



Welcome Address by Mr. R. R. Patil, Vice President, TAI, Mumbai Unit

Mr. R. K. Vij, President, The Textile Association (India) while addressing the seminar highlighted the growing importance of technical textiles in sectors such as healthcare, infrastructure, automotive, defence, agriculture and aerospace. He said the future of the sector will be driven by high-performance materials, smart textiles and sustainability. He emphasised the need for greater collaboration among industry, academia, research institutions and government to promote innovation, testing, skill development and commercialisation. Shri Vij said, India, with its strong textile base and large domestic market, has a significant opportunity to emerge as a global hub for technical textiles, innovation and advanced applications. He called upon the industry to convert ideas into partnerships, new products and commercial opportunities, and expressed hope that the seminar would lead to greater collaboration and action.



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



About Seminar by Dr. Gurudas Aras, Seminar Advisor & Trustee, TAI, Mumbai Unit

Dr. Gurudas Aras, Seminar Advisor and Trustee, TAI, Mumbai Unit while giving his address highlighted the growing importance of technical textiles in Indian textile industry. Dr. Aras said technical textiles are transforming textiles from conventional products into high-performance engineering solutions for infrastructure, healthcare, defence, agriculture, automobiles, filtration, sports and other advanced applications. He emphasised that India has significant advantages, including a strong textile manufacturing base, skilled capabilities across the value chain and a large domestic market. He called for greater

investment in R&D, indigenous technology, industry-academia collaboration, testing, certification and start-up innovation. Dr. Aras stressed that India's ambition should go beyond import substitution and focus on becoming a global innovation and manufacturing hub for technical textiles. He emphasized that the transition from "textiles as products" to "textiles as solutions" will define the next chapter of the Indian textile industry and urged industry stakeholders to actively contribute to creating this future.

Mr. Pramod Khosla, Chairman & Managing Director, Khosla Profil Pvt. Ltd., in his inaugural address, highlighted the journey of innovation over the past four decades and brought out the salient features of Indian industry penetrating in to one of the key nations having significant growth in high-performance textiles especially filtration fabrics and allied technical textile sector.

Dr. Ing. Mohit Raina, Managing Director, Raina Industries Private Limited in his Keynote address said that the innovation in technical textiles focuses on the performance and interdisciplinary approach to harness the high performance of textiles for specialized application in building material, construction, infrastructure and marine sector.

He reiterated that innovation is key factor for developing the raw material and yarn for specialized application especially in textile reinforced concrete Technology in India. His work in the technical textiles in this field is awarded national award.

Dr. Ing. Mohit Raina, Managing Director, Raina Industries Private Limited in his Keynote address said that the innovation in technical textiles focuses on the performance and interdisciplinary approach to harness the high performance of textiles for specialized application in building material, construction, infrastructure and marine sector. He reiterated that innovation is key factor for developing the raw material and yarn for specialized application especially in textile reinforced concrete Technology in India. His work in the technical textiles in this field is awarded national award.



Dr. Ing. Mohit Raina, Managing Director, Raina Industries Pvt. Ltd. delivering the Key Note Address



Mr. Vipan Kalra, Chairman, Madura Industrial Textiles Ltd. receiving The Lifetime Achievement Award by the hands of Chief Guest



Mr. Chakresh Jain, Group President-Technical, Supreme Nonwovens Industries Pvt. Ltd. receiving The Industrial Excellence Award by the hands of Chief Guest



Release of Book of Papers



Inaugural Address by Chief Guest Mr. Pramod Khosla, Chairman & Managing Director, Khosla Profil Pvt. Ltd.

The Textile Association (India), Mumbai Unit felicitated Mr. Vipin Kalra, Chairman, Madura Industrial Textiles Ltd. with “The Lifetime Achievement Award” and Mr. Chakresh Jain, Group President – Technical, Supreme Nonwovens Industries Pvt. Ltd. with “The Industry Excellence Award” for their outstanding contribution in their respective field of technical textiles.



Vote of Thanks by Mr. Haresh B. Parekh, Convenor & Hon. Secretary, TAI, Mumbai



The Distinguished Audience

Mr. Haresh B. Parekh, Convenor of the seminar and Hon. Secretary, TAI, Mumbai Unit, proposed Vote of Thanks.

Technical Sessions

SESSION – I

During the technical session I, following papers were presented by the eminent speakers

- Mr. Varqha Bagwan, Scientific Researcher | Country Representative – India, Fabric Production, ITA – Institut für Textiltechnik of RWTH Aachen University, Germany made the presentation on “From Traditional to Technical Textiles: A Transformation Roadmap for Indian Manufacturers”.
- Mr. Shridhar Dixit, General Manager - Sales & Marketing, Yamuna Machine Works Pvt. Ltd. presented the paper on “Advanced Coating & Lamination Architectures for Technical Textiles”.
- Mr. Manish Mashilkar, Sr. Manager-Sales and Mr. Deepak Karade, Deputy General Manager, Textile Engineering Group – Processing, A. T. E. Enterprises Pvt. Ltd. made the presentation on “Warp Knitting Technical Textiles and Coating Technology for Technical Textiles”.
- Mrs. Manjiri Paranjape, Vice President (R&D), Rossari Biotech Ltd. made the presentation on “Elevating Athletic Performance with Textile Finishes”.
- Mr. Anish Jiwarajka, Executive Director, Jiwarajka Textile Industries presented the paper on “Technical Textiles - From Yarn to Performance”.

