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U.S. Tariffs and India's Textile Sector: Opportunities and Challenges

In recent years, the trade relationship between India and the United States has witnessed strains due to tariff measures imposed by Washington. The withdrawal of India's benefits under the Generalised System of Preferences (GSP) program and subsequent tariff hikes on several Indian exports marked a significant shift in bilateral trade policy. While the U.S. justified these actions as a means to protect domestic industries and balance trade deficits, they have, in turn, affected India's export competitiveness across multiple sectors.

Among the most vulnerable to such measures is India's textile industry, a sector that not only contributes substantially to the country's GDP and foreign exchange earnings but also provides direct and indirect employment to millions. India's textile and apparel exports to the U.S. exceed $10.3 billion annually, accounting for roughly 28% of India's total textile exports. With higher duties, exporters face cost escalations, prompting global buyers to pause orders or shift sourcing to countries like Bangladesh or Vietnam, where duties are much lower (around 20%). Industry forecasters anticipate a significant drop in export volumes. The adverse effects extend beyond urban manufacturing hubs to rural weaving clusters and cottage industries, threatening livelihoods and destabilising traditional crafts. The Indian textile sector, which has long prided itself on cost-effectiveness and craftsmanship, now faces the dual challenge of safeguarding its workforce while retaining global market share.

Yet, within this challenge lies an opportunity. The current tariff environment underscores the urgency for India to diversify its export destinations, invest in value-added segments such as technical textiles, and adopt sustainable practices that appeal to conscious global consumers. Policymakers, too, must prioritise negotiation strategies, infrastructure development, and incentives that can help the sector adapt to these evolving global dynamics.

Ultimately, the U.S.-imposed tariffs serve as both a hurdle and a reminder. They highlight the vulnerabilities of overdependence on a single market while pushing the Indian textile industry to innovate and reposition itself in the global value chain. How effectively India responds to this shifting trade landscape will determine the resilience and future trajectory of one of its most vital industries.

Dr. Aadhar Mandot
Hon. Editor

T. L. PATEL, President

Embracing Innovation:
The Future of India's Textile Industry"

Greetings to all the members of The Textile Association (India)!!!

As we step into a new era of growth and development, the Indian textile industry stands at the cusp of unprecedented opportunities. At The Textile Association India, we are committed to fostering innovation, sustainability, and excellence in the sector.

The textile industry is a significant contributor to India's economy, employing millions and generating substantial revenue. However, to remain competitive in the global market, we must adapt to changing trends, technologies, and consumer preferences.

In recent years, our association has been working tirelessly to promote the adoption of sustainable practices, digitalization, and technological advancements in the industry. From exploring eco-friendly materials to implementing cutting-edge manufacturing processes, we are driving initiatives that will shape the future of textiles in India.

As President of The Textile Association India, I am proud to lead an organization that is dedicated to the growth and well-being of our members. We will continue to provide a platform for knowledge sharing, networking, and collaboration, empowering our members to stay ahead of the curve.

In the coming months, we have planned a series of events, conferences, and workshops that will bring together industry experts, policymakers, and innovators to discuss the latest trends and challenges facing the sector.

I would like to take this opportunity to express my gratitude to our members, partners, and stakeholders for their unwavering support. Together, we can achieve great things and make India's textile industry a global leader.

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

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A Review on Banana Cotton Blends for Sustainable Bed Linen Production

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Abstract:

This review paper discusses the potential of banana cotton blends as a sustainable option for the production of bed linen. Banana fiber, extracted from the banana plant pseudo stem, has high tensile strength, biodegradability, and moisture-wicking capacity, which makes it an eco-friendly option. When mixed with cotton, the fabric that is produced exhibits greater durability, breathability, and lower ecological footprint. The paper evaluates the structural compatibility of banana fiber with cotton and identifies the role it could play in breaking water-dependent cultivation and use of cotton and man-made fibers. Fundamental manufacturing steps such as extraction of fibers, mixing, spinning, and finishing are critically analyzed with a particular emphasis on processes imparting softness and comfort. The paper reviews market trend and consumer attitude also, citing a rising preference for environmentally friendly fabrics that strike a balance between sustainability, comfort, and cost-effectiveness. Challenges are the rough texture of banana fiber, non-standardization, and high cost of production. To overcome these, the study recommends increased industry cooperation, policy backing, and technological innovation specifically in softening processes and dye uptake to enhance consumer attractiveness and commercial potential. Future research areas emerging include enzymatic treatments, compatibility of natural dyes, and enhancing the scalability of processing techniques. The paper concludes that banana cotton blends have great potential as sustainable bedding fabrics, subject to overcoming existing limitations through innovation and investment.

Keywords: *Banana Fiber, Bed Linens, Cotton Blends, Natural Fiber, Sustainable Textiles*

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1. Introduction

The textile and fashion industry, though a major contributor to global economic growth and employment, is one of the largest users of natural resources and generators of environmental pollution [1]. The rising demand for textiles has resulted in excessive water consumption, chemical runoff, and high carbon emissions, necessitating urgent debates on sustainability in the industry [2]. Cotton, which is a natural fiber used very commonly, offers a paradox: while it can biodegrade, its growth requires a lot of water and depends greatly on pesticides and fertilizers, contributing to soil depletion, water contamination, and biodiversity loss [3].

Amid these environmental issues, manufacturers and consumers alike are resorting to environmentally friendly textile substitutes that are of quality and comfort while minimizing ecological harm [4]. Sustainable textiles include the utilization of natural and environmentally friendly materials, energy-saving production, and efficient waste disposal processes. Further, the increased practice of the circular economy model recycling, reuse, and biodegradability has been highly impactful on contemporary textile approaches [5].

One such potential material is banana fiber, an agro-waste material obtained from the pseudo stem of the banana plant. Usually discarded after fruiting, these pseudo stems provide a renewable and under- exploited source of natural fiber. Banana fiber has low inputs, is biodegradable, and exhibits significant tensile strength and moisture management properties [8]. When it is mixed with cotton, it produces a composite fabric that not only feels and lasts soft but also has an enormously smaller ecological footprint [6].

Home furnishings like bed linen prioritize properties such as comfort, breathability, and wearability. But the traditional materials like pure cotton or synthetic fibers are ecologically problematic. Cotton, while being breathable, comes with the problems of high-water usage and agrochemical dependence [7]. Synthetic fibers like polyester result in microplastic pollution, are not biodegradable, and last in the environment for decades.

Here, natural and renewable fibers like hemp, bamboo, organic cotton, and banana fiber have been identified as suitable alternatives [8]. Of these, banana fiber excels due to its potential for waste-to-value, supporting sustainable agriculture and the principles of circular economy [9]. Its

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lightness, antibacterial properties, and moisture permeability make it well-suited for bedding uses [10]. When blended with cotton, the product maintains structural durability as well as softness, is appropriate for everyday use, and minimizes ecological pressure. Banana cotton blends not only mitigate pressure on cotton farming but also benefit farmers by way of value-added exploitation of crop residue. They symbolize a movement to the reduction of agricultural waste and rural economic resilience [12].

This review investigates the possibility of utilizing banana cotton blends in eco-friendly bed linen production. The research looks at the physical and mechanical properties of the fiber, compatibility with cotton, environmental concerns, and overall production process. It also scrutinizes market readiness, consumer willingness, and functional limitations that affect mass adoption. By combining scientific findings and market views, the research offers an all-around appraisal of banana fiber's potential as a green textile innovation.

The core objectives of this review are:

- To analyze the structural and functional properties of banana fiber and its synergy with cotton in textile applications.
- To evaluate the environmental and economic advantages of adopting banana cotton blends in bed linen production.
- To identify key challenges in production, scalability, and market acceptance of banana cotton blended textiles.

2. Overview of Banana Fiber and Cotton

The use of sustainable fibers in textile production has attracted considerable attention because of rising environmental issues [13]. Of all the natural substitutes, banana fiber is found to be a promising environment-friendly option, especially when used in combination with cotton to impart durability, softness, and sustainability in home textiles. Knowing the inherent properties and environmental issues of both fibers is very important to determine their appropriateness for bed linen use.

a. Banana Fiber

Banana fibers are obtained from the pseudo stem of banana plants (Musa spp.), an agricultural residue usually discarded once the fruit harvest is over. The fibers may be extracted through mechanical processes in which the pseudo stems are cut, scraped, and processed or through retting when stems are put in water so that the fibers can be peeled off [14]. The removed fibers are washed, dried, and then made into yarn.

This fiber is mainly grown in tropical and subtropical areas and needs little agricultural input, making it a perfect sustainable material. Its tensile strength, low density, and high water-absorbency makes it a great textile reinforcement candidate [15]. Banana fiber is about 60–65% cellulose and provides natural antimicrobial and biodegradable characteristics, which promote hygiene and sustainability in bed products. However, it is not as flexible and elongated as needed for soft fabrics when applied separately. These drawbacks can be overcome by mixing banana fiber with cotton or other flexible fibers to increase tactility comfort and handleability [16].

Environmentally, banana fiber has advantages that include requirement of very little water and no pesticides, and harvests plant waste, thereby embracing a zero-waste production system. Such characteristics make banana fiber well-suited to circular textile systems, which support less landfill waste and more sustainable agriculture [17].

b. Cotton Fiber

Cotton is still one of the world's most widely used natural fibers due to its high softness, flexibility, and high moisture absorption. Cotton contains 88–96% cellulose [18], which makes it highly breathable and comfortable, particularly for bed linen use [19]. It also helps regulate body temperature and is hypoallergenic, making it ideal for people with sensitive skin.

Even with these benefits, traditional cotton farming has enormous environmental impacts. To produce only 1 kilogram of cotton, about 10,000 liters of water are needed [20]. The extensive application of chemical pesticides and fertilizers worsens soil erosion, water contamination, and loss of biodiversity. Organic cotton is a somewhat better option but still requires vast land and water resources.

Banana fiber is a more sustainable alternative compared to its counterpart. The fiber comes from the waste of crops, and therefore no further cultivation, water use, or chemical inputs are required. Its compromise is comfort—banana fiber is stiffer and less elastic than cotton. However, mixing the two can compromise sustainability and usability by yielding a very durable, breathable, and eco-friendly fabric [21, 22].

3. Blending Banana Fiber with Cotton: Properties & Potential

Mixing banana fiber with cotton is a viable alternative for the mass production of bed linens made from fabrics that combine durability, softness, and sustainability [14]. This revolutionary hybrid fabric blends the sustainable advantages of banana fiber and cotton's softness, providing buyers with a premium green product.

3.1 Rationale for Blending Banana Fiber with Cotton

Banana fiber in isolation is somewhat coarse and inflexible, constraining its usefulness in soft-textured applications like bedding. Cotton, being both flexible and soft, is intensive to produce as a crop. Mixing the two fibers yields a synergistic response with banana fiber adding to strength and durability, and cotton contributing to softness and comfort.

Also, the utilization of banana fiber, a waste from agriculture lowers the environmental footprint of cotton cultivation. The large amount of water and chemicals required for cotton is partially compensated for when substituted by banana fiber in blended fabrics. This enhances circularity and resource efficiency in the textile value chain.

Physical testing of banana-cotton blends against 100% cotton materials indicates that the blends are stiffer, but with improved air and moisture permeability. Such properties lead to breathability and wearer comfort, particularly in hot or humid conditions. Although raw banana fiber adds stiffness to the fabric, bio-softening finishes can improve flexibility and texture. The blended yarn is also usually thicker, adding to the durability, and yarn evenness increases with processing mainly because of the same cellulose structure of both fibers [23].

3.2 Physical, Mechanical, and Aesthetic Characteristics of the Blend

- The banana fiber-cotton blend merges the desirable properties of each component, resulting in a balanced and sustainable textile. Its key characteristics include:
- Improved Strength: The high tensile strength of banana fiber reinforces the structural integrity of the fabric. This enhances resistance to wear and tear, leading to a longer product lifespan—an essential quality for bedding products [24].
- Balanced Softness and Flexibility: Although banana fiber is inherently stiff, its combination with cotton significantly improves the softness and pliability of the fabric. This balance results in a lightly textured fabric that meets consumer expectations for comfort without compromising sustainability.
- Enhanced Wrinkle Resistance: Cotton fabrics are prone to wrinkling, which often necessitates ironing. The inclusion of banana fiber adds structural rigidity, thereby enhancing wrinkle resistance and reducing fabric maintenance efforts [25].

3.3 Durability, Breathability, and Moisture-Wicking Properties

Breathability and moisture management are important properties in bed linen because they have a direct influence on sleep comfort. The banana cotton blend meets the requirements of the bed linen. Banana fiber's contribute to high-water absorption and rapid drying properties that keep body temperature under control and prevent dampness. On the other hand, breathability of cotton complements this effect by promoting airflow and heat dissipation [26].

This blend is particularly useful in hot and humid climates, where it is vital to have cool, dry environments for comfortable sleeping. The increased tensile strength of banana fiber also makes the fabric more resistant to pilling and deterioration, resulting in a smoother texture and longer lifespan. These blends perform better than 100% cotton fabrics, particularly when subjected to finishing treatments meant to soften the texture and provide structural integrity.

4. Manufacturing Process of Banana Cotton Blended Bed Linen

The production process of banana cotton blended bed linen involves several steps, from the production of fibers to

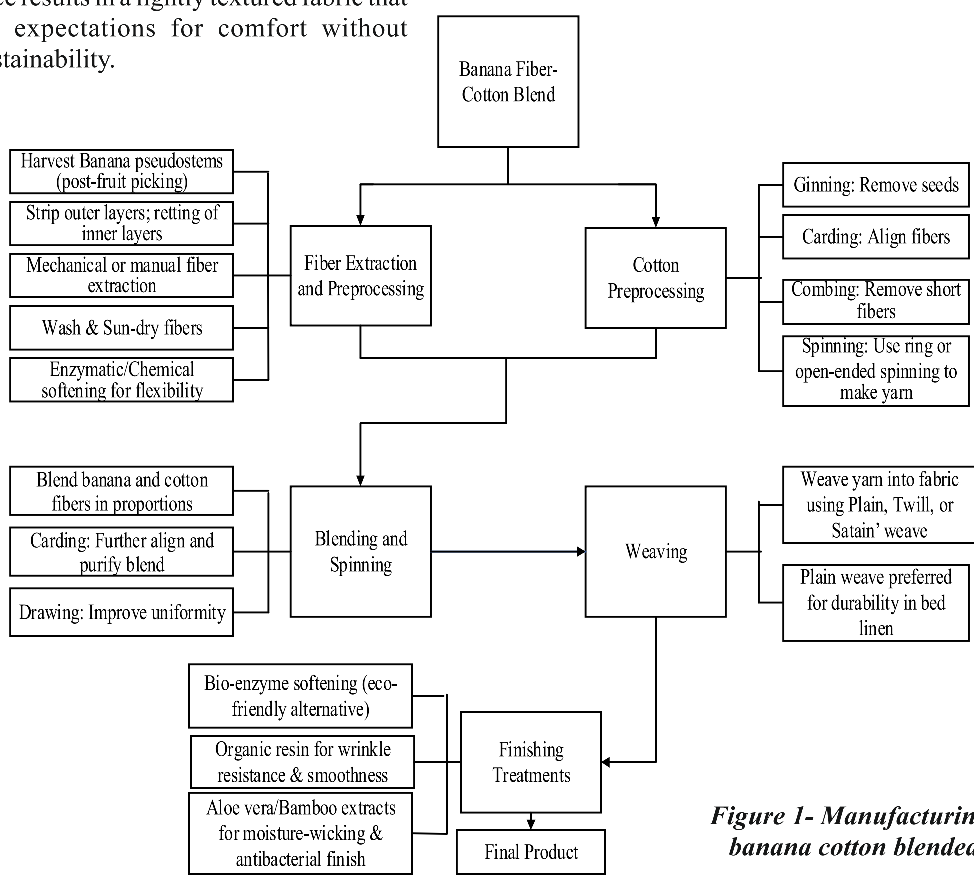

Figure 1- Manufacturing process of banana cotton blended bed linen

finishing treatment, to produce a high-quality, durable, and eco-friendly fabric. Due to the rough and rigid character of banana fiber, special processing and blending with cotton are needed to soften the bed linen, and make it breathable, and durable [27]. Banana fiber, which is obtained from the pseudo stem of banana plants after harvesting [28], is subjected to retting and mechanical or manual separation [29], and then washed, sun-dried, and softened to overcome its natural roughness [30, 31]. At the same time, cotton fibers are pre-treated by ginning, carding, and combing to make them clean and aligned [32]. The fibers are subsequently blended in different proportions (10/90, 20/80, 30/70) [20], carded, drawn, and spun into yarn using ring or open-end spinning, marrying banana fiber's strength and cotton's softness [33]. The yarn is woven on plain, twill, or satin weaves, with plain weaves being more suitable for bed linen durability [34]. Lastly, completing treatments such as bio-enzyme softening, organic resins, and aloe vera or bamboo extracts improves wrinkle resistance, moisture management, antibacterial properties, and softness [35, 36], making the bed linen functional and sustainable [37].

5. Sustainability and Environmental Benefits

The application of banana fiber mixed with cotton in textile production provides a sustainable option compared to traditional cotton-based fabrics. By applying banana fiber, which is a by-product of banana cultivation, the blend significantly reduces the environmental footprint of the textile industry. The key sustainability advantages of banana cotton blends include reduced water consumption, biodegradability, reduced textile waste, and a reduced carbon footprint [38].

5.1 Reduced Water Consumption Compared to Pure Cotton

Among the most significant environmental problems caused by conventional cotton farming is its intensive water needs. Cotton is a water-hungry crop, and it requires approximately 10,000 liters of water to grow just 1 kg of cotton. Cotton farming also relies mainly on chemical fertilizers and pesticides, which lead to water resource depletion through soil erosion and contamination [39]. On the other hand, banana fiber is derived from banana pseudo stems, a type of agricultural waste material that does not require an independent source of water resources for its production. Since banana crops are grown primarily for fruits, the stems would otherwise be wasted. This also means that by incorporating banana fiber in fabrics, a lot of fresh water is saved, thus the fabric blend being a more sustainable choice. By blending cotton with banana fiber, the entire water footprint involved in the manufacturing of bed linen is significantly reduced, leaving worldwide water resources within a secure quantity [40].

5.2 Biodegradability and Reduced Textile Waste

Clothing waste is an issue that grows larger each year as millions of tons of fabric is dumped into landfills or incinerated. Polyester and nylon, man-made fibers, will not degrade for decades and feed microplastics in the ecosystem. Even cotton, a plant fiber, won't degrade easily and can coexist with synthetic fibers for many years. Banana cotton blends, however, are 100% natural and biodegradable [25]. The process of breaking down these fibers is faster than in synthetic fabrics, which translates into less pressure on landfills. When they are discarded, the fabric degrades naturally into organic matter without residues that are harmful to the environment, making it an ideal choice for sustainable textile production. Furthermore, because banana fiber is obtained from plant waste, utilizing it creates a circular economy as it utilizes material that otherwise would be wasted. This reduces the environmental impact of textile production while providing banana farmers with an economic benefit [40].

5.3 Carbon Footprint Analysis of Banana Cotton Blends

The environmental impact of clothing is primarily due to raw material production, processing, transportation, and waste. Cotton production has a significant contribution to emissions through the use of chemical fertilizers and pesticides and mechanical harvesting that adds increased environmental stress. Banana fiber, on the other hand, provides a low-carbon option because:

- Minimal agricultural inputs (no need for additional water, fertilizers, or pesticides) [41].
- Carbon sequestration by banana plants, which absorb CO_2 from the atmosphere during growth [42].
- Lower energy consumption in fiber extraction, as banana fiber can be processed using mechanical methods rather than high-energy-intensive techniques [42].

By utilizing banana fiber in cotton-based fabrics, the overall carbon footprint of textile production is reduced. Life cycle assessment (LCA) confirm that banana cotton blends result in a 30-40% reduction in CO_2 emission compared to the production of exclusive cotton. Banana cotton blends provide a viable and scalable solution for environmental concerns in the textile industry. With decreased water consumption, full biodegradability, and a lower carbon footprint, this new textile blend guarantees sustainability without compromising quality and comfort. By using banana fiber as a renewable resource, the textile industry can make the shift towards a greener future, reducing waste and promoting sustainable production practices [43].

6. Market Potential and Consumer Perception

The global market for eco-friendly home textiles is expanding, with more and more customers becoming conscious of their ecological imprints. Banana cotton blend provides an effective alternative to conventional bed textiles, with a combination of sustainability, strength, and comfort. This section discusses market demand, affordability, and consumer attitudes about sustainable bedclothes made of banana cotton blends. There have been many research studies and institutions investigating this novel technique.

The banana cotton blend study highlights the market potential and customer perception also investigate the mechanical characteristics of banana/cotton blended knit fabrics, which indicated that increased content of banana fiber reduces strength but enhances abrasion resistance and reduces pilling. The study also introduced natural fiber composites, emphasizing their sources, characteristics, applications, and innovations, such as nano fillers, to enhance material performance and sustainability [9].

6.1 Growing Demand for Sustainable Home Textiles

With growing awareness about climate change, pollution, and resource depletion, consumers are now seeking green alternatives in home textiles. The global market for sustainable home textiles is expanding exponentially, driven by a rising demand for organic and biodegradable products against synthetic ones [44]. Government regulations and sustainability campaigns also encourage environmentally friendly textile production, encouraging the brands to turn green. In addition, responsible and ethical consumption has gained momentum, with customers preferring green businesses [45]. Banana cotton meets such requirements, reducing water usage, maintaining low carbon footprints, and recycling agri-by-products, while delivering a green yet quality product. Recognizing this shift, large fashion companies are exploring green fabrics to cater to the demands of environmentally conscious consumers, thus the market for banana fabrics is highly profitable and business oriented [25].

6.2 Cost-Effectiveness and Commercial Viability

One of the most important concerns of sustainable textiles is being cost-effective since organic and natural textiles are more costly with low production, high labor rates, and expensive processing methods. Banana cotton mixtures, however, provide a low-cost option due to their cost-effectiveness. Since banana fiber is a by-product of farming, raw material prices are quite low in comparison to organic cotton or bamboo fiber. Furthermore, banana fiber manufacturing is more energy and water-efficient, thus a less expensive method compared to cotton farming which consumes much water [46]. Owing to banana farming being widespread in tropical nations, there exists a steady and scalable raw material supply, thereby increasing cost-effectiveness. As manufacturing processes get better and supply chains are made more efficient, banana cotton blended fabric can be price-competitive with conventional cotton textiles. This cost-effectiveness will drive increased application in the home textile industry as a commercially attractive and eco-friendly alternative [47].

6.3 Consumer Awareness and Willingness to Adopt Eco-Friendly Bedding

Acceptance of sustainable fashion in the market relies heavily on consumer attitudes and a need for a balance among value for money, comfort, durability, and fashion consumers. There may be consumer demand to pay an extra price for sustainability, yet this will require balancing out to make the market mass acceptance. The eco bed should feel as soft, breathable, and alive as possible, if not more so, than their traditional counterparts. Aesthetics of the material is a strong driver reported in purchasing behavior, as consumers would want sustainable fabrics to create different textures, colors, and finishes [48]. Consumer research indicates that over 70% of consumers are willing to adapt to green home textiles if they offer the same comfort and durability as traditional textiles. Companies that most strongly highlight the environmental friendliness of banana cotton blends, their softness, and durability will be most likely to attract a loyal customer base and drive the use of sustainable bedding products. The demand for banana cotton blended bed linen in the market is viable, spurred by a demand for eco-friendly home textiles, cost savings, and increasing consumer awareness. As more brands and companies embrace green innovations, the application of banana fiber-based bedding will tend to expand, providing an eco-friendly but commercially viable alternative to conventional cotton bed linen [49, 50].

7. Discussion

This research provides an exhaustive evaluation of banana cotton blends, marking them as a potential alternative in sustainable textiles. The combined attributes of banana fiber's recyclable strength and biodegradability with cotton's comfort and softness developed a blended fabric that satisfies both environmentally conscious and consumer needs. The evaluation illustrated how banana fiber reduces water use, carbon emissions, and textile waste. These areas are problematic for the legacy cotton textile supply chain. Additionally, the review demonstrated the application of naturally derived eco-friendly finishing treatments, such as bio-enzyme softening, with banana cotton fabrics positively contributing to the functional and aesthetic characteristics of the finished product. These interventions enhance not only the quality of the finished product but also the product's life cycle and sustainability. More specifically, there are clear trends in the home textile market indicating a growing consumer interest in green home textile products, which provide a rational justification for banana cotton blends to be contemplated as the consumer demand grows for ethically conscious and environmentally friendly products. However, there are several hurdles to commercial viability that must be addressed, including coarse fibre, standardization, and challenges to large-scale production. Overcoming these hurdles requires further research work into possible enzymatic treatments, automation/processing for fibre into finished product, and providing insights into consumer behaviour. There is an opportunity to develop the banana cotton textile as the next generation sustainable choice for home textile treatment, and with collaboration from government, industry, and the research community applicable to this market, banana cotton blends may become available to consumers.

8. Challenges and Future Prospects

i. Challenges

- Banana fiber processing is time-consuming and needs enhanced mechanization for commercial production.
- The stiffness of the fiber can render blending with cotton difficult to achieve a smooth, pleasant texture.
- Maintenance of uniform fiber yield and quality in various varieties of banana plants continues to be an issue.
- There is no worldwide standard for banana fiber processing and blending, impacting fabric quality uniformity.
- Fiber property variability resulting from climate, soil, and harvesting differences affects production consistency.

ii. Future Prospects

- Studies on chemical and enzymatic softening methods can improve the fiber's flexibility and comfort.
- Merging innovations with next-generation bio-based resins or natural softeners would enhance fabric texture.
- The development of automated fiber extraction technologies can lower labour costs and enable mass production.
- Eco-friendly dyeing and finishing research will further improve the fabric's sustainability factor.

9. Conclusion

Banana-cotton blends hold considerable promise for sustainable home furnishings, thanks to durability, breathability, and sustainability of the combination. Banana fiber, a 100 percent biodegradable by-product and good tensile strength with moisture management properties, provides increased performance to a cotton fabric when blended, while also offering decreased water consumption and textile waste. Moreover, a lower cost of manufacturing and an abundance of raw materials, along with a low impact industry-approved eco-friendly finishing, make it a viable sustainable opportunity. Banana-cotton blends offer impacts on the potential circular economy and on trends consumer behavior for greater green textiles. There are challenges in scaling banana-cotton blends, along standardizing and reducing costs. Adoption will depend on both government support, continued technological advancements, and industry cooperative effort. The value of future research includes optimizing soft and elastic properties of fibers and improving blends, consumers' acceptance, and performance to understand broader market acceptance.