The papers were well received by the delegates as witnessed by formal and informal interaction with each speaker

SESSION – II

During the technical session II, following five papers were presented by the eminent speakers.

- Mr. Avinash Misar, Director & CEO, Coreshield Industries Pvt. Ltd. made the presentation on “Emerging Growth Opportunities - Protective Textiles”.
- Mr. Dayal Mehta JAIN, CEO & Business Evangelist, Alliance of Indian Technical Textile Industries & Startups



L to R: Mr. Deepak Karade, Mr. Manish Mashilkar, Mrs. Manjiri Paranjape, Mr. Anish Jiwarajka, Mr. Varqha Bagwan, Mr. Shridhar Dixit



L to R: Mr. Avinash Misar, Mr. Paresh Shah, Mr. Sudipto Mandal, Mr. Shridhar Dhumal, Mr. Dayal Mehta Jain, Mr. Abhishek Shankar Kamble

(AiTTiS), Country Head & CGO, AF. Corp., Taiwan presented paper on “Startup Opportunities in Technical Textiles: From Innovation to Commercialisation”.

- Mr. Paresh Shah, Business Head, Rabatex Industries Private Limited made the presentation on “Technical Textiles Innovation & Machinery Excellence”.
- Mr. Abhishek Shankar Kamble, Director, Clean Globe India Pvt. Ltd. made the presentation on “Sustainability in Fashion / Textile & Certification”.
- Mr. Sudipto Mandal, Regional Sales Director, Barmag India Pvt. Ltd. and Leading Nonwoven Technology Innovation engineered for Performance and Mr. Shridhar Dhumal - Regional Sales Director, Barmag India Pvt. Ltd. made the presentation on “Focus on Advance Machinery for Activewear/Sportswear | Bico-Component Yarn Demand, Fiber Architectures, Market Insights | Barmag Bico Spinning Technology & Concepts”.

At the end of presentations by all the speakers, delegates got an opportunity to exchange ideas with the speakers on their respective areas of presentation.

SESSION III- Panel Discussion

A Panel Discussion on the topic “Future of Technical Textiles: Innovation, Sustainability & Market Readiness” was featured as one of the important events of the seminar. The discussions were moderated by Mr. Avinash Mayekar, Managing Director, Suvin Expo LLP and the panel was comprised of senior leaders from the technical textile industry. The panel members came up with some radical thoughts which could be helpful for the growth of Technical Textile industry.

- Mr. Mahesh Bapat, Founder & CEO, Threads Technology India
- Mr. Chandrashekhar V. Kanade, Chief Operating Officer-Technical Textiles, Strata Geosystems (India) Pvt. Ltd.
- Mr. Tejas Mashruwala, CEO/President, Fiberglass Division, SKAPS Industries
- Mr. Avinash Misar, Director & CEO, Coreshield Industries Pvt. Ltd.



L to R: Mr. Avinash Misar, Mr. Tejas Mashruwala, Mr. Avinash Mayekar, Mr. Chandrashekhar V. Kanade, Mr. Mahesh Bapat

The panel discussions were followed by a very good question & answer session with thoughtful exchange of notes by panel members and delegates on the prospects of development of Technical Textiles in India.

The TAI Mumbai Unit's Seminar organised at Vapi was a grand success and was attended by over 200 participants.

Call for Articles

Journal of the Textile Association

Journal of the Textile Association (JTA) is open access bimonthly prestigious Peer Reviewed Journal. Blind Review Process is being followed to ensure the integrity of the blind peer review for submission to this journal. Every effort is made to prevent the identities of the authors and reviewers from being known to each other. For this the reviewer should not be from the same organization as that of the author. The author should submit three reviewers, which are related to the field of the subject paper with full contact details and reasoning for suggesting this reviewer.

JTA welcomes Original Manuscripts, Research Papers, Review Paper and Case Studies from the researchers, academicians and business people all around the globe. Especially we are publishing new and emerging areas of Textile Science, Technology, Engineering and Management. Your contribution of Research & Review Article is an honor for us. Follow the Guidelines.

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Seminar on “Next-Gen Textile Industry”



Dignitaries on the dais from left Mr. Pavan Panwala, Hons. Secretary TAI-SGU, Mr. Virendra Jariwala, Convenor of Seminar, Mr. Mahendrabhai Patel, Vice President TAI, Mr. Avinash Mayekar, Honourable Speaker, Mr. Minesh Adhvaryu, Chairman TAI-SGU, Mr. Siddharth Kamat, Honourable Speaker, Mr. Hiren Vyas, Honourable Speaker, Dr. Prakash Khatwani, Advisor of Seminar, Mr. Krushnaram Kharwar, Vice President TAI-SGU.

Continuing its commitment to promoting knowledge sharing and technological advancement in the textile sector, The Textile Association (India) (TAI), South Gujarat Unit successfully organized an insightful seminar titled “Next-Gen Textile Industry” on 11th July 2026 (Saturday) at The Palace Hall, 3rd Floor, Junomoneto Tower, Opp. RTO, Pal, Surat. The seminar focused on the theme “In Context of Man-Made Textiles: Sustainability Challenges and Growth Avenues with AI-ML & Government Schemes.”

The event witnessed an enthusiastic participation of textile industrialists, entrepreneurs, academicians, researchers, students, consultants, and professionals from across the South Gujarat textile fraternity. The seminar served as an excellent platform to discuss the latest developments in sustainability, artificial intelligence, digital transformation, and government initiatives that are shaping the future of the Indian textile industry.

Distinguished Dignitaries

The seminar was organized under the leadership of:

- President: Mr. Niraj Modi
- Chairman: Mr. Minesh Adhvaryu
- Convenor: Mr. Virendra Jariwala
- Vice President: Mr. Krishnakant Kharwar
- Hon. Secretary: Mr. Pawan Panwala
- Hon. Treasurer: Mr. Minesh Patwa
- Advisors: Dr. P. A. Khatwani and Mr. Ketan Jariwala



Their collective efforts ensured the successful planning and execution of the technical event.

Technical Sessions

The seminar featured three highly informative presentations delivered by eminent experts from the textile and industrial sectors.

Session I: Challenges of Sustainability for Man-Made Textiles

Speaker: Mr. Avinash Mayekar (Managing Director – SUVIN)

Mr. Mayekar delivered an enlightening presentation on sustainability challenges faced by the man-made textile sector. He emphasized the increasing importance of environmental compliance, ESG reporting, circular economy practices, carbon footprint reduction, waste management, resource optimization, and sustainable manufacturing practices. The session highlighted how industries must balance profitability with environmental responsibility to remain globally competitive.



Session II: Enhancing MSMEs Competitiveness Through ZED & Lean Scheme

Speaker: Mr. Hiren Pandya (Technical Expert – Lean Manufacturing, ZED & ESG, Empanelled Consultant, MSME, Government of India)

The second technical session focused on Government of India initiatives aimed at strengthening Micro, Small and Medium Enterprises (MSMEs). Mr. Pandya explained the objectives and benefits of the Zero Defect Zero Effect (ZED) Certification Scheme and Lean Manufacturing Competitiveness Scheme. He elaborated on how these initiatives help textile industries improve productivity, minimize waste, enhance product quality, reduce operational costs, and become globally competitive through continuous improvement methodologies.

Participants gained valuable insights into financial assistance, implementation strategies, and practical benefits available under various government schemes.



Short Presentation on Various Schemes by SPCB Surat

Session III: Making Textile Industries Globally Competitive with AI & Smart Technologies

Speaker: Mr. Siddharth Kamat, (Industry Engagement Lead – MSMEs | AI Centre of Excellence (AI CoE), Department of Science & Technology (DST), Government of Gujarat)

The final technical session explored the transformative role of Artificial Intelligence (AI), Machine Learning (ML), Automation, Data Analytics, Smart Manufacturing, and Industry 4.0 technologies in the textile industry.



Mr. Kamat demonstrated how digital technologies are revolutionizing production planning, quality control, predictive maintenance, inventory management, energy optimization, and supply chain efficiency. He also discussed emerging opportunities for Indian textile manufacturers to leverage AI-driven innovations to enhance productivity, reduce operational costs, improve customer satisfaction, and strengthen their global competitiveness.

The session generated considerable interest among participants, particularly young professionals and students eager to understand the future direction of textile manufacturing.

Interactive Discussion

Following each presentation, an engaging question-and-answer session allowed participants to interact directly with the speakers. Industry professionals discussed practical challenges faced by textile manufacturers, while students sought guidance regarding future technologies, sustainability practices, career opportunities, and skill development in the evolving textile landscape.

The discussions reflected the growing interest of the textile community in embracing innovation and sustainable growth.

Acknowledgement

The seminar was successfully conducted with the generous support of The Surat People's Cooperative Bank Ltd. as the sponsoring partner, Kushal Textile Institute, Surat as the supporting partner and Textile Insight as the media partner.

The Textile Association (India), South Gujarat Unit, expresses sincere gratitude to all the distinguished speakers, sponsors, supporting organizations, participants, volunteers, and members whose valuable contributions made the seminar a grand success.

Conclusion

The seminar "Next-Gen Textile Industry" proved to be a highly informative and thought provoking event, offering valuable insights into sustainability, government support schemes, and cutting-edge digital technologies shaping the future of the textile industry. The program reaffirmed TAI South Gujarat Unit's commitment to fostering knowledge sharing, encouraging innovation, and strengthening industry-academia collaboration for the sustainable development of the Indian textile sector.

Texference 2026 - Sustainable Textiles: Innovation to Implementation

The Department of Fibres and Textile Processing Technology, Institute of Chemical Technology (ICT), Mumbai, successfully organized the second edition of Texference 2026, an Inter-Institute Technical Conference on the theme "Sustainable Textiles: Innovation to Implementation" on 11th July 2026.

The conference provided a common platform to academicians, researchers, industry experts, and students to deliberate on recent developments in sustainable and technical textile applications. Building on the success of the inaugural edition in 2025, Texference 2026 focused on promoting knowledge exchange, fostering collaborative research, and strengthening the interface among academia, research organizations, industry, and government.



Padma Bhushan Prof Joshi speech

The programme commenced with the lighting of the ceremonial lamp and the ICT-Vidyapeeth Geet. The inaugural session began with a welcome address by Prof. Ashok Athalye, Head of the Department of Fibres and Textile Processing Technology, who emphasized the department's commitment to advancing research and innovation in textile science and technology.

Prof. Parag Gogate, in-charge Vice Chancellor and Dean Academic Programmes, ICT highlighted the institute's vision of translating scientific research into technologies that contribute to national development. The conference was formally inaugurated by the Chief Guest, Shri Ajay Pandit, Additional Textile Commissioner, Ministry of Textiles, Government of India, who spoke about the importance of sustainable manufacturing, indigenous technologies, and stronger collaboration between academia and industry to enhance the global competitiveness of the Indian textile sector.