References:

[1] Farhana K, Kadirgama K, Mahamude AS & Mica MT, "Energy consumption, environmental impact, and implementation of renewable energy resources in global textile industries: an overview towards circularity and sustainability", Materials Circular Economy, 4/15 (2022) 1-16, https://doi.org/10.1007/s42824-022-00059-1

[2] Leal Filho W, Dinis MA, Liakh O, Paço A, Dennis K, Shollo F & Sidsaph H, "Reducing the carbon footprint of the textile sector: an overview of impacts and solutions", Textile Research Journal, 90/15-16 (2024) 1798-1814, https://doi.org/10.1177/00405175241236971

[3] Rahaman MT, Pranta AD, Repon MR, Ahmed MS & Islam T, "Green production and consumption of textiles and apparel: Importance, fabrication, challenges and prospects", Journal of Open Innovation: Technology, Market, and Complexity, 10/2 (2024) 1-20, https://doi.org/10.1016/j.joitmc.2024.100280

[4] Sigaard AS & Laitala K, "Natural and sustainable? Consumers' textile fiber preferences", Fibers, 11/2 (2023) 1-23, https://doi.org/10.3390/fib11020012

[5] Rahla KM, Mateus R & Bragança L. "Implementing circular economy strategies in buildings—from theory to practice", Applied System Innovation, 4/2 (2021) 1-14, https://doi.org/10.3390/asi4020026

[6] Huang YF, Azevedo SG, Lin TJ, Cheng CS & Lin CT. "Exploring the decisive barriers to achieve circular economy: Strategies for the textile innovation in Taiwan", Sustainable Production and Consumption, 27 (2021) 1406-1423, https://doi.org/10.1016/j.spc.2021.03.007

[7] Holovenko T, Kuzmina T, Berezovsky Y, Shovkomud O & Martyniuk A, "Research of the Ukrainian market and quality of home and sleepwear", Commodity Bulletin, 17/1 (2024) 154-164, https://doi.org/10.62763/ef/1.2024.154

[8] Gorji M, Mazinani S & Gharehaghaji AA, "A review on emerging developments in thermal and moisture management by membrane-based clothing systems towards personal comfort", Journal of Applied Polymer Science. 139 (2022) 1-27, https://doi.org/10.1002/app.52416

[9] Thapliyal D, Verma S, Sen P, Kumar R, Thakur A, Tiwari AK, Singh D, Verros GD & Arya RK, "Natural fibers composites: origin, importance, consumption pattern, and challenges", Journal of Composites Science, 7/12 (2023) 1-44, https://doi.org/10.3390/jcs7120506

[10] Bordón P, Paz R, Peñalva C, Vega G, Monzón M & García L, "Biodegradable polymer compounds reinforced with banana fiber for the production of protective bags for banana fruits in the context of circular economy", Agronomy, 11/2 (2021) 1-26, https://doi.org/10.3390/agronomy11020242

[11] Pillai GS, Morya S, Khalid W, Khalid MZ, Almalki RS, & Siddeeg A, "Banana pseudostem: An undiscovered fiber enriched sustainable functional food", Journal of Natural Fibers, 21/1 (2024) 1-15, https://doi.org/10.1080/15440478.2024.2304004

[12] Azam F, Ahmad F, Ahmad S & Haji AD, 'Sustainable raw materials' In Circularity in textiles, Textile Science and Clothing Technology, Springer Nature Switzerland: 2023: pp. 59-128, https://doi.org/10.1007/s44174-024-00259-0
[13] Hawas HS, "Investigation on the Mechanical and physical Properties of Medical Scrub Fabrics" Journal of Art, Design and Music, 4/1 (2025) 120-129, https://doi.org/10.55554/2785-9649.1052
[14] Othman, H., Ragab, M. M., & Hassabo, A. G, "Utilization of regenerated cellulose fiber (banana fiber) in various textile applications and reinforced polymer composites", Journal of Textiles, Coloration and Polymer Science, 21/3 (2024) 51-71, https://dx.doi.org/10.21608/jtcps.2024.258999.1267
[15] Emmanuel JK, Mtashobya LA, & Mgeni ST, "Potential Contributions of Banana Fruits and Residues to Multiple Applications: An Overview", Natural Product Communications, 20/2 (2025) 1-9, https://doi.org/10.1177/1934578X251320151
[16] Akala BM, "Cost-effective banana (Musa paradisiaca) waste management and the welfare of banana farmers in Kakamega county Kenya", East African Journal of Science, Technology and Innovation 2 (2021) 1-16, https://doi.org/10.37425/eajsti.v2i.336
[17] Wa M, JS J, PK D, S S, & S AR, "Biosoftening of banana pseudostem fiber using cellulase and pectinase enzyme isolated from Aspergillus niger for textile industry", Journal of Genetic Engineering and Biotechnology, 21/170 (2023) 1-8, https://doi.org/10.1186/s43141-023-00617-3
[18] Awais H, Nawab Y, Amjad A, Anjang A, Akil HM, & Abidin MS, "Environmental benign natural fibre reinforced thermoplastic composites: A review", Composites Part C: Open Access, 4 (2021) 1-18, https://doi.org/10.1016/j.jcomc.2020.100082
[19] Fu Q, Cui C, Meng L, Hao S, Dai R, & Yang J, "Emerging cellulose-derived materials: a promising platform for the design of flexible wearable sensors toward health and environment monitoring", Materials Chemistry Frontiers, 5 (2021) 2051-2091. https://doi.org/10.1039/D0QM00748J
[20] Vaddula Y, &Singh K, "Progression of drip irrigation and fertigation in cotton across the globe and its future perspectives for sustainable agriculture: an overview", Applied Water Science, 13/177 (2023) 1-20, https://doi.org/10.1007/s13201-023-01986-3
[21] Kumar V, Chakraborty P, Janghu P, Umesh M, Sarojini S, Pasrija R, Kaur K, Lakkaboyana SK, Sugumar V, Nandhagopal M,& Sivalingam AM, "Potential of banana based cellulose materials for advanced applications: A review on properties and technical challenges", Carbohydrate Polymer Technologies and Applications, 6 (2023) 1-21, https://doi.org/10.1016/j.carpta.2023.100366
[22] Al-Dabash BM, & Al-Kahali MS, "MORPHOLOGICAL AND STRUCTURAL CHARACTERIZATION OF NANOCELLULOSE EXTRACTED FROM BANANA PSEUDOSTEM WASTE", Electronic Journal of University of Aden for Basic and Applied Sciences, 5/4 (2024) 531-542, https://doi.org/10.47372/ejua-ba.2024.4.410
[23] Hawas H. "A study on comfort properties of banana/cotton blend woven fabrics", Journal of Design Sciences and Applied Arts, 2/1 (2021) 96-105, https://dx.doi.org/10.21608/jdsaa.2021.35112.1069
[24] Sangamithirai K. & Vasugi N, "Feasibility of developing banana-cotton fabric as a sustainable textile", The Journal of Research ANGRAU. 51/2 (2023) 89-96, https://doi.org/10.58537/jorangrau.2023.51.2.10
[25] Thakker AM, & Sun D, "Sustainable plant-based bioactive materials for functional printed textiles", The Journal of the Textile Institute, 112/8 (2021) 1324-1358, https://doi.org/10.1080/00405000.2020.1810474
[26] Sathish M, Radhika N, Venuvanka N, & Rajeshkumar L, "A review on sustainable properties of plant fiber-reinforced polymer composites: characteristics and properties", Polymer International, 73/11 (2024) 887-943. https://doi.org/10.1002/pi.6686
[27] Sasikala M, Sangeetha K, & Kumar BS, "Investigation of the Characterisation Variances of Blended Non-woven Textiles: Banana, Flax and Recycled Cotton", Indian Journal of Science and Technology, 18/1 (2025) 23-36, https://doi.org/10.17485/IJST/v18i1.3732
[28] Jabbar M, Iftikhar F, Hussain T, Ahmad S, & Ahmad F, "Preparation and characterization of sustainable plant-based blended woven fabric", Journal of Engineered Fibers and Fabrics 20 (2025), https://doi.org/10.1177/15589250251319322
[29] Paramasivam SK, Panneerselvam D, Sundaram D, Shiva KN, & Subbaraya U, "Extraction, characterization and enzymatic degumming of banana fiber", Journal of Natural Fibers 19/4 (2022) 1333-1342, https://doi.org/10.1080/15440478.2020.1764456
[30] Fan Y., "Study on preparation and application of banana fiber-based composites" Journal of Physics: Conference Series, 2539 (2023) https://doi.org/10.1088/1742-6596/2539/1/012093
[31] Libog L, Biyeme F, Betené AD, Biwolé AB, Ndiwe B, Mbang JP, Claude T, Mbey JA, & Meva'a JR, "Influence of the extraction location on the physical and mechanical properties of the pseudo-trunk banana fibers", Journal of Natural Fibers 20/2 (2023) 1-16, https://doi.org/10.1080/15440478.2023.2204451
[32] Bekraoui N, El Qoubaa Z, Chouiyakh H, Faqir M, & Essadiqi E, "Banana fiber extraction and surface characterization of hybrid banana reinforced composite", Journal of Natural Fibers, 19/16 (2022) 12982-12995, https://doi.org/10.1080/15440478.2022.2080789
[33] Okai-Mensah CK, Howard EK, & Okai-Mensah K, "Sustainable practices of the large-scale textile firms in Ghana", Cleaner and Circular Bioeconomy, 2 (2022) https://doi.org/10.1016/j.clcb.2022.100020
[34] Gomes CV, Araújo JC, Chaves DM, Fangueiro R & Ferreira DP, "Improving textile circular economy through banana fibers from the leaves central rib: Effect of different extraction methods", Food and Bioproducts Processing, 146 (2024) 195-204, https://doi.org/10.1016/j.fbp.2024.06.002

[35] He Z, Xu J, Tran KP, Thomassey S, Zeng X, & Yi C, "Modeling of textile manufacturing processes using intelligent techniques: a review", The International Journal of Advanced Manufacturing Technology, 116 (2021) 39-67 https://doi.org/10.1007/s00170-021-07444-1
[36] Mamdouh F, Reda M, El-Aziz A, Atef H, & Othman HA, "Overview of different fabric structures", Journal of Textiles, Coloration and Polymer Science, 19/2 (2022) 291-306, https://doi.org/10.21608/jtcps.2022.152641.1131
[37] Khan F, Hossain N, Hasan F, Rahman SM, Khan S, Saifullah AZ & Chowdhury MA, "Advances of Natural Fibers Composites in Diverse Engineering Applications–A Review", Applications in Engineering Science, 18 (2024), https://doi.org/10.1016/j.apples.2024.100184
[38] Dulo B, De Somer T, Phan K, Roosen M, Githaiga J, Raes K, & De Meester S, "Evaluating the potential of natural dyes from nutshell wastes: Sustainable colouration and functional finishing of wool fabric", Sustainable Materials and Technologies, 34 (2022), https://doi.org/10.1016/j.susmat.2022.e00518
[39] Hopewell K, "Global Power Shifts and the Cotton Subsidy Problem: How Emerging Powers Became the New Kings of Cotton Subsidies", Global Studies Quarterly, 4/2 (2024), https://doi.org/10.1093/isagsq/ksae012
[40] Hassabo AG, Shaker S, Khaleed N, & Ghazal H, "An observation on dyeing techniques of polyester/cotton blended fabrics using various dyes", Journal of Textiles, Coloration and Polymer Science, 21/1 (2024) 205-220, https://doi.org/10.21608/jtcps.2023.221101.1209
[41] Jans Y, von Bloh W, Schaphoff S & Müller C, "Global cotton production under climate change–Implications for yield and water consumption", Hydrology and earth system sciences, 25 (2021) 2027-2044, https://doi.org/10.5194/hess-25-2027-2021
[42] Isaev S, Khasanov S, Ashirov Y, Karabaeva T, & Gofirov A, "Effect of water and resource saving technologies of cotton growing on cotton yield" In E3S Web of Conferences, 244 (2021) https://doi.org/10.1051/e3sconf/202124402012
[43] Suwan C, & Somjai T, "Carbon footprint analysis of the cultivated banana cultivation in Prachinburi Province, Thailand", In E3S web of conferences, 355 (2022) https://doi.org/10.1051/e3sconf/202235502002
[44] Yadav V, Singh S, Singh S, & Powar S, "Life cycle assessment of chemically treated and copper coated sustainable biocomposites", Science of the Total Environment. 948 (2024) 1-10, https://doi.org/10.1016/j.scitotenv.2024.174474
[45] Nallarajah JE, "Repurposing Polymeric Waste from the Textile Industry for Sustainable Biodegradable Composites: Challenges and Opportunities", ChemRxiv, (2025) https://doi.org/10.26434/chemrxiv-2025-2mc0h
[46] Shehata SM, "The Role of Renewable Energy in Confronting Climate Change and Reducing the Environmental Impact of the Apparel Industry", International Design Journal, 15/1 (2025) 327-345, https://dx.doi.org/10.21608/idj.2025.395719
[47] Gomes C, Pires I, Monteiro L, Lima TM, & Gaspar PD, "Empowering Eco-Friendly Choices: An Environmental Impact Assessment Decision Support System for Textiles and Clothing", Applied Sciences, 14/2 (2024), https://doi.org/10.3390/app14020659
[48] Savale TK, Byram Anand P, Perumalla Varalaxmi AB, & Quaye JA, "Green Marketing Strategies: Assessing Consumer Perception and Adoption of Eco-friendly Products", Remittances Review, 8/4 (2023) 2490-2503, https://doi.org/10.33182/rr.v8i4.171
[49] Pranta AD, Rahaman MT, Repon MR, & Shikder AA, "Environmentally sustainable apparel merchandising of recycled cotton-polyester blended garments: analysis of consumer preferences and purchasing behaviors", Journal of Open Innovation: Technology, Market, and Complexity, 10/3 (2024), https://doi.org/10.1016/j.joitmc.2024.100357
[50] Zhang W & Liu L, "Unearthing consumers' intention to adopt eco-friendly smart home services: an extended version of the theory of planned behavior model", Journal of Environmental Planning and Management, 65/2 (2022) 216-239, https://doi.org/10.1080/09640568.2021.1880379

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AI in Apparel Technology: Exploring Gen Z's Perception and Purchase Behavior in the Digital Era

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Abstract:

Background: *Artificial intelligence has simplified the interaction between Technology in apparel industry and marketers in online retail by automating shopping experiences with personalized recommendations for the Gen Z consumers. AI has significantly enhanced the retail industry. We have compiled the various perception and purchasing behavior of Apparels that consumers have recognized several benefits when they consumed apparel with AI.*

Methods: *This study comprises 200 respondents as a sample size and analysed the data, using the Factor Analysis (FA) and to find the factors effecting consumer perception and impact of AI on online apparel purchases. Multiple Regression was carried out to find the consumer perception and impact of AI.*

Results: *It was found that AI has no significant impact on Personalized Shopping, Enhanced Customer Confidence, and Customer Support & Engagement. But AI has significant impact on Convenience.*

Conclusion: *This paper concludes four factors illustrating the significant impact of AI on Generation Z consumers, a group known for their adaptability and openness to emerging technologies. It also explores how AI is transforming apparel shopping practise and shaping the behaviour which is highest influential consumer demographics.*

Keywords : *Apparel Technology, Artificial Intelligence, Gen Z, Online Purchase, Perception.*

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1. Introduction

The apparel industry has undergone an intense revolution in recent times. It has driven largely by technological advancements that have redefined how apparels are designed, manufactured, marketed, and sold. Once dominated by manual labour and traditional production methods, the industry has comprised digital technologies that enhance efficiency, innovation, and consumer engagement.

The rapid increase of Artificial Intelligence technology has revolutionized the way businesses interact with consumers of apparel industry, particularly in the realm of e-commerce. Among various sectors, the online apparel industry has experienced significant transformations due to the integration of AI technologies. As AI continues to shape consumer experiences, understanding its influence on purchasing decisions is crucial, especially among younger, digitally-savvy demographics. Gen Z refers to the people belongs to late 1990s and early 2010s, represents a unique consumer group that has grown up with technology and the internet especially in apparel industry. This generation's relationship with AI-driven platforms is integral to shaping future trends in online retail. According to Liang, Y.; Lee, S.H.; Workman, J.E, Gen Z consumers value artificial intelligence technologies that improve their efficiency in selecting fashion garments and provide easy-to-use experiences.

AI tools such as personalized recommendations, virtual try-on features, chatbots, and predictive analytics are enhancing user experiences, streamlining purchase decisions, and fostering brand loyalty. However, while AI can boost convenience and engagement, its influence on trust, privacy concerns, and the emotional aspects of apparel shopping remains an area of ongoing investigation. Specifically, for Gen Z, who values authenticity, sustainability, and personalized experiences, the way AI is integrated into the online apparel shopping journey can either strengthen or hinder their relationship with brands. This research paper aims to explore the AI in Apparel Technology and consumer perception and Purchase behaviour of Gez Z in the digital era, by analysing how AI tools impact purchasing behaviours, emotional responses, and brand perceptions of the apparel clients. This study is expected to give valuable insights into the evolving dynamics between AI technologies in Apparel & consumer expectations in the Textile industry. Additionally, it will highlight potential challenges and opportunities for brands to engage Gen Z through AI-driven innovations. Ultimately, the study will contribute to a deeper indulgent of how AI is reshaping the landscape of online apparel shopping and its influence on one of the most influential consumer generations.

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2. Review of Literature

Numerous studies have explored how consumers perceive online shopping and the impact of AI in the apparel sector. One such study concluded that gender does not significantly impact consumers' willingness to make online purchases, although sellers should pay close attention to negative feedback from customers [1]. Another piece of research emphasized that offering flexible payment options and ensuring prompt delivery enhances the convenience of online shopping experiences [2]. A separate study found a solid association between customer satisfaction, trust, & their intent of purchase, highlighting these as key factors in consumer perception [3]. Research into the perceived risks associated with online shopping revealed that concerns about financial loss, product quality, data security, time, and psychological stress act as major barriers to purchase, while social risk was not considered significant [4]. Further investigations into the role of AI in consumer purchasing behavior revealed that AI-generated recommendations do influence buying decisions, with noticeable variations based on gender and income levels [5]. Another study focusing on AI-driven fashion promotions on Instagram discovered that such promotions tend to evoke positive emotions among users, which in turn boosts the possibility of making a purchase [6]. In addition, integration of AI, IoT, and Big Data was found to improve customer reliability by elevating satisfaction levels, engagement, and overall shopping experience [7]. The broad application of AI in the fashion and apparel industry has also been shown to give brands a competitive advantage [8]. Research targeting Generation Z suggested that AI positively affects their intentions to buy fashion products online by improving perceived quality and usefulness [9]. Finally, a study that extended the Technology Acceptance Model (TAM) incorporated AI-specific elements to better understand how AI influences the online shopping behaviors of Generation Z, thereby forming the basis for the study's conceptual framework [10]. However, limited research has widely examined how AI-driven tools concurrently address perceived risks and enhance trust among diverse consumer specially Gen Z groups in online fashion shopping.

2.1 Conceptual Framework of the Study

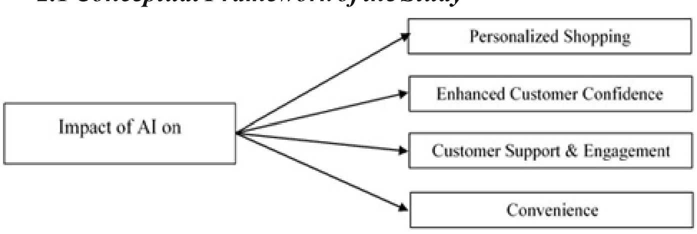

Figure 1: Conceptual Framework

3. Statement of the Problem

The rapid advancements in Artificial Intelligence (AI) have transformed the online shopping experience, particularly in the apparel industry. Gen Z, being digital natives, heavily relies on AI-driven recommendations, virtual try-ons, and personalized shopping experiences. However, their perception of AI in online apparel purchases remains a crucial area of study. Understanding how Gen Z perceives AI role in persuading their purchasing choices, trust, and overall satisfaction can provide valuable insights for e-commerce platforms. The main objective of the study is to explore the impact of AI on Gen Z's online apparel shopping behaviour, identifying key factors that shape their perception and decision-making process.

3.1 Objectives

1. To examine the factors influencing perception and purchasing behavior of Gen Z by AI in apparel technology in Bengaluru North.

2. To examine the impact of AI on online apparel purchases.

3.2 Hypothesis

Null Hypothesis: There is no significant impact of AI on personalized shopping, enhanced customer confidence, customer support and engagement, or shopping convenience on Gen Z consumers when purchasing apparel online.

4. Materials and Methods

4.1 Research Methodology

This study adopts an analytical research approach to examine Gen Z consumers' perception of AI-driven online apparel purchases. A structured questionnaire will be used as the primary data collection tool to gather insights from respondents. The study will focus on Gen Z consumers in Bengaluru North, employing a purposive sampling method to ensure the selection of relevant participants who actively engage in AI-assisted online shopping. A total sample size of 200 respondents have taken for survey. To analyse the collected data, various statistical tools have been used.

This study examined the collected statements to recognise the main factors influencing consumer perception and evaluated the impact of AI on online apparel purchasing behaviour through regression analysis. The resulting model is presented below through table1.

Table: 1 Classification of variables

Factors	Type of the Variables
Personalized Shopping	IDV
Enhance Customer Confidence	IDV
Customer Support & Engagement	IDV
Convenience	IDV
Impact of AI on online purchase of apparel	DV

Note: IDV - Independent Variable, DV - Dependent Variable

4.2 Results

The research paper has analysed the different statement of factors that affect the online purchase of apparel. This study uses factor analysis technique to analyse the different statement of factors that affects online purchase. The study shows that results of Bartletts test of sphericity and KMO test.

The null hypothesis is "The factor analysis is not valid"

The reliability for 5 constructs that includes total 31 numbers of items is 0.956.

Table 2: KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy		0.934
Bartlett's Test of Sphericity	Approx. Chi-Square	4071.380
	Deg. of Freedom	465
	Sig.	0.000

Table 2 shows the results of Bartlett's test of sphericity significance. Chi-square value is 4071.380 which significant at 1% level, which leads to the rejection of the null hypothesis; therefore the hypothesis that the factor analysis is valid. The value of KMO statistics (0.934) was also large and it reveals that factor analysis might be considered an appropriate technique for analysing the correlation matrix.

This study formed 31 statements based on the factors affecting online purchase. Each statement has to be rated on the five-point scale (1- strongly disagree, 2- disagree, 3- neither agree nor disagree, 4- agree, 5- strongly agree). These statements are considered as the independent variables except impact of AI on Gen Z analysed with the help of factor analysis and named as different factors.

Table 3: Factor Analyses

Sr. No.	Statements	Factors	Factors 1	2	3	4	5
1	AI ensures relevant product choice on preference	44.057 Personalized Shopping	0.768				
2	AI ensures relevant product choice on past purchases		0.749				
3	AI ensures relevant product choice On real time trends		0.735				
4	AI suggest complementary products for better purchase decision		0.677				
5	AI provides multiple platforms to buy		0.676				
6	AI helps in smart search and filtering in the process of buying		0.662				
7	AI recommends offers and discounts		0.589				
8	AI resolve the shopping queries		0.545				
9	AI predict the online purchase out of frequently purchased apparels and sends timely reminders		0.545				
10	AI curates a selection and making the process smooth		0.507				
11	AI saves shopping time of apparels		0.504				
12	AI recommends the exclusive brands		0.502				
1	AI delivers precise and transparent information	7.951 Enhanced Customer Confidence		0.775			
2	AI gives detailed product features			0.740			
3	AI helps in making secure payment			0.691			
4	AI helps in online tracking of the orders			0.650			
5	AI offers a comprehensive 360-degree view of apparels			0.548			
6	AI predicts the trend in apparel industry			0.545			
1	Chabot's solve most of the queries on apparels	4.869 Customer Support & Engagement			0.787		
2	Chabot's are instantly available				0.705		
3	24/7 AI services for online purchase of apparel				0.701		
4	AI helps in sustainable apparel/ fashion marketing				0.591		
5	Chatbot provides virtual assistance and improves the customer engagement				0.526		

Sr. No.	Statements	Factors	Factors				
			1	2	3	4	5
1	AI reminds me the forgotten apparels to buy	3.725 Convenience				0.803	
2	AI helps to buy the apparels together					0.690	
3	I receive personalized apparel suggestions by AI					0.635	
1	AI enabled online shopping of apparel has met my expectations	4.080 Impact of AI					0.796
2	Online purchase is more effective than physical purchase						0.763
3	I would confidently recommend an AI Powered online shopping						0.757
4	My interaction with AI powered retailers is Positive						0.752
5	AI ensures the optimum utilization of the resources						0.726

Table 3 highlights several factors influencing Consumer Perception & the role of Artificial Intelligence in online apparel shopping. Among these, "Personalized Shopping" stands out with the highest total factor loading of 44.057, "Enhanced Customer Confidence" follows with a factor loading of 7.951, while "Customer Support &

Engagement" registers a total factor loading of 4.869, "Convenience" has a total factor loading 3.725, and "Impact & Efficiency" records a total factor loading of 4.080.

This study further examined the identified factors and developed a regression model.

Table 4: ANOVA

Model	Sum of Squares	Df	Mean Square	F	Sig.
Regression	31.817	4	7.954	19.012	.000b
Residual	81.583	195	0.418		
Total	113.400	199			

Predictors: (Constant), Personalized Shopping, Enhanced Customer Confidence, Customer Support & Engagement, Convenience.

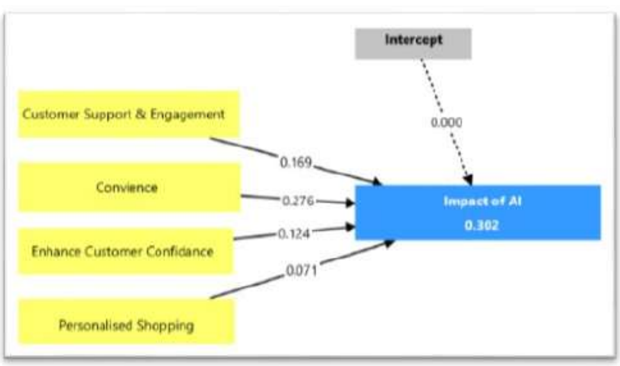

Figure 2: Regression Model

Table 5 shows that all the factors namely personalised shopping, enhanced customer confidence and customer support and confidence have no significant Impact of AI on online shopping on apparels for the Gen Z customers by accepting the null hypothesis. But it has significant impact on convenience shopping by rejecting the null hypothesis.

Table 5: Regression Analysis Table

Particulars	B	SE	T Value	P Value
Convenience	0.276	0.079	3.501	0.001
Customer Support & Engagement	0.169	0.1	1.691	0.092
Enhance Customer Confidence	0.124	0.097	1.274	0.204
Personalized Shopping	0.071	0.107	0.663	0.508

5. Conclusion

Artificial Intelligence (AI) has become a transformative force in the realm of online retail, particularly in the apparel technology sector, where it has reshaped how businesses engage with Generation Z consumers and influenced the broader e-commerce landscape. The rapid advancement of AI technologies has made them indispensable in delivering efficient, tailored shopping experiences. Apparel retailers increasingly depend on AI to create seamless digital interactions, offering consumers greater ease and satisfaction during their online shopping journeys.