The keynote address was delivered by Padma Bhushan Prof. Jyeshtharaj Joshi, Hon'ble Chancellor of ICT, who inspired participants to pursue impactful research that addresses industrial and societal challenges through scientific excellence and interdisciplinary collaboration. The conference overview was presented by Dr. Santosh Biranje, Convener of Texference 2026, who outlined the conference's objectives and highlighted the need for collective efforts to develop sustainable textile technologies.

The conference featured two technical sessions, each comprising presentations from distinguished experts from leading academic and research institutions. The first technical session included presentations by Dr. Vishaka Karnad from the College of Home Science, Nirmala Niketan, Mumbai, on research opportunities in textiles and fashion; Dr. G. Krishna Prasad from ICAR-CIRCOT Mumbai presented high-performance protective gloves developed from recycled para-aramid fibre blends; and Shri Ravi Singh from SASMIRA Mumbai narrated innovative technical textile solutions for ground improvement.

The second technical session focused on emerging sustainable materials and advanced textile technologies. Dr. Surajit Some from the Department of Speciality Chemicals Technology discussed the translation of chemically tailored, sustainable nanomaterials from laboratory research to industrial applications. Dr. Suranjana Gangopadhyay from VJTI, Mumbai, presented a field study on innovative sustainable agro-textile products. Ms Karishma Hemani from BTRA Mumbai showcased eco-friendly encapsulation of biogenic oils for sustainable aroma-finished cotton fabrics. Mr. Vaibhav Vankundre from WRA, Thane, presented the use of coarse wool as a sustainable thermal insulation material for buildings and Dr. Sandeep More from ICT Mumbai delivered the final technical presentation on novel approaches to functionalizing textile materials.

Each presentation generated enthusiastic participation from delegates, with engaging discussions on sustainable materials, recycling, nanotechnology, agro-textiles, functional finishes, technical textiles, and commercialization of research outcomes. The interactive question-and-answer sessions provided an excellent opportunity to exchange ideas among researchers, faculty members, students, and industry representatives.

The conference attracted more than 80 delegates, including faculty members, scientists, researchers, postgraduate and undergraduate students, and representatives from academia, research organizations, and industry. The event successfully brought together experts from ICT Mumbai, ICAR-CIRCOT, BTRA, SASMIRA, VJTI, WRA, and the College of Home Science, Nirmala Niketan, providing a valuable platform for interdisciplinary interaction and future collaborations.



Participants at the end of the event

The event received generous financial support from various segments of the textile value chain, including Arvind Advanced Materials, Pulcra Chemicals, Colortex, Meghmani Dyes, Zydex, and SF Dyes. This reflects the strong partnership between industry and academia in promoting sustainable innovations in the textile sector. The event concluded with a Vote of Thanks delivered by Dr. Saptarshi Maiti, followed by the Rashtra Gaan.



With Industry Sponsors

Texference 2026 successfully fulfilled its objective of promoting dialogue on sustainable textile technologies and strengthening collaboration among academia, research institutions, industry, and government. The conference reaffirmed ICT Mumbai's commitment to advancing research excellence and supporting the sustainable growth of the Indian textile sector through knowledge sharing and collaborative innovation.

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National Handloom Day, 2026, - National Conference

A National Conference was organised in Mumbai on 10-08-2026 to commemorate National Handloom Day 2026, bringing together more than 100 participants, including government officials, textile professionals, academicians, designers, students, researchers and stakeholders from the handloom sector.

The conference was held at the Textiles Committee Conference Hall, Mumbai, it was organised by Anveshanam Foundation, Textile Value Chain and the Textiles Committee, Ministry of Textiles, Government of India.

The collaboration brought together institutions working across textile education, design, research, heritage, skill development and community engagement, creating a multidisciplinary platform for discussion on the present and future of Indian handloom.



Shri Kartikay Dhanda, Secretary, Textiles Committee, Ministry of Textiles, Government of India, was the Chief Guest. Ms. Geeta Castelino, Executive Director, Kala Ghoda Association and an educationist and advisor to the textile and garment industry, was the Special Guest.

The conference featured a distinguished panel of speakers representing government, academia, design, industry, NGO and social organisations. Speakers included Dr. Ela Dedhia, Shri Dr. K. S. Muralidhara, Shri Santosh P. Shinde, Prof. Dr. Anshu Sharma, Prof. Dr. Monika Aggarwal, Tasneem Merchant, Dhara Padia, Neena Lokare, Dr. Manjula Jagatramka, Dr. Jignasa Shah, Bijal Dedhia and Dr. Ambre.

Release of Conference Journal

A journal containing all the papers and abstracts presented at the conference, edited by Anveshanam Foundation and Textile Value Chain and published by Textile Value Chain, was also released during the conference. The publication brings together the research, experiences and perspectives shared by the participating speakers and serves as a valuable record of the discussions and knowledge presented on National Handloom Day 2026.

Felicitations of Guests, Speakers and Partners

During the conference, the Chief Guest, Special Guest, all the speakers, organising partners and SVRR were felicitated in recognition of their valuable contribution and participation in the National Handloom Day 2026 National Conference. The felicitation acknowledged the collective efforts of the government, academic institutions, industry, design professionals, social organisations and community initiatives in creating a meaningful platform for dialogue, knowledge sharing and collaboration for the future of Indian handloom.

The organising partners of the conference were The Alumni Association of the College of Home Science, Nirmala Niketan (AACHSNN); the Department of Textile Science and Apparel Design, S.N.D.T. Women's University; Sophia Shree B.K. Somani Polytechnic; SASMIRA's Institute of Design & Textiles (SIDT), Mumbai; Dr. Bhanuben Mahendra Nanavati College of Home Science; JD Institute; and Anjuman-I-Islam's Begum Jamila Haji Abdul Haq College of Home Science.

Exhibition, Student Showcases and Artisan Stalls

The conference also featured stalls and student showcases highlighting the diverse dimensions of handloom, sustainable textiles, design and inclusive livelihoods.

Anveshanam Foundation displayed a range of upcycled products made from pre-consumer fabric waste, including bags and fabric jewellery, produced by urban Self-Help Group of women demonstrating how textile waste can be transformed into useful and attractive products while creating livelihood opportunities for women.

Anveshanam Foundation in collaboration with SVRR showcased its handwoven products, including woven towels, bags, napkins and other utility items, providing participants an opportunity to see and appreciate the skills and capabilities of adults with intellectual disabilities engaged in handloom weaving.

Students of Dr. BMN College showcased kurtis and tops designed and made by its students. The display demonstrated how textile education can translate traditional and contemporary textile knowledge into practical, wearable products while encouraging creativity and design innovation among students.

Students of Sophia Shree B.K. Somani Polytechnic displayed traditional handloom sarees through a small walk in the conference room. The presentation allowed participants to see and appreciate a selection of traditional handloom sarees in an engaging manner and highlighted the richness, diversity and continuing relevance of India's handloom heritage.

Together, the stalls and student showcases added a practical and experiential dimension to the conference, connecting the discussions on heritage, sustainability, circularity, design innovation, inclusion, education and livelihoods with tangible products and creative expressions. They also demonstrated how educational institutions can play an active role in connecting students with India's textile heritage while encouraging them to explore contemporary applications and opportunities within the handloom sector.

Chief Guest Shri Kartikay Dhanda highlighted the importance of handloom as a means of recognising and preserving India's cultural and traditional heritage. He noted that India has around 800 Geographical Indication (GI) certificates, with more than 423 associated with the handloom and handicrafts sectors. He explained that a GI does more than identify a product it communicates the culture, heritage, uniqueness and identity associated with its place of origin. The Textiles Committee, he noted, has undertaken more than 85 GI facilitation programmes for the handloom and handicrafts sectors across different regions of India.

He also emphasised the importance of the Handloom Mark in protecting authentic handloom products and safeguarding the interests of artisans. With technological developments enabling machine-made products to closely resemble handwoven textiles, authentication has become increasingly important. He highlighted the proposed regulation under which products claiming to be handloom would require the Handloom Mark, strengthening authenticity and consumer protection. He also spoke about proposed labelling regulations that would make composition labelling compulsory for packaged textile products, enabling consumers to make more informed choices.

Sustainability was another important theme of the address. Shri Dhanda highlighted the Textile Committee's work with Tissar, SBI and New Bombay Municipal Corporation on post-consumer textile waste. The initiative trained 85 women to convert textile waste into useful products and generated more than ₹6 lakh worth of inventory/products. He emphasised, however, that such initiatives must also achieve financial and commercial viability and discussed the need for appropriate technology and new applications for textile waste. He encouraged young people and organisations interested in meaningful social initiatives to explore such opportunities, with handholding support in technology and know-how.

The address also drew attention to opportunities available through Ministry of Textiles schemes for sustainability and textile-related research. Shri Dhanda encouraged educational institutions to explore these schemes and undertake studies relating to sustainability, textile products, institutions and their social impact.

The livelihood dimension of handloom was strongly emphasised. Drawing from his experience with cluster development programmes, Shri Dhanda highlighted that the fundamental question for artisans is whether their work provides adequate earnings. He stressed the importance of establishing direct connections between weavers and buyers and creating market linkages that can generate sustainable orders and livelihoods. He also observed that handloom continues to provide an important source of livelihood and survival in rural areas where alternative opportunities may be limited.

A major concern discussed was the movement of younger generations away from handloom. Shri Dhanda emphasised the need to introduce children and young people to the nature, processes and unique characteristics of handloom. He encouraged students to understand the craft deeply and communicate its uniqueness through stories, videos and creative content so that consumers can appreciate the value of handmade products and artisans can obtain better prices. He also highlighted the potential of sustainability and social responsibility to create stronger consumer interest in Indian handloom.

He further stressed the need for new fashion ideas and product transformation. Referring to cluster-level interventions, he described how traditional cotton products could be diversified into silk products, demonstrating how new ideas can expand the market potential of existing weaving communities. He emphasised that such innovation can emerge when senior academicians and young students work together towards a common goal.

The sessions explored various dimensions of the Indian handloom sector, including traditional weaving practices, design innovation, education, technology, sustainability, market opportunities, artisan livelihoods, intervention through Universal Human Values and the future of handloom. Together, the presentations demonstrated that the future of Indian handloom lies not

only in preserving traditional skills but also in strengthening livelihoods, encouraging innovation, improving market access, using appropriate technology and ensuring that traditional knowledge remains relevant to younger generations.