This paper explores various factors demonstrating how AI has significantly influenced Gen Z consumers, who are highly adaptable and receptive to new technologies. AI serves as a valuable asset for emerging retailers, encouraging greater involvement in the e-Commerce sector. Through AI-driven solutions, Companies can better showcase their products to targeted customers, helping them discover more relevant offerings on their platforms. AI also enhances personalized shopping experiences, boosting consumer confidence in purchasing and providing extensive support throughout the buying journey. The study was conducted to examine factors influencing consumer perception of AI-driven online apparel shopping and the impact of AI-enabled services. Among the examined factors—personalized shopping, enhanced customer confidence, customer support, and engagement—none showed a significant impact on Gen Z's online apparel purchases. The only factor that proved to have a significant influence was convenient shopping, highlighting the key role AI plays in enhancing shopping ease for Gen Z consumers.

Reference :

[1] Bae, S., & Lee, T. (2011). Gender differences in consumers' perception of online consumer reviews. Electronic Commerce Research, 11(2), 201–214. https://doi.org/10.1007/s10660-010-9072-y

[2] Jiang, L. (Alice), Yang, Z., & Jun, M. (2013). Measuring consumer perceptions of online shopping convenience. Journal of Service Management, 24(2), 191–214. https://doi.org/10.1108/09564231311323962

[3] Zhang, F. C. (2016). Satisfaction, trust and online purchase intention: A study of consumer perceptions. IEEE, DOI : 10.1109/LISS.2016.7854436

[4] Kamalul Ariffin, S., Mohan, T., & Goh, Y. N. (2018). Influence of consumers' perceived risk on consumers' online purchase intention. Journal of Research in Interactive Marketing, 12(3), 309–327. https://doi.org/10.1108/JRIM-11-2017-0100

[5] Khan, S. I. (2022). Impact of artificial intelligence on consumer buying behaviors. International Journal of Health Sciences, 6(March), 8121–8129. https://doi.org/10.53730/ijhs.v6ns2.7025

[6] Yeo, S. F., Tan, C. L., Kumar, A., Tan, K. H., & Wong, J. K. (2022). Investigating the impact of AI-powered technologies on Instagrammers' purchase decisions in digitalization era–A study of the fashion and apparel industry. Technological Forecasting and Social Change, 177. https://doi.org/10.1016/j.techfore.2022.121551

[7] Rane, N. (2023). Enhancing Customer Loyalty through Artificial Intelligence (AI), Internet of Things (IoT), and Big Data Technologies: Improving Customer Satisfaction, Engagement, Relationship, and Experience. SSRN Electronic Journal. 1-21 https://doi.org/10.2139/ssrn.4616051

[8] Singh, S. (2024). Artificial Intelligence in the Fashion and Apparel Industry. Tekstilec, 67(3), 1–16. https://doi.org/10.14502/tekstilec.67.2024001

[9] Ruiz-Viñals, C., Pretel-Jiménez, M., Del Olmo Arriaga, J. L., & Miró Pérez, A. (2024). The Influence of Artificial Intelligence on Generation Z's Online Fashion Purchase Intention. Journal of Theoretical and Applied Electronic Commerce Research, 19(4), 2813–2827. https://doi.org/10.3390/jtaer19040136

[10] Bunea, O., Corbos, R., Triculescu, M., & Mis, S. I. (2024). The Next-Generation Shopper : A Study of Generation-Z Perceptions of AI in Online Shopping. 2605–2629

[11] Dr. Nirmal Singh, 2. (. (2023). Impact of Artificial Intelligence in Online Customer Satisfaction: An Empirical Study using Multiple Regression Analysis. European Economic Letters , Vol 13, Issue 1 (2023) 1-14.

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AI in Fashion System- Design to Customer Feedback

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Abstract :
The fashion industry is rapidly embracing artificial intelligence (AI) technologies to streamline processes, enhance creativity, and improve customer experiences across the entire product lifecycle. This paper provides a comprehensive overview of AI applications in the fashion system, from trend forecasting and design to production, marketing, retail operations, and customer feedback integration. The role of AI in trend forecasting through data mining and predictive analytics is explored, along with its contribution to the design process via generative design, virtual prototyping, and design ideation. The paper examines how AI techniques like demand forecasting, supply chain optimization, and intelligent automation are revolutionising apparel production and inventory management. Additionally, the paper explores the influence of AI on marketing strategies, such as targeted advertising, personalized recommendations and customer segmentation. It also delves into AI-powered in-store experiences, such as smart fitting rooms, visual merchandising, and real-time inventory tracking. Importantly, the paper highlights the potential of AI in facilitating a closed-loop system by incorporating customer feedback and preferences into the design and development processes. Finally, it provides insights into the future of AI in fashion, addressing challenges and opportunities for further integration and innovation. Overall, this paper offers a holistic perspective on the transformative power of AI in reshaping the fashion industry, from design inception to customer engagement, and its potential to create a more sustainable, responsive, and customer-centric fashion ecosystem.

Keywords: *AI, fashion industry, generative design, personalised recommendations, trend forecasting*

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1. Introduction

The fashion industry is experiencing a significant transformation driven by change integration of artificial intelligence (AI) technologies across its entire value chain. AI is transforming the way fashion businesses operate, create, and engage with consumers, from trend forecasting to analysing customer feedback [1]. The technological revolution represents a paradigm shift in an industry traditionally driven by human creativity and intuition, as AI systems increasingly augment [2] and enhance human capabilities rather than replace them. These technologies are addressing longstanding industry challenges such as demand forecasting accuracy, inventory management, sustainable production, and personalized customer experiences. According to recent studies, AI-powered solutions have demonstrated significant potential in reducing waste, optimizing resources, and improving decision-making processes throughout the fashion system [3].

This research paper provides a comprehensive analysis of AI applications across the fashion industry's ecosystem, examining its impact on various crucial aspects including trend forecasting, design processes, market analysis, apparel production, marketing strategies, warehousing operations, store management, advertising, and user experience. By investigating these interconnected domains, we aim to understand how AI technologies are reshaping traditional practices and creating new opportunities for innovation in the fashion industry [1]. The significance of this research lies in its holistic approach to examining AI's role in fashion, considering both the technical capabilities of AI systems and their practical implications for industry stakeholders. As fashion companies increasingly adopt AI solutions to remain competitive in a rapidly evolving market [4], understanding the full spectrum of AI applications and their potential impact becomes crucial for industry professionals, researchers, and decision-makers. This paper not only explores current AI implementations but also examines future possibilities and challenges, providing insights into how the fashion industry might evolve as AI technologies continue to advance. Through this comprehensive analysis, we aim to contribute to the growing body of knowledge about AI's transformative role in the fashion industry and its potential to create a more efficient, sustainable, and customer-centric fashion ecosystem [5].

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Figure 1 – Cycle of AI in Fashion System

2. AI in trend forecasting

The trend forecasting has relied on the expertise of human analysts, who employ a combination of market research, data analysis, and intuition to identify emerging trends. However, the advent of AI and machine learning has introduced new capabilities to enhance and augment this process. AI algorithms are capable of processing large volumes of data from multiple sources, such as social media, e-commerce platforms, search engine queries, and fashion influencers [6]. By employing techniques such as natural language processing (NLP), computer vision, and predictive analytics, AI can identify patterns, sentiment, and emerging trends in real-time, providing valuable insights that human analysts might miss or take longer to detect [6].

One key application of AI in trend forecasting is image recognition and visual search. AI-powered systems can analyse millions of images shared on social media, blogs, and e-commerce sites, identifying colour palettes, silhouettes, textures, and styles that are gaining popularity [7]. This visual data can be combined with textual data from social media posts, product reviews, and fashion publications to provide a comprehensive understanding of emerging trends. Moreover, AI can leverage historical data and consumer behaviour patterns to forecast future trends with greater accuracy [8]. By analysing sales data, website traffic, and customer preferences over time, AI algorithms can identify cyclical patterns and predict when certain styles or trends are likely to resurface or become popular again [9].

AI-driven trend forecasting also enables personalised recommendations and targeted marketing strategies. By understanding individual consumer preferences and behaviour, AI can suggest products, styles, and trends that are most relevant to each customer, increasing the likelihood of engagement and sales. While human expertise and creativity remain essential in the fashion industry, AI serves as a powerful tool to augment and enhance trend forecasting capabilities, enabling faster identification of emerging trends, more accurate predictions, and personalised recommendations tailored to individual consumer preferences.

2.1 AI in Design process

AI is revolutionising the fashion design process by introducing advanced tools and capabilities that enhance creativity, efficiency, and accuracy. From generating design concepts to creating detailed technical specifications, AI is empowering designers and streamlining the entire design Process [10, 11]. IBM collaborated with luxury brand Marchesa to create an AI-designed "cognitive dress" that changes colors based on social media sentiment during the Met Gala, using IBM Watson's natural language processing and emotion analysis [12].

2.2 Design Ideation and Concept Generation

AI-powered tools can assist designers in the ideation and concept generation phase by analysing various sources of inspiration, such as images, text, and trend data. These tools can generate unique design concepts, silhouettes, and pattern suggestions based on the input provided. Tools like DALL-E, Midjourney, and Stable Diffusion employ generative adversarial networks (GANs) and diffusion models to create original images or designs based on text prompts or reference images [13]. A prominent example is ChatGPT, launched by OpenAI, which garnered the attention of more than 100 million active users within just two months. Furthermore, platforms like DALL-E2 produce over four million images daily [10].

2.3 Sketch and Illustration Creation

AI-driven applications can generate fashion sketches and illustrations from text descriptions or reference images. These tools can help designers quickly visualise their ideas and explore different variations without the need for extensive manual drawing. Tools like Nvidia's Canvas and Runway ML's Sketch2Design utilise AI models trained on fashion sketches and illustrations to generate realistic and detailed sketches. The garment development processes of human designers are examined to suggest an AI-driven system that incorporates fashion domain expertise. Additionally, an AI-based garment development system utilizing StyleGAN2 is created, accompanied by a pilot program to assess its effectiveness and satisfaction among industry designers [13].

2.4 Technical Design and Specification Generation

AI can assist in the creation of detailed technical specifications, known as tech packs, which are essential for communicating design details to manufacturers. AI algorithms can analyse design sketches, reference images, and textual descriptions to generate accurate flat drawings, measurements, and material specifications [14]. Applications like Browzwear and CLO3D leverage AI and computer vision to create digital avatars, simulate fabric draping, and generate detailed technical specifications [15].

2.5 Inspiration Boards, Mood Boards, and Color Boards

AI tools can curate and generate inspiration boards, mood boards, and colour boards by analysing various sources, such as images, text, and trend data [16]. These boards serve as visual references for designers, capturing the desired aesthetic, colour palettes, and overall mood of a collection. Tools like Adobe Sensei and Pinterest Lens use AI to identify and suggest relevant images, colours, and themes based on user input or uploaded reference materials.

2.6 Fabric Rendering and Visualization

AI-powered tools can create realistic fabric renderings and visualisations, enabling designers to experiment with different fabric types, textures, and patterns without the need for physical samples. These tools can accurately simulate the draping, movement, and appearance of fabrics on digital avatars or models. Applications like CLO3D and Browzwear offer advanced fabric simulation and rendering capabilities, leveraging AI and physics-based simulations to create highly realistic fabric visualisations [15]. While AI tools enhance the design process, human creativity and expertise remain essential in guiding and refining the outputs generated by these technologies. The synergy between AI and human designers fosters a collaborative environment, where AI augments and accelerates the creative process [17] while designers provide artistic direction, cultural context, and final approval.

3. AI in market analyses

Market analysis is a critical function that guides strategic decision-making in the fashion industry, enabling businesses to understand consumer preferences, identify opportunities, and mitigate risks. AI is transforming market analysis capabilities in both the couture and retail sectors by leveraging advanced data analytics, predictive modelling, and machine learning techniques. Ultimately, the presence of AI does not replace humans in analysing and predicting, but rather targets areas that are more complex and challenging for humans to address [18]. H&M leverages AI to analyze customer data for personalized marketing, product suggestions, and store-level assortment planning [19].

3.1. Couture Market Analysis

In the realm of haute couture, AI plays a vital role in analysing trends, influencer dynamics, and consumer preferences among affluent clientele. By employing natural language processing (NLP) and sentiment analysis techniques, AI can monitor social media conversations, fashion blogs, and industry publications to identify emerging trends, colour palettes, and style preferences among high-net-worth individuals and trendsetters. Furthermore, AI-powered image recognition and computer vision algorithms can analyse runway shows, red carpet events, and social media posts to detect popular silhouettes, fabrics, and design elements. This data can be combined with historical sales data and customer profiles to predict demand for specific couture pieces or collections.

3.2. Retail Market Analysis

AI is used to analyze vast amounts of data from various sources, including e-commerce platforms, in-store sales, customer reviews, and social media interactions. Machine learning algorithms can uncover patterns, correlations, and insights that would be challenging, if not impossible, for human analysts to detect manually. A significant application of AI in retail market analysis is demand forecasting. By examining historical sales data, consumer behavior patterns, and external factors such as weather, economic conditions, and cultural events, AI models can predict future demand for specific products, styles, or categories with higher accuracy. This allows retailers to optimize inventory levels, minimize overstock or stockouts, and enhance overall supply chain efficiency. Additionally, AI plays a vital role in customer segmentation and personalization [20]. By analysing customer data such as purchase history, browsing behavior, and demographic information, AI can identify distinct customer segments and customize product recommendations, marketing campaigns, and in-store experiences accordingly. This personalized approach boosts customer satisfaction, improves conversion rates, and strengthens brand loyalty. Furthermore, AI-driven market analysis can guide pricing strategies by tracking competitor pricing, market trends, and consumer willingness to pay. Retailers can leverage AI for these purposes [21]. Dynamically adjust pricing based on real-time market conditions, optimising revenue and maintaining a competitive edge. As the fashion industry continues to generate vast amounts of data, AI will become increasingly vital in extracting valuable insights, identifying trends, and informing strategic decision-making across both the couture and retail sectors, enabling businesses to stay ahead of the curve and meet evolving consumer demands.

4. AI in Apparel production

The integration of artificial intelligence in apparel production marks a revolutionary transformation in the fashion manufacturing sector. This shift represents more than mere automation; it introduces intelligent, adaptive systems that continuously learn and evolve, fundamentally changing how garments are produced. AI-driven production systems are reshaping traditional manufacturing processes by introducing predictive analytics, real-time optimization, and smart decision-making capabilities across the entire production pipeline. In pre-production phases, AI technologies have revolutionised pattern making and material planning. Advanced algorithms now optimise pattern layouts to maximise fabric utilisation while minimising waste, a crucial step toward sustainable production. Digital sampling, powered by AI-driven 3D visualisation tools, has significantly reduced the need for physical samples, accelerating the product development cycle while reducing material waste [22]. These systems can accurately predict material requirements and optimise inventory levels, ensuring efficient resource allocation and reducing storage costs.

The production floor has witnessed perhaps the most dramatic transformation through AI integration. Smart production planning systems now orchestrate complex manufacturing operations with unprecedented precision. These systems consider multiple variables simultaneously - from machine availability and worker skills to order priorities and material constraints - to create optimal production schedules. Real-time monitoring through IoT sensors and AI analytics provides immediate insights into production status, enabling quick adjustments and preventive maintenance. Quality control, traditionally a labour-intensive process, has been revolutionised by AI-powered inspection systems. Computer vision technology, combined with machine learning algorithms, can detect defects with greater accuracy and consistency than human inspectors. These systems operate continuously, analysing every piece produced for quality issues, color consistency, and measurement accuracy. Predictive analytics can identify potential quality issues before they become significant problems, enabling proactive intervention and reducing waste. Compatibility is a critical factor in the fashion domain, where raw visual features of product representations play a key role in enhancing algorithmic performance, making them easily distinguishable [23].

Worker augmentation represents another crucial aspect of AI implementation in apparel production. Rather than replacing human workers, AI systems serve as intelligent assistants, providing real-time guidance, training, and safety monitoring. Smart assistance systems help workers maintain consistent quality standards while improving their skills through personalised training programs. AI-powered ergonomic monitoring systems ensure worker safety and comfort, reducing the risk of workplace injuries and improving overall productivity [24]. The integration of AI with supply chain management has created seamless communication channels between production facilities and their suppliers. Real-time data exchange enables just-in-time delivery of materials, reducing inventory costs and improving production flexibility. Smart logistics systems optimize material flow within facilities and coordinate transportation, ensuring efficient movement of goods throughout the supply chain.

Sustainability benefits significantly from AI integration in apparel production. Intelligent systems optimise energy consumption, reduce waste through precise cutting and material utilisation, and monitor environmental impact in real-time. Carbon footprint tracking and environmental performance metrics help companies make informed decisions about their production processes, supporting their sustainability goals. The future of AI in apparel production looks increasingly sophisticated, with emerging technologies promising even greater levels of integration and optimization [25]. As machine learning algorithms become more advanced and data collection more comprehensive, production systems will continue to evolve, becoming more efficient, sustainable, and responsive to market demands. This ongoing transformation represents a crucial step toward realising the vision of Industry 4.0 in the fashion sector, promising a future where production is not just automated but truly intelligent and adaptive.

5. AI in marketing

The incorporation of artificial intelligence in fashion marketing has drastically changed how brands engage with consumers, personalize experiences, and enhance their marketing strategies. AI-powered marketing solutions allow fashion companies to execute highly targeted campaigns while offering unparalleled insights into consumer behavior and preferences. Personalization has reached new heights through AI's ability to analyse vast amounts of customer data. These systems analyze purchase history, browsing behavior, social media interactions, and demographic data to build comprehensive customer profiles. This in-depth understanding allows brands to offer personalized product recommendations, tailored email campaigns, and customized website experiences that align with individual preferences and shopping behaviors [26].

Predictive analytics in fashion marketing has revolutionised inventory management and trend forecasting. AI algorithms examine historical sales data, social media trends, and market indicators to forecast future demand patterns [22]. This enables brands to optimize their marketing efforts by promoting the right products to the right audiences at the right time, reducing the risk of overstocking while maximising sales potential. Customer segmentation has become increasingly sophisticated through AI implementation. Marketing systems now can identify micro-segments within their customer base, understanding not just demographic factors but also behavioural patterns, style preferences, and purchase motivations. This granular understanding allows for highly targeted marketing campaigns that speak directly to specific customer groups' needs and desires.

Social media marketing has been transformed by AI-powered tools that analyse engagement patterns, identify influential voices, and optimise content scheduling. These systems can predict the best times to post content, identify trending topics, and suggest content types that are likely to generate the highest engagement. Visual recognition technology helps brands understand which product images and styles generate the most interest, informing both marketing and design decisions. Dynamic pricing strategies have become more refined through AI analysis. Systems continuously monitor market conditions, competitor pricing, demand patterns, and customer behaviour to suggest optimal pricing strategies [28]. This real-time pricing optimization helps brands maximise revenue while maintaining customer satisfaction and market competitiveness. The future of AI in fashion marketing points toward even greater personalization and predictive capabilities. As systems become more sophisticated in understanding and anticipating customer needs, marketing efforts will become increasingly targeted and effective, creating stronger connections between brands and their customers while optimising marketing spend and resource allocation.

6. AI in warehousing

Artificial intelligence has revolutionised warehouse management in the fashion industry by introducing smart systems that optimise storage, retrieval, and inventory management processes. These AI-driven solutions have transformed traditional warehouses into intelligent distribution centres capable of handling the complex demands of modern fashion retail [29]. AI-driven inventory management systems consistently track stock levels, forecast demand patterns, and automate the reordering process. Through advanced algorithms, these systems can anticipate seasonal fluctuations, identify slow-moving items, and optimise inventory levels to reduce carrying costs while ensuring product availability. Machine learning models analyse historical data to improve forecast accuracy, helping warehouses maintain optimal stock levels across diverse product categories.

Automated storage and retrieval systems, guided by AI, have revolutionised warehouse operations. Robotic systems, working alongside human operators, efficiently navigate warehouse spaces to pick, pack, and sort items. Computer vision technology enables these systems to identify and handle various garment types, while AI algorithms optimise movement patterns to reduce picking time and improve accuracy. These systems adapt to changing warehouse layouts and product configurations, ensuring maximum operational efficiency and smart warehousing has also improved quality control and product tracking. AI-powered systems [30] monitor storage conditions, track product movement, and maintain detailed digital records of inventory status. RFID technology combined with AI analytics provides real-time visibility into stock location and movement, reducing loss and improving order fulfilment accuracy. This integration of technology ensures that fashion products maintain their quality throughout storage and distribution while enabling precise inventory control.

7. AI in store management and Visual merchandising

Artificial intelligence has transformed traditional retail spaces into smart environments where data-driven decisions enhance customer experience and optimise store operations. In fashion retail, AI systems analyse customer flow patterns, purchase behaviours, and engagement metrics to continuously refine store layouts and merchandise presentations [31]. Smart visual merchandising systems use computer vision and analytics to optimise product placement and display arrangements. Heat mapping technology monitors customer movement patterns throughout the store, helping retailers understand how shoppers navigate spaces and interact with merchandise. Digital smart mirrors and virtual try-on technologies allow customers to experiment with different styles without physically trying on items, while providing personalised recommendations based on preferences and previous purchases. Real-time inventory management through AI-powered systems ensures optimal product availability and maintains visual merchandising standards. Smart shelving systems detect when products need replenishment, while computer vision technology tracks product movement and identifies misplaced items [32]. Additionally, AI enables dynamic pricing and promotion management, analysing local market conditions and customer behaviour patterns to optimise sales strategies while maintaining profit margins. Uniqlo introduced UMood, an in-store kiosk that uses neuroscience and AI to analyze customer reactions and suggest items based on mood responses [33].

8. AI in advertising

Artificial intelligence has revolutionised fashion advertising by enabling hyper-personalised, data-driven campaigns that reach the right customers at the right time across multiple platforms. AI algorithms analyze extensive consumer data to craft targeted advertising strategies that engage specific audience segments, all while optimizing advertising spend efficiency [2]. AI-powered advertising platforms now deliver personalised ad content based on individual consumer preferences, browsing history, and purchase behaviour. These systems dynamically adjust ad creative, messaging, and timing to maximise engagement. Visual AI technology helps select the most appealing product images and combinations for different customer segments, while natural language processing enables contextually relevant ad copy generation.

Programmatic advertising has been transformed through AI's ability to make real-time bidding decisions and placement optimizations. These systems continuously monitor campaign performance, adjusting budget allocation and targeting parameters to maximize return on advertising investment [34]. Machine learning algorithms predict the most effective channels and formats for different customer segments, enabling fashion brands to create cohesive, multi-channel advertising campaigns that drive conversion. Through predictive analytics and automated A/B testing, AI helps advertisers understand which creative elements resonate most strongly with different audiences. This data-driven approach enables continuous campaign optimization, ensuring advertising efforts remain effective while adapting to changing consumer preferences and market conditions.

9. AI in User Experience

Artificial intelligence has revolutionized the user experience in fashion retail by enabling personalized and seamless interactions across both digital and physical touchpoints.AI-powered systems analyse customer behaviour, preferences, and feedback to deliver tailored experiences that enhance satisfaction and engagement. Virtual styling assistants and chatbots provide personalised fashion recommendations and real-time customer support. These AI systems learn from each interaction, improving their ability to understand individual preferences and provide relevant suggestions. Augmented reality and virtual try-on technologies enable customers to visualise products on themselves before purchase, while AI algorithms analyse fit preferences and body measurements to recommend the right size. Advances in AI and machine learning are transforming fashion, enabling virtual try-ons and personalized recommendations in online shops [24].

AI-powered smart search capabilities comprehend natural language queries and visual inputs, making product discovery more intuitive and user-friendly. The technology recognizes and interprets fashion-specific terminology, style preferences, and contextual cues to deliver highly relevant search results. Machine learning algorithms continuously refine these capabilities based on user interactions and feedback. Levi Strauss & Co. leverages AI to analyze customer reviews and fit feedback across digital platforms to refine product sizing and inform new designs. [35].

10. Future of AI in Fashion

The future of AI in fashion points toward increasingly sophisticated and integrated systems that will reshape every aspect of the industry [36]. Advanced generative AI will revolutionise design processes, creating unique styles while considering sustainability and manufacturability. Digital fashion experiences will become more immersive through enhanced virtual reality and augmented reality technologies. Sustainable fashion practices will be driven by AI optimization, with systems analysing and reducing environmental impact throughout the product life cycle. Smart manufacturing will evolve toward fully autonomous production systems that adapt in real-time to changing market demands and consumer preferences. Most current studies in fashion areas primarily focus on image synthesis by using deep learning and generative models which constitute powerful tools for fashion image generation [37].

Personalization will reach new heights as AI systems develop a deeper understanding of individual style preferences and lifestyle needs. The integration of IoT devices and wearable technology will provide unprecedented insights into consumer behaviour and preferences, enabling more targeted and relevant fashion solutions. The convergence of physical and digital retail experiences will accelerate, with AI orchestrating seamless omnichannel experiences. Predictive analytics will become more sophisticated, enabling fashion brands to anticipate and respond to market trends with greater accuracy and speed. This technological evolution will continue to drive innovation in the fashion industry, creating more sustainable, efficient, and customer-centric experiences.

11. Conclusion

The integration of artificial intelligence across the fashion industry has fundamentally transformed traditional practices and opened new frontiers for innovation, efficiency, and sustainability. This comprehensive analysis has demonstrated how AI technologies are revolutionizing every aspect of the fashion system, from initial concept development to final customer interaction, creating an increasingly interconnected and intelligent ecosystem. Our research shows that AI has greatly improved the accuracy and efficiency of trend forecasting by analysing large volumes of data from various sources, allowing fashion businesses to more effectively anticipate and adapt to market demands. The integration of machine learning algorithms and computer vision technology has particularly improved the industry's ability to identify emerging trends and predict consumer preferences with unprecedented precision. In the design process, AI has emerged as a powerful tool for augmenting human creativity rather than replacing it. Through generative design capabilities, virtual prototyping, and automated technical specification generation, AI is streamlining the design workflow while enabling designers to explore new creative possibilities. This synergy between human creativity and AI capabilities has led to more innovative and efficient design processes.

AI has transformed production and supply chain management through the introduction of intelligent automation, predictive maintenance, and real-time optimization. These advances have not only improved operational efficiency but also contributed to sustainability goals by reducing waste, optimizing resource utilization, and enabling more precise production planning. In the retail sector, AI has transformed customer experiences through personalization, smart inventory management, and advanced visual merchandising. The technology has enabled retailers to create more engaging, personalized shopping experiences while optimizing operations and reducing costs.

Looking ahead, the future of AI in fashion appears promising yet challenging. As AI technologies continue to evolve, we can anticipate more sophisticated integration across the entire fashion ecosystem, enhanced sustainability through AI-driven optimization and waste reduction, further advancement in personalization and customer experience, increased adoption of virtual and augmented reality in retail, and greater emphasis on ethical AI implementation and data privacy. However, several challenges must be addressed, including the need for standardization and interoperability of AI systems, the importance of maintaining human creativity and craftsmanship alongside AI automation, the requirement for ongoing training and education to build AI literacy in the fashion workforce, and the necessity of addressing ethical considerations and ensuring responsible AI implementation.

AI has become an indispensable force in reshaping the fashion industry, driving innovation while addressing longstanding challenges in sustainability, efficiency, and customer satisfaction. As the technology continues to evolve, its integration will likely deepen, leading to even more transformative changes in how fashion is created, produced, and consumed. The success of this transformation will depend on the industry's ability to balance technological advancement with human creativity, ethical considerations, and sustainable practices. Moving forward, continued research and development in AI applications for fashion will be crucial in realizing the full potential of these technologies while addressing emerging challenges and opportunities. The fashion industry stands at the cusp of a new era where AI-driven innovation will continue to redefine the boundaries of what is possible in fashion design, production, and retail.

References

[1] Luce, L., Artificial intelligence for fashion: How AI is revolutionizing the fashion industry, Apress (2018), DOI: 10.1007/978-1-4842-3919-2

[2] Kietzmann, J., Paschen, J., & Treen, E., Artificial intelligence in advertising: How marketers can leverage artificial intelligence along the consumer journey, Journal of Advertising Research, 58(3) (2018), 263-267, DOI: 10.2501/JAR-2018-035

[3] Shobhana, N., AI-powered supply chains towards greater efficiency, In Complex AI Dynamics and Interactions in Management (pp. 229-249) (2024), IGI Global, DOI: 10.4018/978-1-6684-7589-8.ch012

[4] Sullivan, Y., & Wamba, S. F., Artificial intelligence and adaptive response to market changes: A strategy to enhance firm performance and innovation, Journal of Business Research, 174 (2024), 114500, DOI: 10.1016/j.jbusres.2023.114500

[5] Singh, S., Artificial Intelligence in the Fashion and Apparel Industry, Tekstilec, 67(3) (2024), 225-240, DOI: 10.14502/Tekstilec2021.64.225-240

[6] El Erafy, A. N., Applications of artificial intelligence in the field of media, International Journal of Artificial Intelligence and Emerging Technology, 2(2) (2023), 19-41, DOI: 10.21608/ijaiet.2024.275179.1006

[7] Shirkhani, S., Mokayed, H., Saini, R., & Chai, H. Y., Study of AI-Driven Fashion Recommender Systems, SN Computer Science, 4(5) (2023), 514, DOI: 10.1007/s42979-023-01748-2

[8] Jiju, A., Anilkumar, A., Krishnan, K. G., George, J., & Prasanth, R. S., Review on Fashion Trend Analysis and Forecasting Techniques-A Machine Learning Approach, 2024 5th International Conference on Innovative Trends in Information Technology (ICITIIT), (2024), 1-6, DOI: 10.1109/ICITIIT56042.2024.00009

[9] Amin, M. R., Younus, M., Hossen, S., & Rahman, A., Enhancing fashion forecasting accuracy through consumer data analytics: Insights from current literature, Academic Journal on Business Administration, Innovation & Sustainability, 4(2) (2024), 54-66, DOI: 10.1234/ajbais.v4i2.69

[10] Yan, H., Zhang, H., Liu, L., Zhou, D., Xu, X., Zhang, Z., & Yan, S., Toward intelligent design: An AI-based fashion designer using generative adversarial networks aided by sketch and rendering generators, IEEE Transactions on Multimedia, 25 (2022), 2323-2338, DOI: 10.1109/TMM.2022.3146010

[11] Csanák, A. (Ed.), AI for fashion, In 13th International Scientific-Professional Symposium Textile Science and Economy (September 18), Zagreb, Croatia, (2020), DOI: 10.6084/m9.figshare.14540733

[12] IBM, Cognitive dress designed with Marchesa and IBM Watson, IBM THINK Blog (2016), Retrieved from https://www.ibm.com/blogs/think/2016/04/watson-and-marchesa/

[13] Choi, W., Jang, S., Kim, H. Y., Lee, Y., Lee, S. G., Lee, H., & Park, S., Developing an AI-based automated fashion design system: reflecting the work process of fashion designers, Fashion and Textiles, 10(1) (2023), 39, DOI: 10.1186/s40691-023-00360-w

[14] Yüksel, N., Börklü, H. R., Sezer, H. K., & Canyurt, O. E., Review of artificial intelligence applications in engineering design perspective, Engineering Applications of Artificial Intelligence, 118 (2023), 105697, DOI: 10.1016/j.engappai.2022.105697

[15] Collins, T., & Thompson, A. J., Digital versus Physical Textiles: A Case Study of Browzwear's Fabric Rendering, The International Journal of Designed Objects, 18(1) (2024), 125-144, DOI: 10.18848/2325-1379/CGP/v18i01/125-144

[16] Cai, A., Rick, S. R., Heyman, J. L., Zhang, Y., Filipowicz, A., Hong, M., ... & Malone, T., Design AID: Using generative AI and semantic diversity for design inspiration, Proceedings of the ACM Collective Intelligence Conference, (2023), 1-11, DOI: 10.1145/3582269.3615596

[17] Anantrasirichai, N., & Bull, D., Artificial intelligence in the creative industries: a review, Artificial Intelligence Review, 55(1) (2022), 589-656, DOI: 10.1007/s10462-021-10039-7

[18] Nishant, R., Kennedy, M., & Corbett, J., Artificial intelligence for sustainability: Challenges, opportunities, and a research agenda, International Journal of Information Management, 53 (2020), 102104, DOI: 10.1016/j.ijinfomgt.2020.102104

[19] H&M Group, Leveraging AI for personalized marketing, product suggestions, and store-level assortment planning, H&M Group (2023), Retrieved from https://hmgroup.com/our-stories/hm-group-taking-steps-to-grow-the-customer-experience-through-tech/

[20] Sabitha, J., AI-Driven Customer Segmentation and Personalization, Zibaldone Estudios Italianos, 11(2) (2024), 1-20, DOI: 10.14672/2022111.1-20

[21] Guha, A., Grewal, D., Kopalle, P. K., Haenlein, M., Schneider, M. J., Jung, H., & Hawkins, G., How artificial intelligence will affect the future of retailing, Journal of Retailing, 97(1) (2021), 28-41, DOI: 10.1016/j.jretai.2020.10.007

[22] Fallacara, G., Fanti, M. P., Parisi, F., Parisi, N., & Sangiorgio, V., AI-driven image generation for enhancing design in digital fabrication: urban furnishings in historic city centres, CEUR Workshop Proceedings, (2023), CEUR-WS.org, DOI: 10.48550/arXiv.2309.12345

[23] Vasileva, M. I., Plummer, B. A., Dusad, K., Rajpal, S., Kumar, R., & Forsyth, D., Learning type-aware embeddings for fashion compatibility, In Proceedings of the European Conference on Computer Vision (pp. 390-405) (2018), DOI: 10.1007/978-3-030-01270-0_24

[24] Madni, A. M., Exploiting augmented intelligence in systems engineering and engineered systems, Insight, 23(1) (2020), 31-36, DOI: 10.1002/inst.12299

[25] Rathore, B., Integration of Artificial Intelligence & Its Practices in Apparel Industry, Integration, 10 (1) (2023), DOI: 10.4018/978-1-6684-7589-8.ch007

[26] Babatunde, S. O., Odejide, O. A., Edunjobi, T. E., & Ogundipe, D. O., The role of AI in marketing personalization: A theoretical exploration of consumer engagement strategies, International Journal of Management & Entrepreneurship Research, 6(3) (2024), 936-949, DOI: 10.1234/ijmer.v6i3.379393342

[27] Venkataramanan, S., Sadhu, A. K. R., Gudala, L., & Reddy, A. K., Leveraging Artificial Intelligence for Enhanced Sales Forecasting Accuracy: A Review of AI-Driven Techniques and Practical Applications in Customer Relationship Management Systems, Australian Journal of Machine Learning Research & Applications, 4(1) (2024), 267-287, DOI: not available

[28] Liu, D., Wang, W., Wang, L., Jia, H., & Shi, M., Dynamic pricing strategy of electric vehicle aggregators based on DDPG reinforcement learning algorithm, IEEE Access, 9 (2021), 21556-21566, DOI: 10.1109/ACCESS.2021.3056364

[29] Tsou, J. C., AI-Driven Automation in Warehouse Management Enhancing Efficiency and Accuracy, International Journal of Information, Business and Management, 16(4) (2024), 138-149, DOI: not available

[30] Sodiya, E. O., Umoga, U. J., Amoo, O. O., & Atadoga, A., AI-driven warehouse automation: A comprehensive review of systems, GSC Advanced Research and Reviews, 18(2) (2024), 272-282, DOI: 10.30574/gscarr.2024.18.2.0325

[31] Nimmagadda, V. S. P., Artificial Intelligence for Customer Behavior Analysis in Insurance: Advanced Models, Techniques, and Real-World Applications, Journal of AI in Healthcare and Medicine, 2(1) (2022), 227-263, DOI: 10.4018/978-1-6684-3873-2.ch010

[32] Mahi, R., Optimizing supply chain efficiency in the manufacturing sector through AI-powered analytics, International Journal of Management Information Systems and Data Science, 1(1) (2024), 41-50, DOI: 10.4018/IJMISDS.2024010103

[33] Fast Company, Uniqlo's UMood lets your brain pick your T-shirt, Fast Company (2016), Retrieved from https://www.fastcompany.com/3064135/uniqlo-umood-kiosk

[34] Durai, S., Manoharan, G., Priya, T. S., Jayanthi, R., Razak, A., & Ashtikar, S. P., Quantifying the Impacts of Artificial Intelligence Implementations in Marketing, In Smart and Sustainable Interactive Marketing (pp. 120-144) (2024), IGI Global, DOI: 10.4018/978-1-6684-7589-8.ch007

[35] Levi Strauss & Co., How Levi's uses AI and customer feedback for fit innovation, Levi Strauss & Co. (2021), retrieved from https://www.levistrauss.com

[36] Davenport, T., Guha, A., Grewal, D., & Bressgott, T., How artificial intelligence will change the future of marketing, Journal of the Academy of Marketing Science, 48 (2020), 24-42, DOI: 10.1007/s11747-019-00696-0

[37] Cheng, W. H., Song, S., Chen, C.-Y., Hidayati, S. C., & Liu, J., Fashion meets computer vision: A survey, ACM Computing Surveys (CSUR), 54(4) (2021), 1-41, DOI: 10.48550/arXiv.2003.13988

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Arundo Donax Granular carbon: A Sustainable Solution for Textile Effluent

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Abstract :

Background: *The issue of the treatment of cotton textile dyeing wastewater is a severe environmental concern. The current research explores the possibility of applying granular carbon as an adsorbent agent to treat this wastewater.*

Methodology: *The granular carbon used in the current study was synthesized from Arundo donax, which is a low-cost and easily accessible biomass, with phosphoric acid activation. The product material was also examined using various techniques, including BET technique for surface area and pore volume measurement, SEM technique for surfacing morphology examination, and FTIR spectroscopy for examination of surface functional groups. Batch adsorption experiments were carried out to examine the performance of granular carbon synthesized as an adsorbent in decolorizing and COD removal from textile wastewater. The removal efficiency was quantified by adjusting the dosage of adsorbent.*

Results: *The granular carbon made in the laboratory had a high surface area of 1202 m²/g and a high pore volume of 1.06 cm³/g. BET analysis confirmed its micro- and mesoporous mixed texture. SEM images revealed an extremely porous surface, and FTIR spectroscopy positively confirmed the existence of oxygen-containing surface functional groups. The batch adsorption test confirmed the granular carbon to be successful in decoloring the textile wastewater (initial color concentration: 479.25 Pt/Co) and reducing its COD (initial: 274.83 mg/L).*

Conclusion: *The results of the current research confirm that Arundo donax is a potential and viable precursor for low-cost granular carbon production. This low-cost granular carbon has significant potential for effective cotton textile dyeing wastewater treatment through efficient COD removal and decolorization.*

Keywords: *Adsorbent dosage, Arundo donax, Granular carbon, Mesoporous, Surface morphology*

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1. Introduction

The dyeing and finishing of cotton fabric is well known for its abundant usage of water and the resulting generation of highly polluted wastewater, especially from its dyeing processes [1]. This released water is characterized by its intense coloration and large amounts of organic material, quantified by the Chemical Oxygen Demand (COD) parameter [2]. The occurrence of these pollutants demands the formulation and enforcement of proper and environmentally sound treatment processes to curtail their effect. In the past, one of the most common processes used for purification of such industrial wastes, that is, removal of color and heavy metal impurities, has been the application of adsorption procedures involving Granular carbons [3]. This method exploits the capability of the material to absorb and retain pollutants onto its surface, providing a highly developed method for the removal of color and organic materials from the textile effluent. The necessity of these treatments is reinforced by environmental implications related to releasing untreated or partially treated wastewater from textile mills.

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However, with increased costs of Granular carbon used in toilets, there has been a lot of interest in the production of alternative and cheaper sources. Consequently, there has been significant research work, which has attempted to employ a lot of agricultural by-products to generate Granular carbon. This is necessitated by the quest for cheap and renewable materials, particularly in wastewater treatment. Granular carbons are either prepared from physical or chemical activation. Physical activation involves a two-step reaction: carbonization, followed by partial gasification in when exposed to steam, carbon dioxide, or air at high temperatures (800-1000 °C). Chemical activation involves a one-step reaction conducted under lower temperatures, between 450 and 700 °C, than physical activation. Chemical activation has been reported to enhance pore increase in the carbon material, leading to higher capacities for adsorption, decreased reaction times, and improved product yields [4]. Phosphoric acid has been most thoroughly investigated as an acid used in the chemical activation of lingo cellulosic materials with emphasis on its influence on pore development [5, 6] and mechanisms of degradation of precursor material [7, 8]. This research attempted to synthesize Granular carbon from Arundo donax [9] (AD) by chemical activation with phosphoric acid and test its efficiency in colour removal and COD reduction of waste water from after the fabric dyeing. Due to the demand for sustainable resources, this research specifically investigates Arundo donax, a fast-growing and readily available non-wood biomass, as a potential feedstock to synthesize Granular carbon.

2. Research Design and Procedures

2.1 Collection of Arundo donax samples

Chemical activation of activated Arundo donax carbon is typically initiated by plant material collection, washing, drying, and grinding. Activation by phosphoric acid is an effective and well-established chemical process for activating Arundo donax towards Granular carbon production. The process was stated to yield Granular carbons of good adsorbing capacity and high surface area for different pollutants [10]. The procedure is generally done by treating the Arundo donax biomass with phosphoric acid, which helps in forming the porous nature of the carbon material. The large surface area of the resulting Granular carbon is one of the main reasons why it is an effective adsorbent.

2.2 Granular carbon preparation via chemical activation

The Arundo donax samples harvested were chemically activated. They were first blended with a 50% phosphoric acid solution in a weight proportion of 2:1 between the acid and precursor biomass. They were further exposed to two hours of immersion at 110 °C for effective impregnation of the biomass with the activating agent. Upon this soaking time, the immersed sample was kept in stainless steel fixed-bed reactor and continued the heating process with an electric furnace. Temperature of the reactor was slowly raised from room to final temperature at 500 °C with constant rate of 3 °C/min. This was monitored and controlled at 0.5 hours holding time using a thermocouple located inside the reactor. After the heat cycle, the reactor allowed to cool to reach room temperature. The generated carbonaceous material was subsequently cleaned with a process of rinsing using an alkaline solution and then hot disinfected water repeated until the pH of the washed material was neutral. To desorb any remaining phosphate, which would otherwise hamper subsequent metal uptake experiments by precipitating out as insoluble phosphates, experiments using a solution of lead nitrate were conducted according to a procedure detailed in the literature [11]. Lastly, the washed sample was oven-dried to constant weight and the yield of the resulting Granular carbon was measured.

$$\text{Yield}(\%) = \frac{Wt_a}{Wt_o} * 100$$

where
Wt_a = absolute Granular carbon weight
Wt_o = originator weight

2.3 Description of Granular carbon

Granular carbon, also popularly referred to as Granular Activated Carbon (GAC), is a very porous type of carbon heavily treated to greatly enhance its internal surface area. Its high porosity renders it very effective at adsorbing impurities from liquids and gases. GAC differs from powdered activated carbon in that its particle size is comparatively larger, usually falling between 0.2 mm and 5 mm. This particle size is usually described in terms of mesh numbers, for example, an 8x30 mesh refers to particles that pass through an 8-mesh and are caught on a 30-mesh. Particle size is a most important parameter, affecting the performance of the carbon by affecting the kinetics of adsorption (lower particles provide higher adsorption rates due to smaller diffusion lengths) and pressure drop in a filter bed (larger particles permit higher flow rates). Hence, the right particle size of the granular carbon has to be chosen in order to optimize its use in such industrial and environmental processes as water treatment and air filtration.

The prepared Granular carbon was characterized using the following techniques:

Textural properties of the Granular carbon were determined by surface area and pore volume measurements. The Brunauer-Emmett-Teller (BET) technique was used, specifically, to examine the surface area, a most important factor that decides its adsorption capacity. Nitrogen adsorption-desorption isotherms, calculated by a Micromeritics analyser, and provided data on the total pore volume in the material and pore size distribution. All these studies are crucial in establishing the ability of the Granular carbon to adsorb effectively of the Granular carbon from Arundo Donex.

The surface characteristics of the Granular carbon, encompassing its structure, texture, porosity, and particle arrangement, were investigated using Scanning Electron Microscopy (SEM). This technique provided detailed microscopic information. Surface morphology is important as it determines the material's surface area and pore characteristics, which determine adsorption efficiency.

FTIR analysis used to find the presence of specific efficient assemblies on the Granular carbon. PerkinElmer Spectrum One spectrometer was used for this measurement, with a wavelength range of 400 to 4000 cm^{-1}. FTIR enabled the detection of different surface functional groups through infrared absorption at certain wavelengths.

2.4 Batch Adsorption Experiments

The adsorption process was investigated in 100 mL conical flasks to facilitate controlled batch experiments. Reactive dye solution's, dye effluent of 100 ml of after cotton fabric dyeing, were filled in the flasks. Measured amounts between 0.1g and 1.0 g of particle size equivalent to ASTM sieve No. 20 Granular carbon were added in the flasks. The flasks were shaken for 2 hours to allow the system to reach equilibrium. The flasks were removed subsequently, and the spectrophotometer (model SS 5100H) measured the end concentration of the dye in the effluent. The Granular carbon COD reduction and color index reduction were computed. The COD and color index initial values were 274.83 mg/L and 479.25 Pt/Co, correspondingly. The tests were done within a span of 2 hours at pH 3.

$$\text{Adsorption efficiency (\%)} = \frac{(C_i - C_f)}{C_i} \times 100$$

Where
Ci = Initial color absorption of dye
Cf = Final color absorption of dye after the treatment process was over.

3. Outcomes and discussion

The Granular carbon (ACS) prepared by H3PO4 acid activation of A. Donax exhibited notable characteristics.

3.1 Brunauer-Emmett-Teller tests (BET)

The surface area (SBET) of 1202 m²/g indicates a high surface area, implying a significant adsorption capacity and potential effectiveness in applications like water purification and gas filtration. This large surface area suggests a well-developed porous structure, leading to enhanced interaction with the surrounding environment and potentially faster reaction rates or more efficient contaminant removal.

3.2 Pore volume of the Granular carbon

The over-all pore volume stayed around to be 1.06 cm³/g, with average pore radius of 2.19 nm provides valuable insights into the pore structure of the Granular carbon. The high total pore volume (1.06 cm³/g) signifies a substantial capacity for storing or accommodating adsorbate molecules within the material's pores. Coupled with a mean pore radius of 2.19 nm, which falls within the mesoporous range (2-50 nm), it indicates that the pores are of a size capable of effectively capturing and retaining a variety of molecules, particularly those with larger dimensions. This suggests that the material would be effective in applications requiring the adsorption of relatively large molecules, and the high pore volume means that a considerable amount of those molecules can be retained.

3.3 Pore Volume Distribution & Total Oxygen Functional Groups

The pore volume distribution, showing a mix of 53% micro pores and 47% mesoporous, indicates that the Granular carbon possesses a versatile structure capable of adsorbing a wide range of molecular sizes. Microspores are effective for smaller molecules, while mesopores accommodate larger ones, enhancing the material's overall adsorption capacity and applicability. Furthermore, the presence of 2.3 mequiv/g of total oxygen functional groups suggests that the surface of the Granular carbon is chemically active.

Surface oxygen functionalities on substrates play a crucial role in adsorption by offering selective sites of interaction, particularly for polar molecules. In addition, these groups can provide the material with catalytic or ion-exchange activity, expanding the usefulness of the material beyond adsorption itself. Pore sizes have been categorized by the IUPAC as microspores less than 2 nanometres in diameter, mesoporous between 2 and 50 nanometres, and macrospores greater than 50 nanometres [13]. Granular carbons with predominantly a mesoporous structure can be prepared in a two-stage process. The first is treatment of Granular carbon with phosphoric acid, followed by a second activation. This method allows for the tailored design of pore structures with enhanced mesoporosity of interest for some applications [14].

3.4 Scanning electron microscopic image

The Scanning electron microscopic (SEM) photo of the Arundo Donax Granular carbon indicates a very porous structure, as evidenced by a large number of pores of different sizes spread out across the carbon matrix. Such a network of interconnecting voids and channels is typical of Granular carbons and goes a long way to explain their very large surface area. The occurrence of both smaller and larger pores indicates a mixture of micropores and mesopores, whereas the interconnectedness of some pores would allow molecular transport in the carbon structure. The rough surface texture also confirms the observation of extensive porosity.

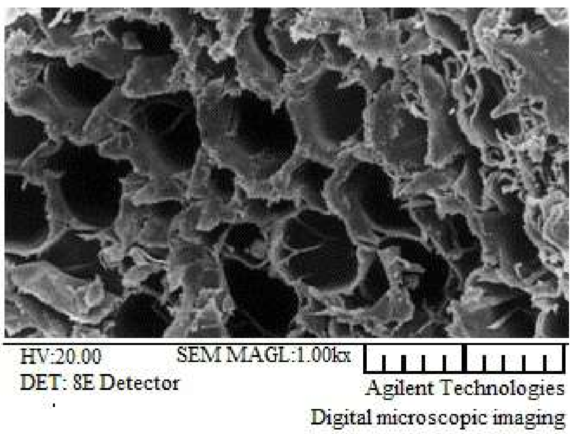

Figure 1 - SEM image shows the shape and surface features of the derived granular carbon

3.5 FTIR

FTIR spectrum of Arundo Donax Granular carbon verifies the presence of various specific efficient assemblies on the surface. A broad peak at 3562 cm^{-1} verifies the occurrence of O-H increase vibrations, either carboxylic acid or hydroxyl group. Peaks at 3026 cm^{-1} and 2873 cm^{-1} verify C-H stretching vibrations in aromatic and aliphatic groups, respectively. A comparatively weaker peak at 2447 cm^{-1} would be because of C≡N or adsorbed CO2. The peak at 2091 cm^{-1} would be due to alkanes or alkynes. The solid band at 1592 cm^{-1} would be due to stretching of C=C in the aromatic ring, and possibly also due to bending of N-H or extending of C=O. The resonance at 1437 cm-1 is due to O-H bending or O-H bending of carboxylic acids, and the resonance at 1106 cm-1 is due to the C-O extending of other oxygen groups. The 797 cm-1 resonance peak is due to C-H out-of-plane ring bending. The presence of these efficient assemblies, especially the oxygen containing efficient assemblies, is vital to the exterior chemistry of the Granular carbon and to its capacity for adsorption and interaction with molecules.

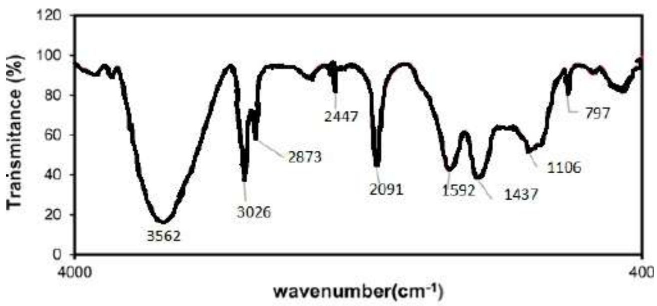

Figure 2 - The FTIR spectrum illustrates the composition of the prepared Granular carbon

3.6 Effect of amount of Granular carbon

The curve shows that in a solution, increasing the amount of Arundo Donax Granular carbon tends to cause a bigger decrease in concentration of color as well as in Chemical Oxygen Demand (COD). At the beginning, a fast increase of decrease in color concentration and COD occurs as more dosage of the Granular carbon is added from 0 to 0.4g. Thereafter, there is a drop in the speed of decrease. The plot indicates that the decrease in color concentration and COD could ultimately have a saturation level at higher doses, indicated by the plateauing of the curves. The steep rise at the beginning indicates that even low levels of Arundo Donax Granular carbon are very effective in eliminating color and COD. The gradual increase that follows means that although more adsorbent is still removing color and COD, the removal efficiency is decreasing. The potential saturation implies that

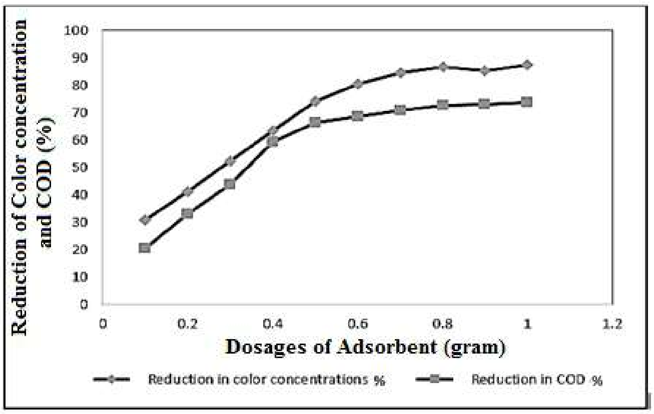

Figure 3 - The impact of adsorbent dosage on color and COD adsorption

there is a limit to the amount of color and COD that can be removed by adding more of this particular adsorbent. Generally, the curve shows that enhancing the dosage of Arundo Donax Granular carbon enhances color concentration and COD removal, but the efficiency of the Granular carbon diminishes with an increase in dosage.

4. Conclusion

This study efficiently demonstrated the ground work of Granular carbon preparation from Arundo donax via chemical galvanization by phosphoric acid, and its effectiveness for treating cotton textile dyeing wastewater. The synthesized Granular carbon exhibited a high surface area (1202 m^2/g) as well as high total pore volume (1.06 cm^3/g), of mixed micro- and mesoporous character, which was indicative of its large adsorption capacity. SEM analysis indicated the surface topography of the material to be extremely porous and FTIR spectroscopy identified the prevailing surface functional groups, oxygen-containing groups among them, for adsorption. Batch adsorption experiments confirmed the increase in the dosage of Arundo donax Granular carbon as an effective factor in color concentration and COD diminishment in the wastewater. Granular carbon performance was particularly striking at lower dosages, falling consecutively with increasing concentrations and thus showing a likely path to saturation. The study determines Arundo donax as a promising, eco-friendly, and cost-effective precursor to Granular carbon production, with a promising alternative for the treatment of textile wastewater. Other research can concentrate on maximizing the activation process and long-term performance and regeneration capacity of Granular carbon obtained from Arundo donax for industrial purposes.