- **Traditional Knowledge, Artisan Livelihoods and Sustainable Development**
The paper “Threads of Tradition: Handloom Weavers, Families, and Sustainable Livelihoods in the Peddapuram, Uppada, and Dulla Clusters of Andhra Pradesh”, presented by Dr Ela Manoj Dedhia, Director Anveshanam Foundation.
- **Innovation, Sustainability and Circularity**
The paper “Rewilding Fashion Futures: Paithani Handloom Textiles as Regenerative Style in Maharashtra”, presented by Prof. Dr. Monika Aggarwal, Dean, Chanakya Foundation.
- **Authenticity, Recognition and Consumer Awareness**
The paper “Indian Handloom Sector: Preserving Heritage through the Handloom Mark Scheme”, presented by Shri Dr. K. S. Muralidhara, Joint Director, and Shri Santosh P. Shinde, Assistant Director, Textiles Committee, Ministry of Textiles, Government of India.
- **Innovation, Sustainability and Circularity**
The presentation “Commercialising Agro-Waste for a Circular Economy – Local Weaves, Global Appeal”, by Tasneem Merchant, Creative Director, Tasneem Merchant Signature Label.
- **Traditional Knowledge, Artisan Livelihoods and Sustainable Development**
The presentation “Tribal Women of Jharkhand at the Back Strap Loom: The Journey of the Tribal Women at PIDT – From Innovation to Indigenisation”, by Dr. Manjula Jagatramka, Director, Vaitarna.
- **Digital Traceability and Contemporary Markets**
The paper “Digital Traceability in Indian Handlooms: The Role of QR Codes and Blockchain”, presented by Dhara Padia, Faculty Incharge, Dr. B. N. College of Design and Communication (Nanavati College).
- **Preserving Tradition through Design Innovation**
The paper “Reviving Handloom through Contemporary Design: A Case Study of Mhysa Clothing”, presented by Dr. Jignasa Shah, HOD, Sophia Shree B. K. Somani Polytechnic.
- **Traditional Knowledge, Artisan Livelihoods and Sustainable Development**
The concerns identified in the Andhra Pradesh study were echoed in the paper “An Overview of Traditional Weaving Units of Meghalaya”, presented by Dr. Anshu Sharma, HOD, TSAD, SNDT Women's University.
- **Education, Youth and Textile Heritage**
The paper “Pedagogy to Practice: Fostering Sustainable Textile Heritage”, presented by Mrs. Bijal Dedhia and Dr. Pradnya Prashant Ambre, Department of Textile Science and Fashion Design, Dr. Bhanuben Mahendra Nanavati College of Home Science,
- **Preserving Tradition through Design Innovation**
The paper “The Next Paithani: Can Tradition Grow Without Losing Its Soul?”, presented by Neena Lokare, Assistant Professor, Fashion Design, NIFT (Ministry of Textiles, Government of India).

A Collective Vision for the Future

The conference concluded with a strong message that protecting India's handloom heritage requires more than preservation alone. It requires a combination of authenticity, fair markets, technology, sustainability, contemporary design, education, youth participation, institutional collaboration and dignity-driven livelihoods.

The presentations and discussions demonstrated that handloom can simultaneously serve as a repository of cultural heritage, a source of rural livelihood, a platform for women's empowerment, a field for design innovation, a contributor to the circular economy and an opportunity for sustainable entrepreneurship.

The Chief Guest also encouraged participants to support artisans directly by purchasing handloom products and recognising the effort involved in creating them. He emphasised that supporting handloom is not merely about buying a product but about contributing to the livelihoods of the people who create it.

The participation of more than 100 delegates made the conference a meaningful platform for dialogue, knowledge sharing and collaboration. The conference reinforced the message that handloom is not only India's heritage it is a living knowledge system and a potential pathway towards sustainable, inclusive and dignified livelihoods for the future.



ITMA ASIA + CITME 2026 Shanghai Showcases Intelligent and Sustainable Manufacturing

From 20 to 24 November 2026, the textile machinery industry will gather in Shanghai for ITMA ASIA + CITME 2026, Asia's leading business platform for textile machinery, to be held at the National Exhibition and Convention Center (Shanghai).

The exhibition will occupy seven halls, with a total gross exhibition area of about 180,000 square metres. The exhibition has expanded by 10% over the last edition which reflects the continued industry interest in the region.

Spotlight on Emerging Technologies

Responding closely to the industry's evolving needs, this edition will introduce several emerging sectors, including equipment for textile-reinforced composites, textile recycling technologies, digital platforms and automation solutions for production processes.

The exhibition will also feature a dedicated Research and Innovation sector, bringing together leading Chinese universities to showcase advanced research developments and examples of industry-academia-research collaboration. The area will feature innovations, which include embodied robots for textile applications, intelligent inspection technologies and artificial intelligence development platforms.

Complete Value Chain Coverage with Leading Industry Players

To date, more than 1,800 exhibiting companies, of which almost 90% are from China, have applied to participate. Exhibits will be organised by production process, encompassing the complete textile and garment manufacturing value chain, including braiding, dyeing and finishing, embroidery, garment making, knitting, man-made fibres, nonwovens, printing, recycling, spinning, testing and packaging, weaving, etc.

Leading domestic and international companies that have confirmed their participation include Atexco, B.T.D., Barmag, Beijing Chonglee, BEST, CHTC, Cixing, Dornier, Epson, Fong's, Hicorp, Hongyuan, Itema, Karl Mayer, Konica Minolta, LMW, Murata, Picanol, Rieter, Rifa, Santoni, Saurer, Shima Seiki, Staubli, Taitan, Texpro, TMT, Truetzschler, Vandewiele, Yingyang and Yoantion.