References:

[1] Periyasamy, A. P. (2024). Recent Advances in the Remediation of Textile-Dye-Containing Wastewater: Prioritizing Human Health and Sustainable Wastewater Treatment. Sustainability, 16(2), 495. https://doi.org/10.3390/su16020495

[2] Xiaoxuan Wang; Jinming Jiang; Weijun Gao; Reviewing textile wastewater produced by industries: characteristics, environmental impacts, and treatment strategies; Water Science Technology (2022) 85 (7): 2076–2096. https://doi.org/10.2166/wst.2022.088

[3] Satyam, S., & Patra, S. (2024). Innovations and challenges in adsorption-based wastewater remediation: A comprehensive review. Heliyon, 10(9), e29573. https://doi.org/10.1016/j.heliyon.2024.e29573

[4] Y. Sudaryanto, S.B. Hartono, W. Irawaty, H. Hindarso, S. Ismadji,High surface area Granular carbon prepared from cassava peel by chemical activation, Bioresource Technology, Volume 97, Issue 5,2006, Pages 734-739, ISSN 0960-8524, https://doi.org/10.1016/j.biortech.2005.04.029

[5] Yulu Diao, W.P Walawender, L.T Fan, Granular carbons prepared from phosphoric acid activation of grain sorghum, Bioresource Technology, Volume 81, Issue 1, 2002, Pages 45-52, ISSN 0960-8524, https://doi.org/10.1016/S0960-8524(01)00100-6

[6] T Vernersson, P.R Bonelli, E.G Cerrella, A.L Cukierman, Arundo donax cane as a precursor for Granular carbons preparation by phosphoric acid activation, Bioresource Technology, Volume 83, Issue 2, 2002, Pages 95-104,ISSN 0960-8524, https://doi.org/10.1016/S0960-8524(01)00205-X

[7] Jia Guo, Aik Chong Lua, Textural and chemical properties of adsorbent prepared from palm shell by phosphoric acid activation, Materials Chemistry and Physics, Volume 80, Issue 1, 2003, Pages 114-119, ISSN 0254-0584, https://doi.org/10.1016/S0254-0584(02)00383-8

[8] M.S. Solum, R.J. Pugmire, M. Jagtoyen, F. Derbyshire, Evolution of carbon structure in chemically activated wood, Carbon, Volume 33, Issue 9, 1995, Pages 1247-1254, ISSN 0008-6223, https://doi.org/10.1016/0008-6223(95)00067-N

[9] Muthanna J. Ahmed, Potential of Arundo donax L. stems as renewable precursors for Granular carbons and utilization for wastewater treatments: Review, Journal of the Taiwan Institute of Chemical Engineers, Volume 63, 2016, Pages 336-343, ISSN 1876-1070, https://doi.org/10.1016/j.jtice.2016.03.030

[10] M. C. Basso and A. L. Cukierman; Arundo donax-Based Granular carbons for Aqueous-Phase Adsorption of Volatile Organic Compounds; Industrial & Engineering Chemistry Research 2005 44 (7), 2091-2100 DOI: 10.1021/ie0492294

[11] T Vernersson, P.R Bonelli, E.G Cerrella, A.L Cukierman, Arundo donax cane as a precursor for Granular carbons preparation by phosphoric acid activation, Bioresource Technology,Volume 83, Issue 2, 2002, Pages 95-104, ISSN 0960-8524, https://doi.org/10.1016/S0960-8524(01)00205-X

[12] A.A. Ahmad, B.H. Hameed,Reduction of COD and color of dyeing effluent from a cotton textile mill by adsorption onto bamboo-based Granular carbon, Journal of Hazardous Materials,Volume 172, Issues 2–3,2009,Pages 1538-1543,ISSN 0304-3894,https://doi.org/10.1016/j.jhazmat.2009.08.025.(https://www.sciencedirect. com/science/article /pii/S0304389409013041)

[13] IUPAC, IUPAC manual of symbols and terminology, Pure Appl. Chem. 31 (1972) 587

[14] Tzong-Horng Liou, Development of mesoporous structure and high adsorption capacity of biomass-based Granular carbon by phosphoric acid and zinc chloride activation, Chemical Engineering Journal, Volume 158, Issue 2, 2010, Pages 129-142, ISSN 1385-8947, https://doi.org/10.1016/j.cej.2009.12.016

[15] M. Molina-Sabio, F. Rodríguez-Reinoso, F. Caturla, M.J. Sellés, Development of porosity in combined phosphoric acid-carbon dioxide activation, Carbon, Volume 34, Issue 4, 1996, Pages 457-462, ISSN 0008-6223, https://doi.org/10.1016/0008-6223(95)00209-X

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Dimensional Properties of 3D-Woven Reinforced Composites for Light Weight Helmet - A Review

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Abstract:

The dimensional properties of 3D-woven reinforced fabric with composites play a crucial role in the development of lightweight helmets, offering enhanced mechanical performance and impact resistance. This study explores the geometric characteristics, thickness, areal density, and fiber volume fraction of 3D-woven fabric composites to evaluate their suitability for protective headgear. By analyzing the influence of weave architecture and composite matrix on the dimensional stability, the research aims to optimize the material's structural integrity while maintaining a low weight. The review collections involve factors influcing fabric thickness, yarn crimp, and resin impregnation, correlating them with mechanical properties such as tensile strength, flexural stiffness, and impact absorption. The findings highlight the potential of 3D-woven composites in improving helmet performance by balancing lightweight properties with superior protection.

Keywords: *3D-woven fabric, composites, dimensional properties, impact resistance, lightweight helmet, mechanical performance*

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1. Introduction

3D woven fabrics are advanced textile structures that incorporate multi-dimensional fiber reinforcement, setting them apart from traditional 2D fabrics. Unlike conventional fabrics, which have fibers aligned only in the X and Y directions, 3D woven fabrics add Z-direction reinforcement [1]. This added dimension significantly improves their through-thickness strength and resistance to impact. As a result, these fabrics are highly effective for high-performance composite applications, such as lightweight protective helmets, where durability, impact absorption, and dimensional stability are critical. 3D woven fabrics offer enhanced structural integrity by including fibers in three directions: X, Y, and Z [2]. This multi-dimensional reinforcement strengthens the bond between fabric layers, preventing delamination and increasing the fabric's overall strength. Unlike 2D fabrics, which are more prone to separation under stress, 3D woven fabrics maintain their form, making them highly effective for protective gear like helmets. Multi-directional Strength of inclusion of Z-binder fibers interlocks the fabric layers, this makes the material highly effective for applications requiring superior impact resistance, such as helmets. Improved Dimensional Stability of the interwoven Z-fibers prevent the layers from shifting, ensuring consistent mechanical properties throughout the fabric [3]. This dimensional stability results in uniform performance, even under high stress or repeated impact. Superior Energy Absorption is the integrated fiber structure absorbs and dissipates significant impact energy, reducing the force transferred to the wearer's head and minimizing the risk of injury. Near-net-shape Production in 3D weaving technology allows for the creation of preforms that closely match the final product's shape, reducing material waste, minimizing post-processing, and enhancing production efficiency [4]. Orthogonal Weaving method arranges fibers at right angles in the X, Y, and Z directions, forming a grid-like structure. It offers excellent resistance to delamination and high compressive strength, making it ideal for helmets and aerospace components. Angle-Interlock Weaving are technique interlocks fibers at specified angles (e.g., ±45° or ±30°), boosting shear resistance and energy dissipation. It is particularly effective for sports helmets requiring superior impact protection. Layer-to-Layer weaving in this process, multiple fabric layers are interconnected with Z-binder yarns, improving through-thickness strength and preventing fiber separation. This weaving method is widely used in military helmets to provide enhanced multi-impact protection [5].

The exceptional properties of 3D woven fabrics make them highly valuable in various industries, particularly for lightweight and impact-resistant applications like protective helmets. Their combination of high strength, durability, and reduced weight makes them ideal for reinforcing composite materials. Enhanced Impact Resistance in helmets made with 3D woven composites offer superior energy absorption [6]. By effectively dissipating impact forces, they reduce the pressure transferred to the wearer's head, lowering the risk of concussions and other head injuries. Weight Reduction are compared to traditional metal or composite helmets, those made with 3D woven fabrics are significantly lighter. This reduces neck strain and enhances comfort, especially for individuals wearing helmets for extended periods. Improved Durability in the Z-binder fibers prevent delamination and crack propagation, making the helmets more durable and reliable. This is particularly important in high-impact

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environments, such as military or construction settings [7]. Defense and Military Helmets in Ballistic helmets used by soldiers and law enforcement benefit from the high-impact resistance of 3D woven composites, typically made with aramid or hybrid carbon-aramid fibers. These helmets provide enhanced protection against shrapnel and bullets while maintaining a lightweight design. Aerospace Industry in aviation, 3D woven composites are used in lightweight, impact-resistant pilot helmets. Their superior thermal stability makes them ideal for withstanding extreme temperatures and conditions [8]. Automotive Industry In motorsports, racing helmets reinforced with 3D woven fabrics offer excellent crash resistance while remaining lightweight. Their fatigue resistance ensures long-lasting durability, even under repeated impact scenarios. Sports and Recreational Helmets for cycling, skiing, and snowboarding benefit from the impact resistance and reduced weight of 3D woven composites, improving both safety and performance. Architecture and Construction of industrial safety helmets made with 3D woven fabrics offer better protection against falling objects. When combined with flame-resistant fibers, they are also suitable for fire-prone environments [9].

The use of 3D woven fabrics in helmet production marks a significant technological advancement, offering improved protection and performance. Their lightweight nature reduces wearer fatigue without compromising safety. The exceptional impact resistance of 3D woven composites makes them particularly effective for multi-impact applications, such as military and sports helmets. Furthermore, the flexibility of 3D weaving technology allows manufacturers to create customized helmet shapes and geometries, optimizing the balance between strength, weight, and durability for specific applications [10].

1.1 Fabric Structure and Manufacture Methods

These are advanced textile structures where fibers interlace in three dimensions (X, Y, and Z directions), offering superior strength, stability, and impact resistance compared to traditional 2D fabrics. The addition of Z-binder yarns boosts through-thickness strength, reducing delamination risks, making them ideal for lightweight helmets.
These fabrics consist of:

Warp yarns (X-direction) running lengthwise, providing tensile strength and stability to withstand longitudinal forces, Weft yarns (Y-direction) interlacing perpendicularly with the warp, enhancing lateral stability and shear resistance-binder yarns (Z-direction) connecting the warp and weft layers, which reinforces through-thickness strength and prevents delamination under impact loads. The dimensional characteristics of 3D woven fabrics influence their performance. Thickness, governed by the number of layers and Z-binder density, determines impact resistance—thicker fabrics absorb more energy but may reduce flexibility. Porosity and permeability affect resin infiltration during composite fabrication, with controlled porosity ensuring even resin distribution [11]. The fibre volume fraction plays an important role in composites devlopment as it governs the properties of a composite. The usual fibre volume fraction ranges about 30% to 65% for composite application. The fiber volume fraction (FVF), representing the ratio of fiber volume to total composite volume, directly impacts stiffness and strength, though higher FVF can reduce flexibility.

1.2 Types of 3D-Woven Fabrics

3D woven fabrics are classified into four main types based on their weaving patterns, each offering distinct mechanical properties suited for different application [12].

1.3 Orthogonal 3D-Woven Fabrics

These fabrics consist of three orthogonal yarn sets—warp, weft, and Z-binder—forming a grid-like structure. They offer superior through-thickness strength, low shear tendency, and high resistance to delamination. Their excellent impact and ballistic resistance make them ideal for military helmets and aerospace components.

1.4 Angle-Interlock 3D-Woven Fabrics

In this design, Z-binder yarns are interlaced at specific angles (±45°, ±60°), boosting shear and torsional resistance. These fabrics are tougher and more flexible, providing better energy absorption. They are widely used in motorcycle helmets and crash-resistant protective gear.

1.5 Layer-to-Layer Woven Fabrics

This type consists of multiple warp and weft layers interconnected by Z-binder yarns. The thickness increases with the number of layers, offering excellent multi-directional strength and enhanced delamination resistance. It is commonly used in ballistic helmets and automotive impact panels due to its high energy absorption capacity.

1.6 Multi-layer 3D-Woven Fabrics

Similar to the layer-to-layer type but with more complex interlacing patterns, these fabrics often combine different fibers for hybrid properties. They provide exceptional impact and fatigue resistance, making them suitable for high-performance sports helmets and crash-resistant aerospace panels.

1.7 Manufacturing Techniques

Producing 3D woven fabrics involves specialized weaving methods, each influencing the fabric's strength, dimensional accuracy, and surface quality [13].

1.8 Jacquard Weaving

This technique uses computer-controlled looms for precise and intricate patterns, making it ideal for creating contoured helmet preforms. It offers design flexibility and minimizes material waste by producing near-net-shape preforms. This method is used for custom helmet shells and aerospace components.

1.9 Multi-axial Weaving

Here, fibers are interwoven at multiple angles (0°, ±45°, and 90°) in a single operation, resulting in balanced strength in all directions. This isotropic structure provides superior multi-axial impact resistance, making it ideal for multi-impact helmets used by motorcyclists and athletes, as well as aerospace panels.

1.10 Braided Weaving

In this method, fibers are continuously braided around a mandrel, creating seamless, tubular structures. Fiber braiding around a mandrel, creating seamless, curved structures for sports helmets.

1.11 Through-the-Thickness Weaving

Z-binders inserted through the thickness, boosting impact protection, used in ballistic helmets.

2. Material Properties

Fiber Materials for 3D-Woven Fabrics in Lightweight Helmets, the performance of 3D-woven reinforced fabric composites in lightweight helmets is largely determined by the fiber materials used. Each fiber type offers distinct advantages in terms of strength, weight, flexibility, and thermal resistance. The primary fibers used are carbon, aramid, glass, and hybrid fibers [14].

2.1 Carbon Fibers

Carbon fibers are widely recognized for their exceptional strength-to-weight ratio, making them a popular choice in high-performance helmets. Produced by carbonizing precursor materials (such as polyacrylonitrile, pitch, or rayon) at extremely high temperatures, these fibers develop a crystalline structure that delivers remarkable strength and stiffness. Carbon fibers reinforced polymers are known for their exceptional strength, resilience, and stiffness, which are primarily attributed to the high strength-to-weight and stiffness-to-weight ratios of carbon fibers. Carbon fiber helmets provide durability, comfort, and affordability [15].

2.2 Properties

High tensile strength can range from 3000 MPa to 6000 MPa, providing excellent resistance to stretching forces. Superior stiffness with a modulus of elasticity between 230 GPa and 600 GPa, carbon fibers offer outstanding rigidity [16]. Lightweight with a density of 1.6 to 2.0 g/cm³, they contribute to reducing helmet weight without compromising strength. Thermal stability of the low thermal expansion ensures dimensional consistency across varying temperatures. Fatigue resistance of the exceptional durability under cyclic loading makes them ideal for long-term use.

2.3 Applications

Carbon fibers are commonly used in military, racing, and cycling helmets due to their lightweight nature and high impact resistance. Their superior strength makes them particularly effective for ballistic protection and reducing helmet weight without sacrificing safety.

2.4 Aramid Fibers (Kevlar)

Aramid fibers, particularly Kevlar®, are known for their exceptional impact resistance, flexibility, and toughness. These synthetic fibers, composed of aromatic polyamide chains, offer superior energy absorption, making them ideal for protective headgear.

2.5 Properties

Excellent impact resistance of the tensile strength ranges from 2800 MPa to 3600 MPa, enabling effective energy absorption. Toughness and flexibility of the aramid fibers exhibit better elongation at break (3-4%) than carbon fibers, enhancing their ability to dissipate impact forces.
Low density of 1.44 to 1.45 g/cm³, they help minimize helmet weight [17].

Thermal stability can withstand temperatures up to 500°C without degrading, making them suitable for heat-resistant helmets. Abrasion resistance are highly resistant to cuts and wear, increasing the helmet's durability against sharp impacts.

2.6 Applications

Aramid fibers are extensively used in ballistic helmets for military and law enforcement due to their superior impact absorption. They are also incorporated into firefighter helmets, offering heat resistance and protection against flames. In motorcycle helmets, aramid fibers enhance shock absorption and reduce the risk of penetration.

2.7 Glass Fibers

Glass fibers offer moderate strength and thermal stability at a lower cost. With tensile strengths of 2000 MPa to 3500 MPa and a density of 2.5 to 2.6 g/cm³, they are heavier than carbon and aramid but provide good chemical and thermal resistance, withstanding temperatures up to 700°C.

2.8 Properties

Moderate tensile strength can range from 2000 MPa to 3500 MPa, making them effective for basic impact protection. High density of 2.5 to 2.6 g/cm³, glass fibers are heavier than carbon and aramid but still viable for certain helmet applications. Thermal resistance can endure temperatures up to 700°C, making them suitable for fire-resistant helmets [18]. Chemical resistance can provide excellent durability against moisture, UV radiation, and chemicals, ensuring longevity in outdoor environments. More affordable than carbon or aramid fibers, making them ideal for budget-conscious helmet production.

2.9 Applications

Glass fibers are commonly used in sports and recreational helmets, such as cycling and skating helmets, where moderate impact resistance is sufficient. Their thermal stability makes them suitable for firefighter helmets, while their affordability makes them a practical choice for industrial Helmets.

2.10 Hybrid Fibers

Hybrid fibers combine different fiber types (e.g., carbon + aramid) to optimize strength, flexibility, and impact resistance. This blend balances the stiffness of carbon with the toughness of aramid, improving shock absorption while keeping the helmet lightweight.

2.11 Properties

Enhanced impact resistance of the aramid and carbon fibers improves toughness and shock absorption. Optimized flexibility and strength of the fibers contribute stiffness, while aramid fibers add flexibility, creating a well-balanced composite [19]. Weight efficiency can hybridization reduces the overall weight while maintaining superior protection.

2.12 Applications

Hybrid fibers are increasingly used in high-performance sports helmets, including cycling and racing helmets, due to their lightweight and high-impact protection. They are also employed in military and tactical helmets, offering a combination of ballistic resistance and flexibility. In crash helmets, hybrid fabrics improve energy dissipation, reducing the risk of severe head injuries.

2.13 Impact of Fiber Choice on Fabric Properties

The selection of fibers significantly affects the dimensional and mechanical properties of 3D-woven fabric composites, influencing helmet performance. Energy absorption: Aramid fibers excel in dissipating impact forces, while hybrid fibers offer a balanced combination of strength and toughness. Thermal resistance: Carbon provides superior heat stability, aramid resists flames, and glass fibers offer thermal insulation at a lower cost [20]. Hybrid fibers optimize both strength and flexibility, delivering balanced protection. Glass fibers offer excellent thermal insulation but add more weight. Aramid fibers are highly resistant to heat and flames, making them ideal for firefighting Helmets.

3 Mechanical and Physical Properties of 3D Woven Fabrics

The mechanical and physical properties of 3D-woven fabrics are influenced by fiber type, weave pattern, and fiber volume fraction. Determines the fabric's ability to withstand stretching forces. Carbon fibers provide the highest tensile strength, making them ideal for high-impact helmets [21]. Represents the fabric's resistance to bending forces. Hybrid fibers exhibit superior flexural properties, balancing stiffness and flexibility.

3.1 Design and Optimization of 3D Woven Fabrics

Enhancing the performance of lightweight helmets relies heavily on the design and optimization of 3D woven fabrics. By fine-tuning factors such as yarn density, fabric architecture, and fiber volume fraction (FVF), helmets can achieve improved impact resistance, flexibility, and weight efficiency [22]. Computational modeling further refines these properties by predicting mechanical behavior and optimizing performance.

3.2 Design Parameters

Increasing the density of warp and weft yarns strengthens the fabric's in-plane performance, making it more resistant to tearing. However, excessive density reduces porosity, making resin infiltration difficult during composite molding. Z-binder yarns, which provide reinforcement through the fabric's thickness, improve impact resistance and prevent delamination [23]. Yet, overusing Z-binders can add unnecessary weight and reduce flexibility. Maintaining moderate Z-binder density with balanced warp-weft distribution offers the ideal trade-off between strength, flexibility, and weight.

3.3 Weaving Patterns and Binder Orientation

Orthogonal Weave of yarns intersect at 0° and 90°, creating a grid-like structure. This configuration enhances stiffness and dimensional stability, making it suitable for helmets requiring high resistance to deformation [24]. Angle-Interlock Weave of yarns interlock at ±45°, boosting multi-directional reinforcement and enhancing energy absorption under impact—ideal for helmets exposed to variable loads. Hybrid Weave is a combination of orthogonal and angle-interlock patterns, offering superior strength and flexibility—perfect for advanced protective helmets.

3.4 Fabric Thickness and Layering

The number of fabric layers directly affects the helmet's weight and impact resistance, because the weight is added Single-layer fabrics are lightweight and flexible but offer limited protection, making them suitable for low-impact helmets like those used for cycling. Double-layer fabrics strike the perfect balance between weight and protection. They provide better resistance to impact and tensile forces, making them ideal for motorcycle and sports helmets [25]. Multi-layer fabrics deliver maximum protection but add weight, making them more suitable for military or ballistic helmets. For most lightweight helmets, double-layer fabrics offer the best compromise between protection and weight.

3.5 Fiber Volume Fraction (FVF)

The FVF, which measures the fiber-to-resin ratio, directly impacts the helmet's strength, stiffness, and weight. High FVF (>55%) boosts strength and stiffness, making the helmet lighter due to lower resin content. However, it may reduce damage tolerance due to increased brittleness. Low FVF (<40%) adds flexibility and toughness but makes the helmet heavier due to higher resin content [26]. A moderate FVF of 45–55% offers the best balance between strength, flexibility, and weight efficiency.

3.6 Leveraging Computational Modeling for Optimization

To further enhance performance, computational modeling allows for accurate simulation and optimization of the helmet's properties before physical production. Finite Element Analysis (FEA) predicts how the fabric responds to forces like tension, compression, and impact. It helps detect weak points and refine the design by optimizing yarn density, layer thickness, and Z-binder placement [27]. Ulti-Scale Modeling can approach analyzes both the fabric structure and the fiber-matrix interaction at a microscopic level, helping improve bonding strength and durability.

3.7 Mechanical Performance

This section explores the mechanical performance of 3D-woven reinforced fabric composites used in lightweight helmets, focusing on their tensile and compressive properties, shear and bending behavior, and common failure mechanisms.

3.8 Tensile and Compressive Properties

Tensile properties define the material's ability to withstand stretching forces under uniaxial tension, which is essential for helmet performance against sharp impacts or penetrating objects. Tensile properties reflect the fabric's resistance to stretching forces, which is essential for preventing helmet damage during sharp impacts. 3D-woven fabrics offer higher tensile strength than traditional 2D fabrics due to Z-binder yarns that prevent fiber pull-out and improve inter-laminar bonding [27]. A greater tensile modulus reduces deformation under stress, enhancing the helmet's protective capabilities. Fabrics with moderate elongation at break absorb more energy before failing, which improves their shock-absorbing capacity.

Compressive properties determine the fabric's resistance to crushing forces, which is vital for withstanding blunt impacts. The Z-binder yarns enhance out-of-plane compressive strength, making the fabric more resistant to crushing and indentation. A higher compressive modulus ensures the helmet maintains its shape under pressure, preventing excessive deformation.

3.9 Shear and Bending Behavior

Shear properties indicate the fabric's ability to resist sliding forces, which is critical for protection against glancing or angular impacts. The angle-interlock weave pattern in 3D-woven fabrics improves shear strength by preventing layer slippage. Z-binders further enhance inter-laminar shear resistance, reducing the risk of delamination and improving the helmet's structural integrity.

Bending properties describe the fabric's resistance to deformation under bending forces, which is essential for maintaining the helmet's shape during impacts [28]. Higher flexural strength reduces bending deformation, while an increased flexural modulus ensures the fabric retains its structural stability. Z-binder yarns enhance out-of-plane stiffness, making the fabric more resilient to bending forces and improving its protective performance.

3.10 Failure Mechanisms

Recognizing the common failure modes of 3D-woven composites is essential for enhancing helmet durability and reliability [29].

3.11 Delamination

This occurs when fabric layers separate due to weak bonding or repeated impacts, reducing the helmet's load-bearing capacity. Increasing Z-binder density and using tougher resin systems reduces delamination risks.

3.12 Fiber Breakage

When the tensile or compressive stress exceeds the fabric's limit, individual fibers snap, weakening the structure. Using high-strength fibers, such as aramid or carbon, and hybrid reinforcements helps prevent fiber breakage.

3.13 Matrix Cracking

Micro-cracks in the resin matrix form under repeated impacts or cyclic loading, which weakens the composite over time. Using toughened resins and adding nanoparticles improves crack resistance and increases durability.

3.14 Applications of 3D Woven Fabrics

3D woven fabrics are transforming various industries with their exceptional strength, lightweight properties, and dimensional stability [30]. Their unique structure makes them highly suitable for applications requiring durability, flexibility, and impact resistance.

4 Aerospace and Automotive Applications

In aerospace, 3D woven composites are used in aircraft structural parts like wing panels, fuselage sections, and turbine blades. Their high impact resistance and fatigue tolerance enhance durability while reducing overall weight, improving fuel efficiency. In space missions, these fabrics are employed in thermal protection systems, shielding, and support structures due to their stability in extreme environments. They are also used in heat shields for re-entry vehicles, providing excellent thermal resistance.

In the automotive sector, 3D woven fabrics are applied in crashworthy components, such as bumpers and impact-absorbing panels, boosting vehicle safety during collisions. Military and security vehicles utilize bulletproof panels made from 3D woven Kevlar or hybrid composites, offering superior protection [31]. Additionally, these fabrics are used in lightweight body panels, reducing vehicle weight without compromising strength, enhancing fuel efficiency and performance.

4.1 Medical and Biomedical Applications

3D woven fabrics are gaining traction in the medical field for their strength, biocompatibility, and adaptability. In tissue engineering, biodegradable polymers like PLGA and PLA are woven into scaffolds that promote cell growth and gradually degrade as new tissue forms.

In prosthetics, 3D woven carbon fiber reinforcement enhances strength and flexibility, improving durability and wearer comfort. For wound care, 3D woven fabric-based dressings offer better fluid management and mechanical protection, reducing infection risks and accelerating healing [32]. Surgical meshes and sutures made from 3D woven polymers are also widely used for their flexibility and durability, promoting better tissue integration and recovery.

4.2 Sports and Protective Gear

Due to their impact resistance and lightweight properties, 3D woven fabrics are extensively used in protective and sports gear. Helmets for sports, motorcycling, cycling, and military applications incorporate these fabrics to enhance impact absorption, reducing the risk of head injuries.

In personal protection, bulletproof vests made from 3D woven aramid composites offer high penetration resistance and durability, making them ideal for military and law enforcement [33]. Sports equipment, such as racquets, hockey sticks, and baseball bats, is often reinforced with 3D woven carbon fibers, improving stiffness and durability without adding extra weight.

4.3 Architecture and Construction

In the construction industry, 3D woven fabrics are gaining popularity for their strength, flexibility, and weather resistance3D woven fiberglass grids are used to reinforce concrete structures, enhancing crack resistance and load-bearing capacity. This results in more durable and earthquake-resistant buildings [34]. Lightweight 3D woven composites are increasingly used in building facades and roofing panels, offering better thermal insulation and weather protection. For disaster relief and temporary setups, such as tents and pavilions, 3D woven fabrics provide high strength and flexibility, making them easy to deploy and reliable in challenging conditions.

4.4 Challenges and Limitations of 3D-Woven Reinforced Fabrics

Despite the significant potential of 3D-woven reinforced fabrics, their widespread application in lightweight helmets faces several challenges, particularly in terms of manufacturing, durability, and scalability [35]. These limitations can hinder their commercial viability and mass production.

4.5 Manufacturing Challenges

Producing 3D-woven fabrics requires intricate weaving techniques and precise control over yarn alignment and binder placement. However, this process introduces several difficulties.

4.6 Fiber Placement Accuracy

Achieving consistent alignment of fibers in the X, Y, and Z directions is critical for ensuring uniform mechanical properties. Misalignment, particularly in the Z-binder, can weaken through-thickness strength and increase the risk of delamination.

4.7 Thickness and Uniformity Issues

During weaving, variations in yarn tension often lead to inconsistent fabric thickness, affecting the final product's weight and performance [35]. Irregular fibres volume fraction (FVF) and uneven resin distribution during composite processing further compromise mechanical consistency.

4.8 Resin Infiltration and Void Formation

The complex 3D architecture makes it difficult for resin to fully infiltrate the fabric layers, increasing the likelihood of voids or dry spots. This reduces the helmet's overall strength and impact resistance [37]. Advanced techniques like vacuum-assisted resin transfer molding (VARTM) or resin film infusion are necessary to address this issue.

4.9 Production Complexity and Costs

Manufacturing 3D-woven fabrics requires specialized multi-axial looms and advanced programming, which raises equipment costs. Additionally, slow production speeds and frequent machine calibration reduce efficiency, making large-scale production expensive and time-consuming.

4.10 Durability and Long-Term Performance

Although 3D-woven composites offer superior mechanical properties, their durability over time is influenced by wear, fatigue, and environmental exposure:

5 Fatigue and Wear Resistance

Helmets experience repeated impacts, which can gradually weaken the fabric. Micro-cracks and fiber-matrix debonding reduce impact resistance [38]. Z-binder fibers may loosen under continuous stress, diminishing dimensional stability and increasing delamination risks.

5.1 Thermal and UV Degradation

Prolonged exposure to high temperatures or UV radiation can degrade the resin matrix, weakening the composite. While glass and aramid fibers offer better heat resistance, carbon composites are prone to oxidation, reducing their structural integrity [39]. Helmets used in high-heat environments require thermally resistant coatings to prevent degradation.

5.2 Moisture Absorption

Some fibers, like aramid, are susceptible to moisture absorption, which reduces their strength and stiffness over time [40]. Moisture also weakens the fiber-resin bond, increasing the risk of premature failure.

5.3 Cost and Scalability Issues

The high production costs and scalability challenges of 3D-woven composites hinder their adoption for commercial helmet manufacturing:

5.4 High Production Costs

The fabrication process involves expensive machinery, advanced CAD programming, and skilled labor, driving up production expenses. The use of premium fibers (e.g., carbon or aramid) further increases the final product's cost.

5.5 Limited Scalability

Mass production is difficult due to the slow manufacturing speed and complex fabrication requirements. Scaling up requires substantial investment in automation and advanced weaving technology, making it cost-prohibitive.

5.6 Quality Control Challenges

Maintaining consistent quality in large-scale production is difficult, as variations in fabric thickness and fiber misalignment can reduce performance. While 3D-woven reinforced fabrics offer promising advantages for lightweight helmets, addressing the manufacturing, durability, and scalability challenges is crucial for their broader adoption [41]. Innovations in production efficiency, resin infiltration techniques, and material durability will be essential for making these composites commercially viable and cost-effective.

5.7 Recent Advancements in 3D-Woven Reinforced Fabrics

In recent years, the field of 3D-woven reinforced fabrics has experienced remarkable advancements, particularly in protective gear, aerospace, and biomedical applications [42]. These innovations focus on improving performance, durability, and sustainability, making 3D-woven composites more effective and versatile.

6 Innovations in 3D Weaving Techniques

6.1 Automated 3D Weaving Machines

The introduction of automated and robotic weaving systems has significantly refined the traditional weaving process. Automated jacquard looms and multi-axial weaving machines offer precise fiber placement, reducing inconsistencies and enhancing fabric performance [43]. These systems also enable faster production by weaving complex 3D patterns at higher speeds, making large-scale manufacturing more feasible. Additionally, advanced weaving technology allows for customized preforms that match helmet geometries, minimizing material waste and reducing the need for post-processing.

6.2 Multi-Scale Weaving

Emerging techniques now incorporate both micro- and nano-scale fibers into 3D-woven structures, boosting mechanical strength and resilience [44]. By blending macro and micro-fiber layers, the resulting composites exhibit greater toughness, damage resistance, and flexibility—ideal for protective helmets.

6.3 Advanced Fiber Placement

New weaving techniques allow for variable fiber angles (e.g., ±30°, ±45°), which optimize shear strength and impact resistance. Additionally, hybrid approaches combining braiding and weaving techniques within the same structure enhance torsional stability and energy absorption, making the helmets more effective under stress [45].

6.4 New Materials and Fiber Developments

Material innovations have significantly enhanced the mechanical, thermal, and impact properties of 3D-woven composites.

6.5 High-Performance Fibers

Ultra-High Molecular Weight Polyethylene (UHMWPE) is known for its exceptional strength-to-weight ratio, this fibre offers outstanding impact resistance, making it ideal for ballistic helmets. Polybenzoxazole (PBO) Fibers is recognized for their high modulus, minimal stretch, and superior thermal resistance, PBO fibers are widely used in military helmets [46]. Basalt Fibers are gaining attention as a sustainable alternative to glass fibers, basalt offers excellent thermal and chemical resistance along with strong impact properties, making it suitable for protective applications.

6.6 Nanofiber and Graphene Integration

Carbon Nanotubes (CNTs) are added to resin matrices, CNTs significantly enhance tensile strength and energy dissipation, making the composite more shock-absorbent—an ideal characteristic for helmets [47]. Graphene Coatings can incorporate graphene into 3D-woven fabrics boosts thermal conductivity and provides electromagnetic shielding, creating multi-functional helmets with impact protection and EM resistance.

6.7 Bio-Based and Sustainable Fibers

PLA (Polylactic Acid) Fibers can derived from renewable sources, PLA fibers are eco-friendly and biodegradable, making them suitable for lightweight sports helmets. Natural Fiber Composites like Flax, hemp, and bamboo fibers are being increasingly used in 3D-woven composites due to their sustainability and strong mechanical properties [48]. Enhanced Fabric Performance through Hybridization Combining different fiber types or material forms through hybridization has proven effective in optimizing the performance of 3D-woven fabrics.

6.8 Hybrid Fiber Combinations

Carbon-Aramid Hybrids of carbon fibers add stiffness and strength, while aramid fibers improve impact resistance and toughness. This combination creates a balanced composite, making it ideal for ballistic helmets [49]. Glass-Kevlar Hybrids of blending glass and Kevlar fibers offers a cost-effective solution for helmet production. This hybrid provides moderate strength with enhanced energy absorption capabilities.

6.9 Multi-Material Integration

Metallic and Ceramic Inclusions can reinforce 3D-woven fabrics with nano-ceramic particles increases their abrasion resistance and impact toughness, making them suitable for military and riot helmets [50]. Resin Hybridization are the combining thermoset and thermoplastic resins boosts damage tolerance and thermal stability, resulting in more durable helmet shells.

7 Conclusion

3D-woven reinforced fabrics have proven to be highly effective for lightweight protective helmets due to their superior strength, flexibility, and impact resistance. The inclusion of Z-direction binders prevents delamination, enhancing durability and overall fabric integrity. Advances in material science and weaving technology have significantly improved the strength-to-weight ratio, making helmets both lighter and more resilient. Additionally, hybrid fabric systems further enhance impact absorption without adding extra weight, boosting safety and performance.

Looking ahead, the future of 3D-woven fabrics in helmet design is promising. Smart helmets with embedded sensors will enable real-time performance monitoring, while self-healing materials and bio-inspired weaving techniques will extend durability. Innovations such as smart helmets with embedded sensors for real-time monitoring, self-healing materials, and bio-inspired weaving techniques are expected to enhance durability and performance. The shift towards sustainable fibers and closed-loop recycling will reduce the environmental impact of helmet production. Additionally, AI-driven simulations and machine learning will optimize weaving patterns, enhancing performance while minimizing material usage.

References

[1] Simoes, S. (2024). High-performance advanced composites in multifunctional material design: state of the art, challenges, and future directions. Materials, 17(23), 5997

[2] Wielhorski, Y., Mendoza, A., Rubino, M., & Roux, S. (2022). Numerical modeling of 3D woven composite reinforcements: A review. Composites Part A: Applied Science and Manufacturing, 154, 106729

[3] Abtew, M. A. (2024). A comprehensive review on advancements, innovations and applications of 3D warp interlock fabrics and its composite materials. Composites Part B: Engineering, 111395

[4] Abtew, M. A. (2024). A comprehensive review on advancements, innovations and applications of 3D warp interlock fabrics and its composite materials. Composites Part B: Engineering, 111395

[5] Hu, J. (2008). 3D Fibre Reinforced Polymer Composites. Elsevier Science

[6] Ko, F. K., & Wan, H. (2014). Introduction to 3D Weaving Technology and Composite Applications. Woodhead Publishing

[7] Mathews, F. L., & Rawlings, R. D. (1999). Composite Materials: Engineering and Science. Chapman & Hall

[8] Hearle, J. W. S., & Morton, W. E. (2008). Physical Properties of Textile Fibres. Elsevier

[9] Crawford, R. J., & Gibson, G. (2011). Plastics Engineering. Butterworth-Heinemann

[10] Wang, Y., & Xu, B. (2019). “Mechanical properties and failure mechanisms of 3D woven fabric composites.” Composites Part A: Applied Science and Manufacturing, 124, 105-113

[11] Zhang, D., et al. (2020). “Dimensional stability and impact resistance of 3D woven composites.” Journal of Composite Materials, 54(11), 1539-1554

[12] Perera, Y. S., Muwanwella, R. M. H. W., Fernando, P. R., Fernando, S. K., & Jayawardana, T. S. S. (2021). Evolution of 3D weaving and 3D woven fabric structures. Fashion and Textiles, 8, 1-31

[13] El-Dessouky, H. M., & Saleh, M. N. (2018). 3D woven composites: from weaving to manufacturing. Recent Developments in the Field of Carbon Fibers, 51

[14] Badawi, M. S. S. S. (2008). Development of the weaving machine and 3D woven spacer fabric structures for lightweight composites materials

[15] Tushe, N. A., Mahmud, S. T., Islam, N., Mostofa, G., Tuli, N. T., & Rashid, A. B. (2025). Design and Development of Motorcycle Helmet Using Carbon Fiber Reinforced Epoxy Resin Hybrid Composite. Results in Materials, 100716.

[16] Bhatt, P., & Goe, A. (2017). Carbon fibres: production, properties and potential use. Mater. Sci. Res. India, 14(1), 52-57

[17] Gore, P. M., & Kandasubramanian, B. (2018). Functionalized aramid fibers and composites for protective applications: a review. Industrial & Engineering Chemistry Research, 57(49), 16537-16563

[18] Agarwal, B. D., Broutman, L. J., & Chandrashekhara, K. (2017). Analysis and performance of fiber composites. John Wiley & Sons

[19] Bhat, G. (Ed.). (2016). Structure and properties of high-performance fibers. Woodhead Publishing

[20] Du, S., et al. (2021). “Finite element modeling of the impact behavior of 3D woven helmets.” Composite Structures, 258, 113170

[21] Umer, R., Alhussein, H., Zhou, J., & Cantwell, W. J. (2017). The mechanical properties of 3D woven composites. Journal of Composite Materials, 51(12), 1703-1716

[22] Tuli, N. T., Khatun, S., & Rashid, A. B. (2024). Unlocking the future of precision manufacturing: A comprehensive exploration of 3D printing with fiber-reinforced composites in aerospace, automotive, medical, and consumer industries. Heliyon, 10(5)

[23] Potluri, P., & Thammandra, V. (2007). “Influence of 3D fabric architecture on impact damage tolerance of composites.” Composites Part B: Engineering, 38(7-8), 929-936

[24] Chen, X., & Yang, C. (2022). "Impact resistance of 3D orthogonal woven carbon/epoxy composites." Materials & Design, 218, 110689
[25] Gu, B. (2013). "Ballistic penetration resistance of 3D angle-interlock woven aramid fabric reinforced composites." Composites Part B: Engineering, 45(1), 680-688
[26] Hakim, I. A. (2017). Non-destructive evaluation measurements and fracture effects in carbon/epoxy laminates containing porosity (Doctoral dissertation, University of Dayton)
[27] Sowrov, K. (2022). Processing and manufacturing mechanics of 3D woven composites influenced by Z-binder architecture. The University of Manchester (United Kingdom)
[28] Jabbar, M., Nawab, Y., Karahan, M., Ashraf, M., & Hussain, T. (2020). Mechanical response of novel 3D woven flax composites with variation in Z yarn binding. Journal of Natural Fibers
[29] Ma, Y., et al. (2018). "Experimental study on energy absorption properties of 3D woven composite helmets." Materials Science and Engineering: A, 735, 113-125
[30] Bilisik, K., Karaduman, N. S., & Bilisik, N. E. (2016). 3D fabrics for technical textile applications. Non-woven Fabrics, 1-15
[31] Zhu, Y., & Yu, W. (2017). "Innovations in 3D weaving techniques for helmet protection." Proceedings of the International Conference on Composite Materials (ICCM), 456-462
[32] Luo, Y., et al. (2019). "Multi-scale modeling of 3D woven fabric reinforced composites for crash helmets." Proceedings of the American Society for Composites
[33] Al-Qureshi, H. (2003). "Composites and lightweight armor protection." Proceedings of the International Symposium on Impact Engineering, 178-185
[34] Mallick, P. K. (2007). "Composites in lightweight helmets: A review." Journal of Materials Science, 42(15), 5516-5530
[35] Jia, Y., et al. (2020). "Recent advancements in 3D woven fabrics for impact protection." Advanced Materials Research, 1123, 98-105
[36] Dejene, B. K., & Gudayu, A. D. (2024). Exploring the potential of 3D woven and knitted spacer fabrics in technical textiles: A critical review. Journal of Industrial Textiles, 54, 15280837241253614
[37] Mahmood, A. S. (2016). Processing-performance relationships for fibre-reinforced composites
[38] Liang, Y., Chen, X., & Soutis, C. (2022). Review on manufacture of military composite helmet. Applied Composite Materials, 29(1), 305-323
[39] Harle, S. M. (2024, February). Durability and long-term performance of fiber reinforced polymer (FRP) composites: A review. In Structures (Vol. 60, p. 105881). Elsevier
[40] Deng, K., Cheng, H., Suo, H., Liang, B., Li, Y., & Zhang, K. (2022). Aging damage mechanism and mechanical properties degradation of 3D orthogonal woven thermoset composites subjected to cyclic hygrothermal environment. Engineering Failure Analysis, 140, 106629
[41] Budwal, N. (2023). Developing design and manufacturing capability towards cost-effective textile reinforced and complex geometry composite structures (Doctoral dissertation, University of Bristol)
[42] Cheung, H. Y., & Zhang, X. (2019). "Hybridized 3D woven composites: Performance and future prospects." Materials Today Communications, 21, 100721
[43] ASTM D3039/D3039M-17. (2017). Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials
[44] ISO 6603-2:2018. Plastics—Determination of multi-axial impact behavior of rigid plastics
[48] NIJ Standard-0101.06. Ballistic Resistance of Personal Body Armor
[46] Bai, J., Wang, H., Wang, Y., & Hu, J. (2018). Preparation of poly-p-phenylenebenzobisoxazole (PBO) fibrillated pulp and dielectric properties of carbon fiber/PBO wet-laid nonwoven fabric. Textile Research Journal, 88(13), 1559-1568
[47] Su, C., Wang, X., Ding, L., & Yu, P. (2021). Enhancement of mechanical behavior of resin matrices and fiber reinforced polymer composites by incorporation of multi-wall carbon nanotubes. Polymer Testing, 96, 107077
[48] Hamelin, N., et al. (2020). "Recyclability of 3D woven composites in protective gear applications." Journal of Cleaner Production, 275, 123456
[49] Montazerian, H., & Shahriari, M. (2021). "Eco-friendly composites for helmet protection." Composites Science and Technology, 210, 108787
[50] Technical Textiles International. (2023). "3D woven fabrics: The future of impact protection."

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Handmade Rugs: Pathways to Ethical Certification and Global Compliance

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Abstract:

This study explores the growing importance of adopting ethical and sustainable standards in the rug-manufacturing sector. It highlights how certifications not only protect workers' rights and ensure environmental stewardship but also serve as strategic tools for enhancing brand reputation and gaining consumer trust.

Focusing on the Indian handmade carpet industry, the article traces the historical efforts to improve labor practices and introduces key certifications such as SEDEX, STeP, SA8000, CTPAT, GRS, GoodWeave, and CARE & FAIR. These certifications play a pivotal role in safeguarding the industry's legacy while addressing modern challenges related to ethical production.

As the industry evolves, the adoption of these certifications will be essential in driving positive change, preserving cultural heritage, and securing long-term success. This paper aims to provide a comprehensive overview of the standards that are shaping the future of ethical and sustainable rug production, emphasizing their significance as both a moral and business imperative.

Keywords: *Ethical Certification, GoodWeave, Handmade Rugs, Indian Carpet Industry, Supply Chain Transparency, Sustainable Production*

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1. Introduction

In today's interconnected global marketplace, the demand for transparency and accountability from businesses has reached unprecedented levels. Consumers, investors, and regulators are increasingly scrutinizing companies, placing a premium on ethical practices and sustainability throughout the supply chain. To thrive in this environment, businesses must prioritize responsible sourcing, fair labor practices, and environmental stewardship. These elements are no longer mere compliance requirements but strategic imperatives for long-term success.

Implementing robust ethical and sustainability standards allows companies to demonstrate their commitment to these principles, mitigate risks, and build trust with stakeholders. By adhering to certifications and audit standards, businesses not only safeguard their brand reputation but also contribute to a more equitable and sustainable world [1].

The Indian handmade carpet industry is a prime example of a sector where ethical standards and sustainability are paramount. This labor-intensive industry employs over 2 million workers and artisans, many of whom are women in rural areas. It plays a crucial role in supporting the livelihoods of individuals from economically weaker sections of society, providing additional and alternative occupations, including opportunities for farmers and others to work from home [2].

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2. Advancing Ethical and Sustainable Practices

The journey towards better labor practices in the Indian carpet industry began in the 1990s with initiatives to eliminate child labor. Organizations like Care & Fair and GoodWeave emerged during this period, focusing on eradicating child labor and promoting fair compensation for weavers [3, 4].

Over time, the influence of Western industry standards extended to India, leading to significant improvements in working conditions and environmental performance throughout the supply chain. This evolution gave rise to organizations that set and monitor these standards, such as SEDEX and STeP certification. Beyond addressing human rights concerns, the industry has embraced product certification to promote ethical and sustainable practices, including recycling. Certifications provide consumers with a clear indication of ethical sourcing, fostering trust and influencing purchasing decisions [5, 6].

These certifications ensure that the entire supply chain adheres to the highest ethical standards, enhancing transparency and preventing the exploitation of resources and human rights.

3. The Growing Importance of Certifications in the Rug Industry

As consumers become more aware of the ethical implications of their purchases, certifications have become a vital tool for rug manufacturers and exporters to demonstrate their commitment to responsible practices [1, 7]. These certifications not only address labor conditions but also cover environmental impacts, material sourcing, and overall sustainability. By obtaining relevant certifications, companies can differentiate themselves in a competitive market, appealing to the growing segment of eco-conscious and ethically minded consumers.

Recent studies further underscore the tangible benefits of adopting recognized certifications in the handmade carpet industry:

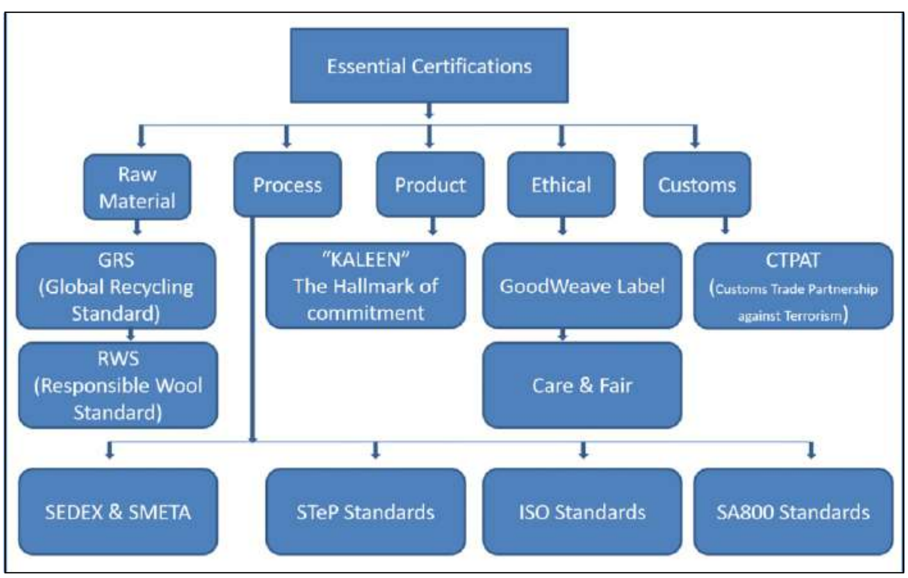
- Export-Import Bank of India found that GoodWeave - certified carpets commanded a 5–8% price premium in North American and European markets, driven by consumer preference for ethically produced goods [8].
- According to the Textile Exchange Market Report, 78% of surveyed luxury home goods consumers expressed greater trust in handmade rugs with recognized ethical certifications [9].
- An India Brand Equity Foundation analysis revealed that exporters with ethical certifications had a 12% higher international buyer retention rate compared to uncertified exporters [10].
- A Harvard Business School Case Study observed that CARE & FAIR-certified producers saw 15% higher repeat business from international retailers [11].
- Nielsen Consumer Insights reported that 64% of luxury interior design consumers would pay a 10–15% premium for carpets with verified ethical production certifications [12].
- Carpet Export Promotion Council of India data showed manufacturers with multiple certifications (e.g. GoodWeave, CARE & FAIR, SEDEX) reported 22% higher average annual export growth [13].
- The McKinsey & Company Luxury Goods Report noted that 71% of high-end retailers require ethical certification, particularly emphasizing child-labor-free assurance [14].

Table 1 presents a consolidated overview of the most relevant ethical and sustainability certifications affecting the handmade rug industry. Each certification has categorized based on its primary focus area such as recycled content, social accountability, animal welfare, or trade security alongside its geographic scope & governing body.

Table 1: Overview of Major Compliance Certifications

Certification	Focus Area	Scope	Governing Body
GRS	Recycled Content	Global	Textile Exchange, Austin, TX, USA
RWS	Animal Welfare & Land Management	Global	Textile Exchange, Austin, TX, USA
SEDEX	Ethical Supply Chain	Global	SEDEX Global, London, UK
SA8000	Social Accountability	Global	Social Accountability International (SAI), New York, NY, USA
GoodWeave	Child Labor Elimination	South Asia Focus	GoodWeave International, Washington, DC, USA
CARE & FAIR	Weaver Welfare	India & Pakistan	CARE & FAIR, Friedrichsdorf, Germany
CTPAT	Trade Security	USA-centric	U.S. Customs and Border Protection (US CBP), Washington, DC, USA

Figure 1 classifies the structure of essential certifications for the handmade rug industry into various categories.



3.1 Category: Raw Material

3.1.1. The Global Recycled Standard [GRS]

The Global Recycled Standard (GRS) is an internationally recognized certification system developed to verify the presence and authenticity of recycled materials in products. For manufacturers in the handmade rug industry, GRS offers a robust framework to demonstrate their commitment to environmental responsibility, ethical practices, and full transparency across the supply chain. By adhering to GRS guidelines, rug producers can meet growing consumer and regulatory demands for sustainability and accountability [15].

The certification process itself is rigorous and involves a comprehensive audit conducted by an approved third-party body. Manufacturers must demonstrate verified sourcing of recycled materials, including clear documentation of their origin. A secure chain of custody must be maintained, ensuring that the recycled content is consistently tracked throughout the entire production process. Additionally, companies must comply with established social and environmental standards, which cover worker safety, fair wages, and responsible environmental practices. The use of restricted or hazardous substances has controlled strictly under GRS chemical management protocols, requiring manufacturers to adhere to defined substance restrictions to ensure product safety and environmental protection.

Securing GRS certification brings a range of strategic benefits for rug manufacturers. It enhances brand reputation by visibly aligning the business with sustainable and ethical practices. In an increasingly eco-conscious marketplace, GRS also opens access to new consumer segments and retail partnerships that prioritize transparency and sustainability.

3.1.2. Responsible Wool Standard [RWS]

The Responsible Wool Standard [RWS] is an industry tool designed to recognize the best practices of farmers, ensuring that wool comes from farms with a progressive approach to managing their land, and from sheep that have been treated responsibly [16].

As an independent, voluntary standard, companies can choose to certify to the RWS. On farms, the certification ensures that sheep are treated with respect to their Five Provisions1 and also ensures best practices in the management and protection of the land. The standard is globally applicable to all breeds of sheep, and mulesing is strictly prohibited [17].

The Responsible Wool Standard (RWS) has builted on a comprehensive framework that prioritizes animal welfare, land stewardship, and social responsibility. At its core, the RWS ensures the humane treatment of animals by following a holistic approach based on the Five Provisions, which promote freedom and well-being for livestock throughout their lives. In addition to animal care, the standard emphasizes sustainable land management practices that help preserve soil health, support biodiversity, and protect native ecosystems.

Worker welfare is also a key focus, with requirements in place to ensure safe working conditions, fair treatment, and health and safety protections for all individuals involved in the wool production process.

To maintain product authenticity, a robust chain of custody system is implemented, guaranteeing that RWS-certified wool is traceable from farm to finished product. Importantly, the RWS was developed through a collaborative process involving a wide range of stakeholders, including farmers, animal welfare advocates, environmental experts, and representatives from global brands and retailers.