These companies will present their latest innovations in digitalisation, intelligent manufacturing and automation designed to enhance sustainability, improve energy and resource efficiency, and enable smarter production.

Visitor Promotion Gains Momentum

The 2024 edition attracted visitorship of more than 90,000 from 111 countries and regions, with almost 90% of visitors coming from China. Participation from South American markets, led by Argentina, Brazil and Colombia, recorded particularly strong growth. Increase in visitorship was also seen from Algeria, Japan, Italy, Sri Lanka, Türkiye and the United Kingdom.

From April to July 2026, the organiser conducted a series of overseas promotional and outreach activities in India (Coimbatore, Ludhiana and Surat), Indonesia (Jakarta), Japan (Tokyo), Malaysia (Kuala Lumpur), and Türkiye (Bursa and Istanbul).

Further activities will be held in Bangladesh, Brazil, Egypt, Pakistan, South Africa and other countries and regions, extending the exhibition's outreach and encourage international visitor participation.

Trade Visitor Pre-Registration Opens with Exclusive Group Benefits

The trade visitor pre-registration opened on 25 May and will remain available until 19 November 2026.

Trade visitors may pre-register through the official exhibition websites at www.itmaasia.com and www.citme.com.cn. Registration is also available through the WeChat accounts of "International Textile Machinery Exhibition", the China Textile Machinery Association and the China Council for the Promotion of International Trade, Textile Industry Sub-Council.

Trade visitors can enjoy a 40% discount on early-bird admission tickets.

Domestic and international trade associations, industry organisations and corporate visitor groups comprising six or more participants may also apply for preferential group admission packages, enabling a more seamless and efficient exhibition experience.

For media enquiries, please contact:

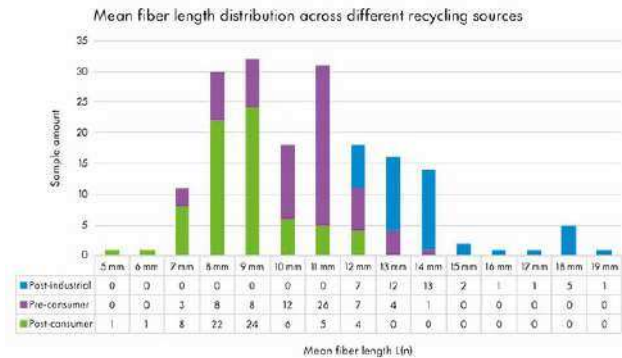
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USTER®

Driving circularity with Uster Recycled Fiber Matrix

The two-way street for assessing mechanically recycled materials



Fiber length distribution

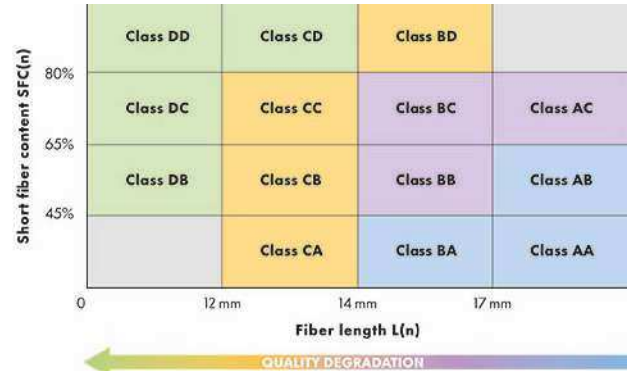
The textile industry's commitment to circularity continues to accelerate, and mechanical recycling is viewed as a targeted approach to cutting textile waste and its environmental impact. At the forefront of this drive, Uster has developed the Recycled Fiber Matrix, a two-dimensional assessment of mechanically recycled fibers to guide optimum processing and end-uses.

Recycled cotton fibers are difficult to categorize because of their inconsistency and variability. How can the industry evaluate mechanically recycled material accurately and match it to the most suitable spinning methods and product end-uses? Help is at hand from Uster, in the form of the Recycled Fiber Matrix. It provides an objective assessment of recycled cotton, so that recyclers, spinners and brands are guided towards what can be made from it, and how.

The concept fits perfectly with the industry's need for greater circularity and transparency in recycling.



Uster AFIS 6



Uster Recycled Fiber Matrix

The facts that matter

Precise data about the physical characteristics of recycled fibers is essential to understand how they will behave in spinning and their end-use. The Uster Recycled Fiber Matrix focuses on the essential numbers – such as length of fibers (L(n)), of the longest 5% fibers (5% L(n)), and short fiber content (SFC(n)).

The background to the development of the Recycled Fiber Matrix involved testing of a significant number of 100% mechanically recycled cotton fiber samples from key recycling regions, including China, India and Europe. Samples included greige materials, as well as colored and bleached recycled fibers. Sources were categorized as post-industrial, pre-consumer or post-consumer waste, as evenly distributed as possible.

Measurements of the recycled samples with Uster AFIS 6 were the basis of trends used in the Recycled Fiber Matrix. From this, Uster developed its application report on the Recycled Fiber Matrix. It evaluates the current state and potential challenges of using different types of mechanically recycled cotton fibers in spinning.

The Uster Recycled Fiber Matrix is an ongoing and dynamic process, with more samples being collected and analyzed from global recycling hubs, to reflect variability as source materials and processing conditions evolve.

How it works

Measured Uster AFIS 6 values are presented as clear and easy-to-understand quality levels, from A to D, color-coded for intuitive practical application. The color-coded regions correlate fiber parameters with their typical raw material sources, to provide a strategic guide for optimized yarn production.

Mechanically recycled cotton cannot be accurately classified by a single fiber parameter. So the Recycled Fiber Matrix uses two-dimensional evaluation. Only a combination of these two parameters can properly determine processing behavior and yarn quality.

For example, the x-axis might represent a length parameter, such as mean fiber length, while the y-axis could be a quality-limiting factor like short fiber content or nep count. Each position in the matrix thus reflects two interacting fiber properties simultaneously. In practice, this means that two fiber lots with the same mean fiber length could behave differently in spinning if one had high short fiber content and the other low. The two-dimensional matrix makes this visible and comparable.

Benefits in industrial application

The Recycled Fiber Matrix lets customers directly translate AFIS measurements into clear quality categories. This makes the quality level and the limitations of a lot transparent.

Based on Recycled Fiber Matrix, the class can be applied to bale management and machine settings. For optimum yarn performance, the class is useful to estimate the expected short-fiber load, and to define suitable blending ratios.

Uster experts generally advise users to enhance fiber sorting by separating bales according to length, source, and color, thus reducing variability. Effective bale management helps maintain consistency in key parameters, ensuring uniform quality throughout production. It's also recommended to enhance the spinning process by adjusting draft settings, twist, and spinning speed to suit the specific quality of recycled fibers. Increasing maintenance and cleaning frequency would also help.

Mixing recycled cotton with virgin cotton or synthetic fibers is still regarded as the best blending strategy to compensate for quality deficiencies. Uster is currently working in this field to provide benchmarks for blend levels and their subsequent influence on yarn quality.

Free application report

The Uster Recycled Fiber Matrix provides a data-driven framework for objective classification of recycled fiber lots. The application report on the Recycled Fiber Matrix is a valuable educational document, with several graphs and illustrations. It is available as a free download under www.uster.com/recycledfibermatrix. It contains shared insights empowering spinning mills, recyclers, and brands to make informed decisions about fiber suitability. It helps expand the use of recycled cotton in textile products, while optimizing processing parameters.

As recycling technologies and fiber preparation methods continue to evolve, Uster is convinced that ongoing data collection and matrix updates play an important part, refining classification accuracy and supporting sustainable circularity goals in the textile industry.

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Congratulation!!!

Prashant Annaso Chougule Completes M. Tech in Textile Technology



Shri Prashant Annaso Chougule, Life Member of the Textile Association (India), has successfully completed his M.Tech in Textile Technology from Government S.K.S.J. Technological Institute, Bengaluru, under Visvesvaraya Technological University (VTU), Belagavi, securing the top position in the 2024–2025 M.Tech Textile Technology

batch.

His research, titled “Study on Effect of Process Parameters of Polyester and Lycra Air-Covered Yarns and Functional Properties of Woven Fabrics,” was guided by Mrs. Geetha Desai, Assistant Professor.

The study focuses on optimizing air-covered yarn manufacturing and evaluating fabric performance, with potential applications in sportswear and other performance textiles.

Shri Chougule also secured first position in the PGCET entrance examination for M.Tech and completed five NPTEL courses in textile-related subjects, achieving Topper positions in three courses and earning Elite certificates.

He completed his Diploma in Textile Manufacture from D.K.T.E. Society's Textile & Engineering Institute, Ichalkaranji, in 1995, followed by a GMTA qualification through The Textile Association (India) in 2010. He brings 10 years of industrial experience in the spinning industry and has developed core expertise in spinning and man-made textiles. He currently handles subjects related to man-made textile technology at DKTE.

In recognition of his academic excellence, he received the TAI Best Student Award in 2012 at the 10th International and 68th All India Textile Conference. He was also the recipient of the Best Staff Award at DKTE in 2008.

Shri Chougule received valuable support from the DKTE management, Director Dr. Mrs. L. S. Admuthe, Deputy Director Dr. U. J. Patil, faculty members and technical support staff during his M.Tech studies.

The Textile Association (India) congratulates Shri Prashant Annaso Chougule on this achievement and wishes him continued success in textile education, research and professional service.

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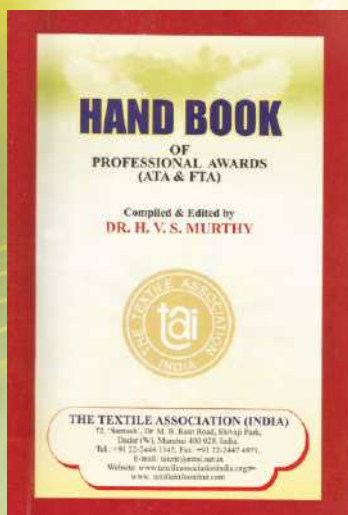
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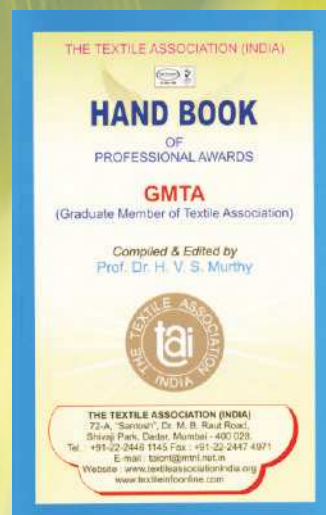
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