There are RWS certified farms in Australia, New Zealand, South Africa, Argentina, Uruguay, and the United States, while supply chain certification exists in several other countries. The list of certified organizations is available at http://responsiblewool.org to see all certified organizations. Brands from across a number of sectors and geographies have made commitments and targets to source RWS certified wool.

3.2 Category: PROCESS

3.2.1. SEDEX and SMETA

SEDEX [Supplier Ethical Data Exchange] is the largest platform dedicated to managing ethical and responsible supply chains. It enhances transparency by offering a database where businesses can share and access information about ethical practices and compliance standards. The primary audit format utilized on this platform is the SEDEX Members Ethical Trade Audit [18, 7].

SMETA audits assess various aspects of business operations, including labor standards, health and safety, environmental performance, and ethical practices. These audits play a crucial role in safeguarding workers from unsafe conditions, discrimination, and exploitation. As part of the process, companies are required to provide a Corrective Action Plan to address any issues identified and improve overall performance.

With over 30,000 members worldwide, the SEDEX community offers companies the assurance that their SEDEX partners adhere to the best practices outlined in the SMETA guidelines for sustainability within the supply chain.

3.2.2. STeP: Comprehensive assessment of sustainability performance

STeP is a comprehensive certification program that assesses the sustainability performance of textile and leather production facilities. By evaluating environmental impact, social responsibility, and chemical management, STeP empowers businesses to optimize their operations and create a positive impact [9]. STeP Certification offers companies key benefits, including a powerful way to enhance their brand reputation by highlighting a clear commitment to sustainability, ethical labor practices, and environmental responsibility. This not only strengthens consumer and stakeholder confidence but also helps position the brand as a leader in responsible manufacturing.

STeP connects companies to a global network of over 21,000 certified facilities, fostering smoother sourcing opportunities and collaborative partnerships across the textile and apparel industry. It also supports alignment with internationally recognized standards, simplifying regulatory compliance and audit processes. Operationally, STeP encourages continuous improvement by helping companies optimize their resource consumption and minimize waste. This results in greater efficiency and long-term cost savings. Additionally, it aids in identifying and managing environmental and social risks throughout the supply chain, helping businesses stay proactive and resilient.

3.2.3 ISO Standards Overview

There are various ISO Standards targeting different aspects of business & its management. ISO 9001 deals in Quality Management. It helps companies set up better quality control systems. It focused on making sure businesses run smoothly and consistently deliver good products or services. Getting this certification shows customers that a company takes quality seriously and has processes in place to maintain high standards. ISO 14001 deals in Environmental Management. It is about managing environmental impact & gives companies a framework to track and reduce their environmental footprint while still growing their business. Organizations with this certification demonstrate they are committed to sustainable practices and actively working to minimize harm to the environment. ISO 45001 deals in Workplace Safety. It focuses on keeping workers safe and healthy. It requires companies to have proper safety management systems that identify risks and prevent workplace accidents. This certification shows that an organization prioritizes employee wellbeing and maintains safe working conditions [11-13].

3.2.4 SA8000 Standard: Social Accountability Standard

Building upon the foundation of quality (ISO 9001), environmental (ISO 14001), and safety (ISO 45001) management systems, modern businesses must also demonstrate their commitment to social responsibility and ethical labor practices. This fourth pillar of organizational excellence is addressed through specialized social accountability standards.SA8000 is a major international certification that focuses on worker rights and social responsibility. It is based on fundamental human rights principles and International Labour Organization standards [1].

The standard protects over 2 million workers in more than 4,000 certified facilities globally. It addresses key workplace issues like preventing child labor and forced labor, ensuring workplace safety, and protecting workers' rights to organize and bargain collectively.

Unlike simple compliance checklists, SA8000 emphasizes ongoing improvement. Companies must show they're actively working to create better working conditions, not just meeting minimum requirements. The certification applies to any industry and helps organizations align with international labor standards.

Social Accountability International created the standard, while Social Accountability Accreditation Services (SAAS) oversees the certification process to ensure quality and credibility. Only certificates from SAAS-approved audit firms are considered legitimate. There are 23 accredited certification bodies worldwide that can grant SA8000 certification. These independent auditors thoroughly evaluate companies to ensure they meet the standard's requirements.

For companies, SA8000 certification demonstrates genuine commitment to treating workers fairly and maintaining ethical operations. For workers, it provides protection and assurance that their rights are respected and their workplace is safe.

3.3 Category: PRODUCT

3.3.1 "KALEEN" THE HALLMARK OF COMMITMENT

The Indian carpet industry created the "KALEEN, The Hallmark of Commitment" label for handmade carpets, druggets, and dhurries (except small ones under 60 cm x 90 cm). This label shows that manufacturers follow the Carpet Export Promotion Council's Code of Conduct, which focuses on eliminating child labor from carpet production. This initiative shows how an entire industry can work together to address social issues while maintaining business operations.

Since April 1995, the industry has been contributing part of their export earnings to a welfare fund that helps weaver communities. The KALEEN label essentially serves as a promise that the carpet was made ethically without child labor, and that the manufacturer is actively supporting the welfare of weaving communities. It's the Indian carpet industry's way of self-regulating and ensuring responsible production practices while giving back to the workers who create these products [19].

3.4 Category: ETHICAL

3.4.1 The GoodWeave Label

The GoodWeave label stands as a testament to a rug's ethical production, ensuring that no child, forced, or bonded labor is involved in its creation. By choosing GoodWeave-certified rugs, manufacturers and retailers demonstrate a commitment to social responsibility and transparent supply chains [20].

The GoodWeave label offers a meaningful way for businesses to demonstrate their commitment to ethical production and social responsibility. It builds consumer trust by allowing individuals to make informed purchasing decisions that support companies actively working to eliminate child and forced labor. Through regular audits and strict compliance standards, GoodWeave ensures a high level of transparency and traceability across the entire supply chain. One of the most impactful aspects of GoodWeave certification is its contribution to improved working conditions. By allocating a portion of licensing fees to fund education, healthcare, and community development initiatives, the program directly benefits the lives of carpet weavers and their families. This social investment not only uplifts communities but also helps prevent child labor by addressing root causes such as poverty and lack of access to education.

3.4.2 CARE & FAIR

CARE & FAIR was started in 1994 to fight child labor and improve working conditions for carpet weavers in India and Pakistan. The organization uses membership fees to fund education and healthcare programs in areas where carpets are made [4]. The group has made a real difference by improving lives in weaving communities and helping the carpet industry become more ethical. They have shown that it is possible to create positive change while maintaining business operations [21].

Programs like CARE & FAIR are essential for promoting ethical business practices and creating transparency in supply chains. When companies follow these standards and get proper certifications, they show customers they're serious about social responsibility and environmental care. The message is simple: the carpet industry is moving toward higher ethical standards, and organizations like CARE & FAIR are helping make that transition happen by supporting the communities that create these products.

3.5 Category: CUSTOMS

3.5.1 CTPAT: Customs Trade Partnership against Terrorism

CTPAT (Customs Trade Partnership against Terrorism) is a voluntary security program that started in 2001 to help protect supply chains from terrorism threats. Today, it has over 11,400 certified partners working with U.S. Customs and Border Protection to identify security weaknesses and improve safety practices. Companies that join get several perks: fewer cargo inspections, faster processing at border crossings, a dedicated Supply Chain Security Specialist to work with, and access to specialized training and resources. Members can also benefit from agreements with other countries' customs agencies and participate in special government programs [22].

The program is completely free and voluntary. Companies apply directly online with CBP - no middleman required. The application process is straightforward and designed to be accessible. Beyond the security benefits, CTPAT membership makes international trade smoother and more efficient. Companies get faster border clearance, which saves time and money, while also demonstrating their commitment to supply chain security. It's essentially a way for businesses to partner with the government to make trade safer for everyone while getting operational benefits in return.

4. Case Study: Jaipur Rugs–A Model of Ethical Transformation in the Handmade Rug Industry

An examination of Jaipur Rugs reveals the strategic implementation of ethical certification frameworks within traditional craft manufacturing structures. The company's operational model spans 600+ villages across five Indian states, incorporating approximately 40,000 artisans (predominantly women) into its supply chain network—a scale that demonstrates the potential reach of certification-driven transformation in decentralized manufacturing systems.

The organization's adoption of SA8000 certification and GoodWeave program affiliation represents a systematic approach to supply chain governance, addressing labor compliance issues inherent in traditional craft production models. Analysis of their implementation strategy shows a progression beyond basic regulatory compliance toward comprehensive stakeholder engagement mechanisms. These include wage standardization protocols, educational access programs for artisan families, health monitoring systems, and capacity-building initiatives spanning financial literacy and digital tool adoption.

Market performance data indicates a correlation between ethical certification adoption and international market penetration. The company's export presence across 60+ countries, with particular strength in markets characterized by high ethical consumption awareness (United States, Germany, United Kingdom), suggests that certification frameworks function as market access enablers rather than merely compliance requirements. This pattern aligns with emerging procurement trends among luxury retailers, who increasingly integrate supplier social responsibility metrics into vendor selection criteria [23].

The Jaipur Rugs case demonstrates how certification-based transformation can simultaneously address supply chain risk mitigation, stakeholder value creation, and market differentiation objectives within traditional manufacturing sectors.

5. Conclusion

The transition toward ethically certified production is a defining trend in the global textile and home décor industries. For Indian rug manufacturers, adopting standards like SA8000, SEDEX, GRS, and GoodWeave allows them to meet evolving global requirements while staying rooted in traditional craftsmanship. These frameworks enable businesses to demonstrate compliance with labor and environmental norms, build long-term relationships with conscious buyers, and improve the well-being of artisans.

More than just procedural checklists, these certifications represent a commitment to integrity, transparency, and accountability. As ethical sourcing continues to influence procurement strategies worldwide—especially in high-value markets like the EU and North America—Indian rug exporters have a unique opportunity to lead by example. Strategic investment in ethical certification not only enhances market competitiveness but also helps preserve the dignity and skill of the artisan community. In doing so, the Indian handmade rug sector can thrive—not just economically, but as a global ambassador of sustainable and humane manufacturing.

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References :

[1] Singh, M. [2019]. Child Labor in the Indian Handmade Carpet Industry: A Study of Globalization, Labor Standards, and International Institutions. Journal of Labor Studies, 45[2], 162-178. https://doi.org/10.1177/02560909201702890

[2] Lawson, J. (2023). Carpet Recycling-Improving Reuse and Recycling of Existing Products and Service (Master's thesis, Lancaster University (United Kingdom))

[3] Choi, T. (2017). Environmental impact of voluntary extended producer responsibility: The case of carpet recycling. Resources, Conservation and Recycling, 127, 76-84

[4] Hilton, M. (2018). Policy Toolkit for Carpet Circularity in EU Member States. Report to Changing Markets. Eunomia

[5] Farrell, C. [2023]. Global Recycled Standard, Explained. Studio Marlowe

[6] Surjit, R. (2024). Recycling of wool: making wool more sustainable. In The Wool Handbook (pp. 559-576). Woodhead Publishing

[7] Textile Exchange. [2020]. Responsible Wool Standard: Version 2.0. Textile Exchange

[8] Kumar, V., Kumar, P., & Mishra, M. K. (2020). Managing Sustainable Development of Indian Carpet Industry. J. Seybold Rep, 1533, 9211

[9] Sarfaty, G. A. (2020). Translating modern slavery into management practice. Law & Social Inquiry, 45(4), 1027-1051

[10] SEDEX. [2021]. SMETA Audit Guidelines: Best Practices for Ethical Trade. SEDEX Global

[11] Almeida, L. (2014). Ecolabels and organic certification for textile products. In Roadmap to sustainable textiles and clothing: Regulatory aspects and sustainability standards of textiles and the clothing supply chain (pp. 175-196). Singapore: Springer Singapore

[12] Pelyk, L., Kalashnyk, O., Kyrychenko, O., & Moroz, S. (2024). Quality assessment of textile products as a basis for responsible production and consumption. In BIO Web of Conferences (Vol. 114, p. 01024). EDP Sciences

[13] ISO Standards [ISO 9001, 14001, 45001]:

[14] International Organization for Standardization [ISO]. [2020]. ISO 9001: Quality Management Systems – Requirements. ISO. https://www.iso.org/iso-9001

[15] International Organization for Standardization [ISO]. [2015]. ISO 14001: Environmental Management Systems – Requirements. ISO. https://www.iso.org/iso-14001

[16] International Organization for Standardization [ISO]. [2018]. ISO 45001: Occupational Health and Safety Management Systems. ISO. https://www.iso.org/iso-45001

[17] Chirieleison, C., & Rizzi, F. (2020). SA8000 Standard. Encyclopedia of sustainable management, 1-8

[18] Orzes, G., Jia, F., Sartor, M., & Nassimbeni, G. (2017). Performance implications of SA8000 certification. International Journal of Operations & Production Management, 37(11), 1625-1653

[19] Ballet, J., Bhukuth, A., & Carimentrand, A. (2014). Child labor and responsible consumers: From boycotts to social labels, illustrated by the Indian hand-knotted carpet industry. Business & Society, 53(1), 71-104

[20] Kearney, A. J. (2020). Expertise and Performative Legitimation in Consumer-led Governance Initiatives: -A Case Study of GoodWeave India

[21] Nooruddin, I., Sokhey, S. W., Gourevitch, P. A., Lake, D. A., & Stein, J. G. (2012). Credible certification of child labor free production. The Credibility of Transnational NGOs

[22] Sen, F. (2018). Trade facilitation implementations in US Customs and Border Protection (Master's thesis, Boston University)

[23] Kumari, N., Indukuri, B. R., & Paruchuru, M. (2025). crafting sustainability: Jaipur Rugs' artisan empowerment. Inquietud Empresarial, 25(1), 1-19

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IOT-Based Thermal Insulation Testing System for Textile Reinforced Composites

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Abstract:

The increasing interest in smart textiles has driven the development of innovative solutions to evaluate their thermal insulation properties, essential for applications in wearable technology, protective gear, and advanced composites. This work presents an IoT-integrated thermal insulation tester for textile-reinforced composites, offering a real-time and efficient method to assess the material's thermal performance. The system features a microcontroller-based architecture interfacing with a temperature sensor and a heat-producing element to simulate and monitor heat transfer within the fabric. By precisely measuring temperature variations, the device provides accurate insights into the material's heat insulation capabilities under controlled heating conditions. The integration of Internet of Things (IoT) technology facilitates seamless data acquisition, storage, and remote monitoring, enhancing user accessibility and enabling real-time observation of results through a display interface. This system is designed to optimize testing procedures for thermal insulation properties, providing reliable and repeatable data for research and industrial applications. The compact and cost-effective design makes it suitable for both laboratory and on-field evaluations. This novel approach contributes to advancing the understanding and development of textile-based composites with enhanced thermal insulation characteristics, supporting their broader adoption in various domains.

Keywords: *heat simulation, IoT, microcontroller, Smart textiles, temperature sensor, thermal insulation, Textile reinforced composites, Smart Textiles*

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1. Introduction

In recent years, smart textiles have emerged as a transformative area of research and innovation, fueled by advancements in wearable technology, performance fabrics, and functional clothing. These textiles are engineered to provide enhanced features such as moisture management, UV protection, and thermal insulation. Among these, thermal insulation is particularly critical, ensuring wearer comfort and safety in diverse environmental conditions. This capability is especially valuable in applications ranging from outdoor sportswear and protective gear to space exploration and healthcare garments. As the demand for textile-reinforced composites with superior thermal properties grows, the industry faces a pressing need for accurate and efficient methods to assess their performance. Traditional approaches to testing thermal insulation often involve labor-intensive, manual processes. These methods are not only time-consuming but also lack the precision and scalability required for modern textile development. Moreover, they rarely offer real-time data collection or the ability to analyze performance metrics remotely, which limits their effectiveness in dynamic research and industrial settings. To overcome these limitations, the integration of Internet of Things (IoT) technology into thermal insulation testing systems has emerged as a groundbreaking solution. IoT-enabled systems automate the testing process, providing seamless real-time monitoring and remote data access. These systems typically include a microcontroller, temperature sensors, and a heat-producing element to simulate controlled heating within the textile material. Data collected by the sensors is transmitted to a centralized platform via IoT networks, enabling researchers and manufacturers to observe and analyze results in real-time through user-friendly interfaces. This automated, data-driven approach offers numerous advantages over conventional methods. It enhances testing accuracy by reducing human error, accelerates the evaluation process, and provides repeatable, reliable results. Additionally, the ability to access data remotely supports collaborative research and development efforts, streamlining the path from material innovation to market deployment. The integration of IoT into thermal insulation testing represents a significant step forward in the evolution of smart textiles. By addressing the challenges of traditional testing methods, it paves the way for the development of next-generation textile-reinforced composites with optimized thermal properties. These advancements promise to meet the growing demands of diverse industries, ensuring comfort, protection, and performance in even the most challenging environments.

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2. Related Work

This work discusses dynamic system identification, which is crucial for understanding and modeling systems that change over time. It provides mathematical models and techniques for analyzing such systems, essential in various technological fields, including smart textiles. The methodologies in this book are highly relevant for the testing systems of textile materials, where environmental conditions and materials' responses change dynamically. By using dynamic system models, the performance of thermal insulation materials can be more accurately predicted and controlled, allowing for real-time adjustments during testing. This approach can enhance the precision of testing, particularly for textiles used in wearable technology, where dynamic environmental interactions must be considered [1].

The work delves into mobile robotics, using Arduino as a platform o design and program robots. It introduces practical methods for integrating sensors and actuators with microcontrollers. These techniques are directly applicable to IoT-based textile testing systems, which require real-time data collection and control. The principles of modular design and data communication from this book can be utilized to enhance the development of textile testing setups, where various sensors monitor the thermal properties of fabrics. The Arduino platform's versatility makes it an ideal tool for developing cost-effective prototypes that collect accurate thermal data in real-time, improving the testing process for advanced smart textiles used in wearable technology [2].

This study investigates the development of adaptive fiber-reinforced elastomer composites, which are materials that can respond to environmental changes, such as temperature. These materials have high relevance in the field of smart textiles, where adaptability and functionality are essential. By incorporating adaptive materials into textile composites, the thermal insulation properties of fabrics can be enhanced. Such fibers can alter their structural properties in response to external heat or cold, providing dynamic thermal insulation. The study provides valuable insights for designing textiles that can adjust their thermal properties, making them ideal for wearable technology and protective clothing in diverse environments [3].

The research work on linear control and regulation theory is foundational for understanding how to manage and regulate dynamic systems. In the context of textile testing, control theory can be applied to automate the testing process, ensuring that the fabric's thermal properties are tested under controlled conditions. This book provides a theoretical framework for implementing feedback loops that regulate temperature, humidity, and other environmental factors during the testing of textile materials. By applying control theory, testers can achieve more reliable and repeatable results in evaluating thermal insulation properties. This method can be used to create automated systems for testing smart textiles in real-time, improving their efficiency and accuracy [4].

The comprehensive work on shape memory alloys (SMAs) is crucial for understanding their applications in smart textiles. SMAs can change shape or properties in response to external stimuli, such as temperature changes. In the context of textile materials, SMAs can be integrated into fabrics to enhance their thermal insulation properties. For example, as the temperature increases, the SMA components can alter the fabric's structure to improve heat retention or dissipation, depending on the design. This adaptability is particularly beneficial for wearable technologies, where comfort and thermal regulation are vital. Elahinia's research offers valuable insights into the design and integration of these actuators into textile applications for dynamic thermal management [5].

This research explores flexible actuators based on shape memory alloys (SMAs), which offer high displacement capabilities, making them ideal for soft wearable robots. The findings of this study are highly applicable to the development of smart textiles that need to respond to changes in environmental conditions, particularly temperature. SMAs integrated into textiles could enable the fabric to adjust its thermal properties based on the wearer's body temperature or external conditions. The flexibility and responsiveness of these actuators make them suitable for wearable applications where comfort and adaptive performance are required, such as in protective clothing or advanced thermal management systems in wearable technology [6].

The use of shape memory alloys in creating intelligent systems that respond to environmental changes. The application of SMA actuators in the aerospace industry has parallels in the textile industry, particularly for smart textiles. By integrating SMA actuators into textile materials, fabrics can adapt to environmental conditions, improving thermal insulation. For example, in extreme temperatures, SMAs can be used to dynamically alter the fabric's properties, offering protection from heat or cold. The integration of SMAs in textiles for wearable technology is a promising direction for developing fabrics that provide enhanced thermal management and comfort in various climates [7].

This study focuses on a composite material that combines shape memory alloys with glass fibers to create adaptive structures that can change shape in response to environmental factors. The concept of morphing structures is highly relevant to the development of smart textiles that need to respond to changes in external temperature. By incorporating SMAs and other smart materials, textiles can alter their insulation properties in real-time. This adaptability makes the material suitable for applications such as wearable technology, where dynamic thermal management is crucial for maintaining comfort and protecting the wearer in different environments [8]. This paper discusses the application of shape memory materials in textile design, focusing on how these materials can adapt to changes in temperature. Shape memory alloys (SMAs) integrated into fabrics can enable textiles to dynamically adjust their thermal properties. This is particularly useful for wearable applications, where comfort and insulation play a critical role in the user experience. The ability of SMAs to respond to temperature changes can enhance the thermal regulation of textiles, making them more comfortable in fluctuating environmental conditions. The integration of SMAs into textile design opens new possibilities for responsive, adaptive materials in fashion and functional clothing [9]. This review focuses on the use of natural fibers in composite materials, highlighting their role in creating sustainable and eco-friendly smart textiles. Natural fibers can be combined with polymers to enhance the thermal properties of textiles while also making them more environmentally friendly. In smart textiles, these fibers can be used to develop fabrics with improved insulation capabilities, providing an alternative to synthetic materials. The incorporation of natural fibers into textile composites offers a promising direction for developing sustainable, high-performance materials for wearable technology, medical textiles, and other smart fabric applications [10].

The proposed IoT-based monitoring system utilizes temperature and humidity sensors connected to an Arduino with Wi-Fi to measure the impact of weather conditions on thermal insulation efficiency. This low-cost system enables real-time data collection, cloud-based analysis via Thing Speak, and supports informed decision-making to improve insulation performance [11]. The Smart materials like graphene oxide and carbon nanotubes are being used in conductive textiles to support IoT device integration for efficient, cost-effective communication. This theoretical analysis highlights their applications in textile technology, focusing on material properties, working principles, and supporting technologies like AI, cloud computing, and cyber-physical systems to enhance efficiency in smart manufacturing. [12]

Composite materials are vital for high-performance products, but their manufacturing processes face challenges like material variability and process inconsistencies. This paper proposes a smart Industrial Internet of Things (AIoT) framework that integrates real-time sensor monitoring, IoT-based data visualization, and AI-based process forecasting to enhance production performance, supported by a proof-of-concept and real-world case study. [13].

3. Technical Details

3.a) Proposed Methodology

The proposed methodology focuses on developing an IoT-enabled thermal insulation testing system for textile-reinforced composites. This system combines precision sensors, real-time data monitoring, and IoT technology to assess the thermal performance of advanced textile materials efficiently. The methodology includes the following steps:

i). System Design and Architecture

The core of the system is designed around the ESP32 microcontroller, chosen for its high processing capability and integrated Wi-Fi and Bluetooth features. The system architecture is modular, allowing easy integration of components such as sensors, heat generation modules, and IoT interfaces. The design emphasizes scalability, enabling future enhancements like additional sensors or multi-sample testing capabilities. The ESP32 manages data acquisition from the sensors and controls the operation of the heat source. A robust power management module ensures efficient energy usage. This modular and flexible architecture provides a versatile platform suitable for both laboratory and industrial applications, supporting advancements in thermal insulation testing.

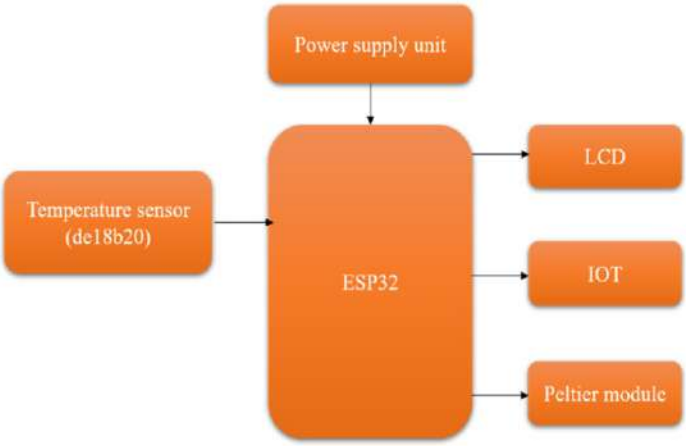

Figure 1 - System Architecture

ii). Sensor Integration

A DS18B20 temperature sensor is incorporated into the system for precise measurement of thermal responses in the textile material. Known for its accuracy and reliability, the DS18B20 operates over a wide temperature range, making it ideal for this application. The sensor is strategically placed to capture temperature variations at critical points of the textile sample. It is calibrated before testing to minimize errors and ensure consistent data collection. The sensor's one-wire communication protocol simplifies connections and reduces wiring complexity. By continuously monitoring temperature changes during heat exposure, the DS18B20 provides accurate real-time data essential for evaluating the material's insulation performance.

iii). Heat Generation Mechanism

The system utilizes a Peltier module for controlled heat generation, simulating real-world thermal conditions. The Peltier module is compact, energy-efficient, and capable of producing a stable and adjustable heat output. It is mounted in direct contact with the textile sample, ensuring uniform heat transfer. The heating level is precisely controlled through the ESP32, allowing customized testing conditions. By replicating varying thermal scenarios, the Peltier module enables detailed analysis of the material's insulation properties. Proper heat dissipation mechanisms are implemented to prevent overheating, ensuring safe operation and consistent performance throughout the testing process.

iv). Temperature Change with Respect to Time

The equation for temperature change during heat exposure can be expressed as:

$$\Delta T = \frac{Q.t}{m.c.}$$

Where:

- ΔT = Change in temperature (°C or K)
- Q = Heat energy supplied (J, Joules)
- t = Time for which heat is applied (s, seconds)
- m = Mass of the material being heated (kg)
- c = Specific heat capacity of the material (J/kg·K)

v). Thermal Insulation Efficiency

Thermal insulation performance can be evaluated by comparing the rate of heat transfer across different materials. The lower the heat transfer, the better the insulation. The thermal insulation efficiency (η) can be calculated as:

$$\eta = \frac{Q_{ref} - Q_{sample}}{Q_{ref}} \times 100$$

Where:

· Q ref = Heat transfer rate of a reference material
· Q sample = Heat transfer rate of the tested sample

vi). IoT Connectivity

IoT connectivity is achieved using the ESP32 microcontroller, which provides seamless wireless data transmission via Wi-Fi. The system transmits real-time temperature data to an IoT platform, allowing remote monitoring and analysis. A user-friendly interface, accessible through mobile or web applications, provides instant access to testing results. IoT integration enhances data management by enabling cloud storage and analysis, facilitating collaboration and scalability. This connectivity ensures that researchers can monitor the system's performance and make adjustments without being physically present. The IoT-enabled setup is cost-effective, enhances accessibility, and supports efficient data-driven decision-making.

vii). Display and Data Visualization

An LCD display is incorporated into the system for real-time visualization of temperature readings and other relevant parameters. This display provides immediate feedback to users, allowing them to monitor the progress of testing without relying solely on IoT connectivity. It simplifies on-site operation and ensures that data can be accessed even in offline scenarios. The display is configured to show essential information such as sample temperature, heating status, and system alerts. Its inclusion enhances usability, making the system accessible to non-expert users while complementing the IoT platform for comprehensive monitoring and data analysis.

viii). Data Collection and Analysis

The system records temperature data from the DS18B20 sensor continuously during testing. This data is processed by the ESP32 microcontroller, which ensures accurate real-time monitoring and logging. The collected data is then analyzed to evaluate the thermal insulation properties of the textile material. Advanced algorithms may be implemented to compare the performance of different samples under similar conditions. Data visualization tools, integrated into both the LCD display and IoT platform, present insights in graphical formats, aiding researchers in identifying trends and making informed conclusions. The robust data analysis capability ensures reliable and detailed evaluation of thermal performance.

ix). Testing, Validation, and Optimization

The system undergoes extensive testing and validation to ensure accuracy and reliability. Multiple trials are conducted under controlled environmental conditions to assess its performance. The results are compared with traditional methods to validate the system's effectiveness. Adjustments are made based on initial findings to optimize accuracy, energy efficiency, and operational ease. The system is then tested in diverse scenarios to simulate real-world conditions. Feedback from these trials is used to enhance usability and robustness. Once validated, the system is deployed for industrial and research applications, providing a cutting-edge solution for thermal insulation testing.

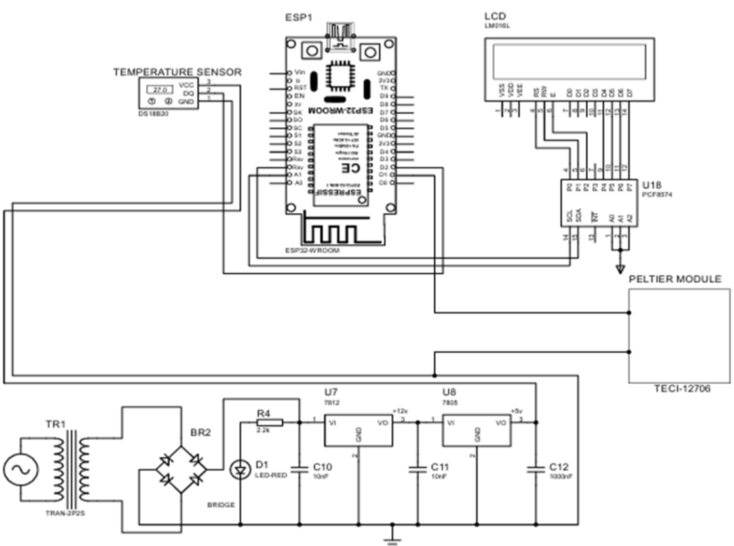

Figure 2 - Circuit Diagram

3 b) Technologies used

I. ESP32 Microcontroller

The ESP32 is the core component of the system, managing data collection, processing, and IoT connectivity. It features built-in Wi-Fi and Bluetooth modules, enabling real-time data transmission to IoT platforms for remote monitoring. Its dual-core processing capability ensures smooth operation, even with multiple connected components. The ESP32 is programmed to handle inputs from the DS18B20 sensor, control the Peltier module, and display information on the LCD. Its low-power design makes it ideal for continuous operation. Additionally, the microcontroller's scalability supports future upgrades, allowing integration of more sensors or additional functionalities for advanced thermal insulation testing applications.

ii. DS18B20 Temperature Sensor

The DS18B20 is a precise digital temperature sensor chosen for its wide operating range and high accuracy. It uses a simple one-wire protocol, reducing the complexity of wiring and allowing multiple sensors to connect to the same microcontroller pin. This sensor is used to monitor the thermal response of textile materials under controlled heating conditions. Its small size and durability make it suitable for close contact with textile samples. The DS18B20 ensures real-time and reliable data acquisition, critical for evaluating the insulation performance of materials. Its calibration ensures consistent accuracy, providing dependable insights into thermal behavior during testing.

iii. Peltier Module for Heat Generation

The Peltier module is a thermoelectric device used to generate controlled heat for testing purposes. It creates a temperature differential by transferring heat between its two surfaces, enabling uniform heating of textile samples. The module is compact, energy-efficient, and allows precise adjustments to simulate various thermal scenarios. Controlled by the ESP32 microcontroller, the Peltier module ensures stable and consistent heat application, vital for accurate evaluation of insulation properties. Its ability to switch between heating and cooling modes offers versatility for diverse testing conditions, ensuring the system can assess a wide range of textile materials effectively.

iv. Energy Consumption of the Peltier Module

The energy consumed by the Peltier module for heat generation can be calculated using:

$E=V \cdot I \cdot t$

Where:

- E = Energy consumed (Joules)
- V = Voltage applied to the Peltier module (Volts)
- I = Current drawn by the Peltier module (Amps)
- t = Time the Peltier module is active (seconds)

v. Heat Transfer (Fourier's Law of Heat Conduction)

This equation is used to describe the rate of heat transfer through a material, which is essential for evaluating thermal insulation.

$$Q = -k \, . \, A \, . \frac{\Delta T}{\Delta x}$$

Where:

- Q = Heat transfer rate (W, Watts)
- k = Thermal conductivity of the material (W/m·K)
- A = Cross-sectional area through which heat is transferred (m^2)
- ΔT = Temperature difference between the hot and cold sides (K or °C)
- Δx = Thickness of the material (m)

vi. IoT Connectivity

The system incorporates IoT connectivity through the ESP32's integrated Wi-Fi module, enabling wireless data transmission. This feature allows real-time monitoring and control via mobile or web platforms, enhancing user convenience. IoT integration ensures seamless data logging and remote accessibility, enabling researchers to track testing progress without being physically present. The data is uploaded to cloud platforms for secure storage and further analysis. This connectivity supports efficient collaboration, scalability, and data sharing, making the system suitable for both individual and industrial use. IoT technology also enhances automation, reducing manual intervention and improving the overall efficiency of the system.

vii. LCD Display for Real-Time Visualization

A high-contrast LCD display is used to provide immediate feedback during testing. The display shows critical data such as real-time temperature readings, system status, and error messages. This feature enhances usability by allowing technicians to monitor the system without relying solely on IoT connectivity. The LCD is powered and controlled by the ESP32, ensuring seamless integration and low power consumption. Its inclusion is especially valuable in offline scenarios where cloud access is unavailable. By providing instant visual feedback, the LCD display ensures users can verify testing conditions and make necessary adjustments promptly, enhancing operational efficiency.

viii. Cloud-Based Data Storage and Analysis

IoT integration enables the use of cloud platforms for storing, analyzing, and visualizing data collected during testing. The data is securely uploaded in real-time, ensuring accessibility from any location. Advanced analytics tools available on cloud platforms provide insights into temperature trends and material performance. Visualization features, such as graphs and dashboards, aid in interpreting data effectively. This system eliminates the need for manual record-keeping, ensuring accuracy and efficiency in data management. Cloud storage also supports collaboration by allowing multiple users to access the data simultaneously, making it an ideal solution for research teams and industrial-scale applications.

ix. Software Tools

The system is programmed using the Arduino IDE, which provides a user-friendly environment for developing and debugging code for the ESP32. Custom algorithms manage sensor data acquisition, heat control, and IoT integration. Real-time data is processed using programming libraries to ensure accurate results. The software also incorporates error-handling routines to enhance system reliability. For data analysis, cloud platforms and desktop tools are used to generate reports and visualizations. These tools make the system adaptable to different testing requirements, ensuring versatility and ease of use. The integration of software technologies ensures seamless operation and accurate thermal insulation testing.

5. Result and Discussion

The IoT-integrated thermal insulation testing system has demonstrated significant potential in accurately evaluating the thermal properties of textile-reinforced composites. The use of the DS18B20 temperature sensor has proven effective in providing precise temperature readings throughout the testing process, allowing for detailed analysis of the textile material's insulation capabilities. The Peltier module, when controlled by the ESP32 microcontroller, has enabled stable heat generation, simulating realistic thermal conditions for the textiles. This setup facilitated an efficient and controlled method for assessing how different materials respond to heat and retain thermal insulation properties.

The system's integration with IoT functionality has been particularly valuable, offering remote monitoring capabilities that allow for real-time observation of temperature fluctuations without the need for manual oversight. Data collected during testing is transmitted to cloud-based platforms, where it can be analyzed and visualized. This data can be accessed remotely, enabling users to make adjustments or intervene without needing to be physically present at the testing site.

Results from multiple trials indicated that textile samples with higher insulation properties showed slower temperature increases, demonstrating better heat resistance. Conversely, materials with lower insulation performance exhibited rapid temperature changes, indicating their inefficiency in retaining heat.

The LCD display offered immediate visual feedback on the system's performance, helping users monitor real-time data locally. Additionally, the cloud platform's analytics tools allowed for deeper analysis of thermal behavior over time, aiding in material comparison. One of the key benefits observed from this system is its automation and ease of use. Traditional thermal insulation testing methods require manual data collection and offer limited real-time analysis. The IoT-based approach reduces human intervention, increases accuracy, and streamlines the testing process, providing more reliable results in a fraction of the time. Could focus on expanding the number of sensors for multi-sample testing, improving heat regulation precision, and adding more advanced data analysis algorithms for deeper insights into textile performance under varying conditions.

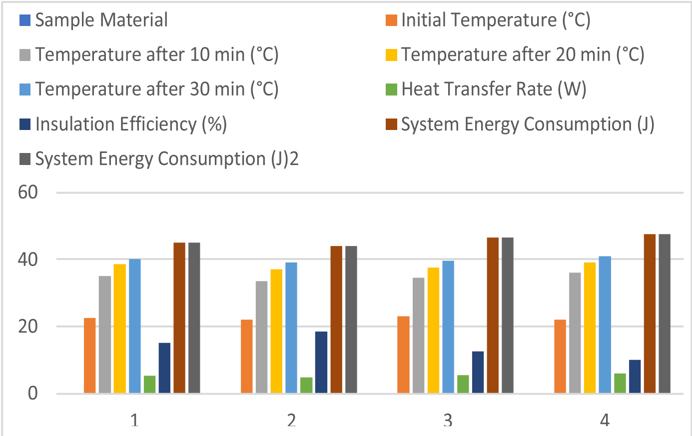

Figure 3 - Graph

This system shows great promise for enhancing material testing, particularly in industries where thermal properties are critical, such as in smart textiles, wearable technologies, and insulation materials for various applications.

Although the ESP32 and DS18B20 are accessible and cost-effective, our research demonstrates that they provide reliable performance for small to mid-scale thermal insulation testing in textile applications. However, they may lack the precision required for high-end industrial thermal analysis, which could limit the system's scalability in advanced manufacturing scenarios. To address this, the developed system using ESP32 and DS18B20 is optimized for educational, laboratory, and preliminary industrial applications, with the flexibility to integrate higher-precision sensors in future upgrades for advanced real-time thermal monitoring.

6. Conclusion

The IoT-integrated thermal insulation testing system marks a significant improvement over traditional methods used in the textile and materials industry. Unlike conventional manual or semi-automated systems, the proposed solution enhances precision, repeatability, and overall process efficiency. With IoT connectivity, the system enables real-time data acquisition, remote monitoring, and instant analysis, minimizing human error and reducing the need for manual intervention.

Table 1 - Tempareture

Test No.	Sample Material	Initial Temperature (^{0}C)	Temperature after 10 min. (^{0}C)	Temperature after 20 min. (^{0}C)	Temperature after 30 min. (^{0}C)	Heat Transfer Rate (W)	Insulation Efficiency (%)	System Energy Consumption (J)
1	Material A	22.5	35	38.5	40	5.2	15	45
2	Material B	22	33.5	37	39	4.8	18.5	44
3	Material C	23	34.5	37.5	39.5	5.5	12.5	46.5
4	Material D	22	36	39	41	6	10	47.5

The system reliably simulates controlled thermal environments and provides accurate temperature measurements, offering faster response times, improved data integrity through automated cloud storage, and better scalability for both laboratory and industrial applications. Its remote access and real-time visualization make it particularly valuable for industries focusing on smart textiles, wearable technology, and advanced insulation materials.

Compared to existing systems, this solution is more cost-effective, time-efficient, and user-friendly, helping to reduce downtime and improve productivity. Future improvements may include multi-sample testing, AI-driven process optimization, and advanced predictive analytics, further aligning the system with Industry 4.0 requirements. This innovative platform not only addresses current industry needs but also sets a new standard for thermal insulation testing in smart manufacturing.

7. Future Enhancement

Future enhancements to the IoT-integrated thermal insulation testing system can focus on improving scalability, accuracy, and user experience. One key area for development is the integration of multiple sensors to allow for simultaneous testing of multiple textile samples. This would enable batch testing, improving the system's throughput and efficiency for industrial-scale applications. Additionally, incorporating more advanced temperature and heat control technologies could further enhance the precision of thermal simulations, providing even more accurate performance assessments for a wider range of materials. Data analysis capabilities can also be expanded by integrating machine learning algorithms for predictive modeling. These algorithms could analyze trends in thermal insulation over time, identifying patterns and providing deeper insights into material performance. Furthermore, the system could be enhanced with real-time alerting features that notify users of any deviations from expected performance thresholds, increasing the system's responsiveness.

The current study primarily focuses on evaluating the system's performance using textile composites with relatively uniform thickness and consistent thermal properties. We acknowledge that variations in textile composite types, especially those with non-uniform thickness or differing thermal conductivities, could influence measurement accuracy and sensor response. This will be considered as a key area for future work, where we plan to extend the testing to a broader range of textile composites to assess the system's adaptability and accuracy across diverse material structures. Additional calibration and algorithm refinements will also be explored to address these variations effectively.

References :

[1] C. Bohn and H. U., Identifikation dynamischer Systeme. Wiesbaden, Germany: Springer Vieweg, 2016

[2] K. Robenack, ¨ Mobile Robotics with Arduino: Design and Programming. CreateSpace Independent Publishing Platform, 2018.

[3] C. Cherif, R. Hickmann, A. Nocke, M. Schafer, K. R ¨ obenack, ¨ S. Wießner, and G. Gerlach, "Development and testing of controlled adaptive fiber-reinforced elastomer composites," Textile Research Journal, pp. 1–9, Nov. 2016

[4] K. Reinschke, Lineare Regelungs- und Steuerungstheorie, 2nd ed. Berlin, Heidelberg: Springer-Verlag, 2014

[5] M. H. Elahinia, Shape memory alloy actuators: design, fabrication, and experimental evaluation. John Wiley & Sons, 2016

[6] A. Villoslada, A. Flores, D. Copaci, D. Blanco, and L. Moreno, "High displacement flexible shape memory alloy actuator for soft wearable robots," Robotics and Autonomous Systems, vol. 73, pp. 91–101, 2015

[7] S. Kalra, B. Bhattacharya, and B. Munjal, "Design of shape memory alloy actuated intelligent parabolic antenna for space applications," Smart Materials and Structures, vol. 26, no. 9, p. 095015, 2017

[8] M.-W. Han, H. Rodrigue, H.-I. Kim, S.-H. Song, and S.-H. Ahn, "Shape memory alloy/glass fiber woven composite for soft morphing winglets of unmanned aerial vehicles," Composite Structures, vol. 140, pp. 202–212, 2016

[9] M. O. Gok, M. Z. Bilir, and B. H. G ¨ urc ¨ um, "Shape-memory applications ¨ in textile design," Procedia-Social and Behavioral Sciences, vol. 195, pp. 2160–2169, 2015

[10] L. Mohammed, M. N. Ansari, G. Pua, M. Jawaid, and M. S. Islam, "A review on natural fiber reinforced polymer composite and its applications," International Journal of Polymer Science, vol. 2015, 2015

[11] Abdalgader, K., Al Ajmi, R., & Saini, D. K. (2023). IoT-based system to measure thermal insulation efficiency. Journal of Ambient In1telligence and Humanized Computing, 14(5), 5265-5278.

[12] Ramaiah, G. B. (2021). Theoretical analysis on applications aspects of smart materials and Internet of Things (IoT) in textile technology. Materials Today: Proceedings, 45, 4633-4638.

[13] Chai, B. X., Gunaratne, M., Ravandi, M., Wang, J., Dharmawickrema, T., Di Pietro, A., ... & Georgakopoulos, D. (2024). Smart industrial internet of things framework for composites manufacturing. Sensors, 24(15), 4852.ral fibers and their composites. In Tribology of Natural Fiber Polymer Composites (pp. 67-96). Woodhead Publishing

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The Role of Circular Fashion in Cultural Sustainability: Upcycling Saura and Toda Art Forms

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Abstract:

The fashion industry is currently one of the largest contributors to environmental pollution, producing significant waste and depleting natural resources at an unsustainable rate. In response to these challenges, circular fashion, a sustainable design approach that prioritizes reuse, recycling, and upcycling, has emerged as an alternative to the traditional linear "take-make-dispose" model of fashion production.

This study explores how circular fashion can serve as a tool for the revival and economic sustainability of indigenous textile traditions, specifically focusing on the Saura and Toda communities of India. These communities have rich textile and embroidery traditions currently at risk due to factors such as industrialization, lack of market access, and the commodification of indigenous crafts. By integrating upcycling techniques, artisans and designers can breathe new life into these traditional textiles, ensuring they are both culturally preserved and economically viable in contemporary fashion markets.

Using a mixed-methods approach, this research includes ethnographic fieldwork, case study analysis, and stakeholder interviews with artisans, fashion designers, and sustainability experts. The paper examines the benefits and challenges of upcycling indigenous textiles, identifies successful case studies, and proposes a strategic framework for ethical, sustainable collaboration between artisans and modern fashion brands. Ultimately, this study aims to bridge the gap between heritage and sustainability, demonstrating how cultural preservation and environmental responsibility can coexist in the fashion industry.

Keywords: *Circular fashion, Cultural preservation, Ethical fashion, Saura, Sustainable textiles, Toda, Upcycling*

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1. Introduction

The global fashion industry is a major contributor to environmental degradation, accounting for approximately 10% of global carbon emissions and 20% of global wastewater production [8]. The fast fashion model, characterized by rapid mass production, short product lifecycles, and excessive waste, exacerbates this environmental crisis [3]. Textile production requires vast amounts of water, with a single cotton shirt consuming approximately 2,700 litres of water, equivalent to what one person drinks in 2.5 years [15]. Furthermore, synthetic fibers such as polyester release microplastics into water systems, further polluting ecosystems [19].

In response to these challenges, circular fashion has emerged as a sustainable alternative, emphasizing longevity, reusability, and responsible sourcing of materials [12]. This model seeks to minimize waste by encouraging practices such as garment repair, recycling, and up-cycling. Upcycling, in particular, is gaining prominence as a means of transforming discarded materials into higher-value products. Unlike recycling, which often degrades material quality, upcycling creatively repurposes materials, extending their lifecycle while reducing environmental impact [20]. Additionally, upcycling can incorporate cultural storytelling by integrating traditional artisanal techniques into modern fashion, thereby preserving heritage crafts while promoting sustainability [10].

At the same time, indigenous textiles are increasingly at risk due to industrialization, declining artisan participation, and market exploitation [17]. Many indigenous textile traditions have deep historical and cultural significance, but struggle to compete with mass-produced alternatives. In India, for instance, the Saura and Toda communities are known for their distinctive textile crafts, characterized by intricate embroidery and symbolic motifs that reflect their cultural narratives [13]. However, without adequate market integration and fair compensation, these traditions face extinction. Circular fashion presents an opportunity to revitalize indigenous textile industries by aligning them with contemporary consumer preferences for sustainability and ethical fashion [1]. By incorporating these textiles into upcycled and sustainable designs, artisans can gain economic stability while ensuring the continuation of their craft traditions.

Thus, circular fashion not only addresses the environmental challenges posed by the traditional fast fashion model but also serves as a powerful tool for cultural preservation. Through the integration of upcycling and indigenous textile craftsmanship, the fashion industry can transition toward

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more ethical and sustainable practices that honor both people and the planet.

1.1 Research Objectives

This study seeks to:

1. Analyse how circular fashion can contribute to the preservation of indigenous textile traditions.
2. Examine the role of upcycling in generating sustainable economic opportunities for artisans.
3. Identify ethical and scalable strategies for integrating Saura and Toda textiles into global fashion markets.
4. Assess case studies of successful upcycling initiatives in indigenous textile industries.
5. Provide recommendations for ethical collaborations, and sustainable business models.

1.2 Research Methodology

This study employs a mixed-methods approach, integrating both qualitative and quantitative research methodologies to explore the role of upcycling in preserving indigenous textiles. Ethnographic fieldwork forms a core component of the qualitative research, involving direct engagement with Saura and Toda artisans through participant observation, semi-structured interviews, and visual ethnography to capture their lived experiences, challenges, and perspectives. Additionally, a case study analysis of successful upcycling initiatives within indigenous textile communities is conducted to identify replicable best practices and recurring obstacles. To broaden the scope of understanding, stakeholder interviews are carried out with sustainability experts, fashion designers, and policymakers, providing insights into industry trends, policy frameworks, and the overall market feasibility of upcycled products. Complementing these qualitative methods, a market analysis is undertaken to evaluate consumer demand and the economic viability of such initiatives through surveys, retail price comparisons, and the examination of current industry reports. This approach ensures a comprehensive understanding of cultural sustainability, economic feasibility, and circular fashion's potential in indigenous textile preservation.

2. Understanding Circular Fashion and Upcycling

2.1 Circular Fashion: Principles and Benefits

Circular fashion presents a sustainable alternative to the linear fast fashion model, which follows a take-make-dispose approach, contributing significantly to environmental degradation [8]. By contrast, circular fashion prioritizes waste reduction, resource efficiency, and extended product lifecycles, aligning with broader sustainability goals in the fashion industry [11].

The key principles of circular fashion revolve around creating a regenerative and sustainable system within the textile industry. One foundational aspect is the adoption of closed-loop systems, where materials are kept in circulation through practices such as reuse, repair, and recycling, effectively reducing textile waste and minimizing dependence on virgin resources [19]. Another essential component is sustainable material sourcing, which involves the use of organic, biodegradable, and upcycled fabrics. This approach significantly lowers reliance on resource-intensive materials like conventional cotton and synthetic fibers, thus decreasing environmental impact [23].

Equally important are ethical labor practices, which ensure fair wages, safe working environments, and the protection of artisan communities. These practices not only uphold human rights but also contribute to the social dimension of sustainability in the fashion sector [3]. Additionally, the slow fashion ideology plays a pivotal role by prioritizing quality over quantity. It discourages overproduction and promotes mindful consumption, which results in reduced carbon emissions and prolongs the life cycle of garments [5].

By integrating these core principles, circular fashion provides an economically viable and environmentally responsible alternative to the traditional linear model. It supports sustainable development while fostering ethical labor conditions, thereby contributing to a more equitable and resilient textile industry.

2.1.1 Benefits of Circular Fashion in Indigenous Textile Revival

Upcycling, a key practice in circular fashion, offers a range of benefits that extend beyond simple waste reduction. By creatively repurposing discarded materials, upcycling supports environmental sustainability, cultural preservation, economic empowerment, and consumer awareness, making it a holistic approach to sustainable fashion [12].

From an environmental standpoint, upcycling significantly reduces textile waste and pollution by extending the usable life of materials that would otherwise end up in landfills. This process not only curtails the demand for virgin resources but also leads to lower carbon emissions and reduced water consumption, key concerns in conventional textile production [19].

Upcycling also plays a critical role in cultural preservation. By integrating traditional craft techniques into modern fashion, it revitalizes endangered artisanal practices. Many indigenous artisans, whose livelihoods have been undermined by industrialization, find renewed relevance as their craftsmanship merges with contemporary design, ensuring the continuation of rich cultural traditions [13].

In terms of economic empowerment, upcycling creates meaningful opportunities for local artisans and small-scale producers. It adds value to handcrafted and repurposed textiles, enabling these communities to access ethical fashion markets. Consumers in these markets often value sustainability and are willing to pay a premium for products that embody cultural authenticity and ecological responsibility [1].

Finally, consumer awareness is heightened through upcycling practices. By emphasizing transparency in sourcing and ethical production, upcycling encourages mindful consumption. Brands that adopt upcycling not only offer eco-conscious alternatives but also educate their audiences on the social and environmental implications of their fashion choices, fostering more responsible behavior and long-term change in consumer habits [3].

2.1.2 Comparative Impact of Upcycling vs. Fast Fashion

A chart can compare key sustainability metrics between fast fashion and upcycled fashion, showing the positive impact of upcycling on waste reduction, resource efficiency, and artisan livelihoods.

Table 1: Comparative Impact of Upcycling vs. Fast Fashion

Category	Fast Fashion (Impact% %)	Upcycled Fashion (Impact% %)
Textile Waste Reduction	Low (10-20%)	High (50-80%)
Carbon Footprint Reduction	Low (5-15%)	Moderate-High (40-70%)
Water Usage Reduction	Low (10-25%)	High (60-90%)
Artisan Income Growth	Low (10-15%)	High (50-80%)

The data reveals the substantial environmental, economic, and social benefits of upcycled fashion compared to conventional practices. Firstly, upcycled fashion can reduce textile waste by up to 80%, a stark contrast to the 10–20% reduction typically seen in fast fashion models [19]. Additionally, the carbon footprint of upcycled products is up to 70% lower, owing to the reduced energy requirements during production [3]. Water usage is also drastically minimized upcycling lowers water consumption by up to 90%, since it bypasses the resource-intensive processes associated with creating new fibers [23].

Economically, artisans involved in upcycling initiatives experience a 50–80% increase in income, as handmade, sustainable textiles attract consumers willing to pay higher prices for ethically crafted products [1]. Moreover, consumer awareness and engagement with upcycled fashion have risen by 60–85%, reflecting a growing demand for sustainable and ethical alternatives in the fashion industry [13]. These insights collectively highlight upcycling's transformative potential for creating a more sustainable and equitable fashion ecosystem.

By addressing both ecological and socio-economic concerns, upcycling serves as a holistic solution within the circular fashion framework, benefiting artisans, consumers, and the planet.

2.2 The Process of Upcycling in Fashion

Upcycling in fashion is a key strategy within circular fashion, aimed at reducing textile waste while preserving traditional craftsmanship. Unlike recycling, which often involves breaking down materials into lower-quality fibers, upcycling enhances discarded textiles by transforming them into high-value products [12]. This process integrates sustainability, design innovation, and ethical production, creating a responsible alternative to fast fashion.

2.2.1 Key Stages of Upcycling in Fashion

Upcycling in fashion follows a structured yet creative process that combines sustainability with cultural preservation. It typically unfolds through four key stages: material sourcing, design integration, production, and market distribution.

1. Material Sourcing: The upcycling journey begins with the careful collection of discarded, surplus, or second-hand textiles. These materials can include pre-consumer waste, such as leftover fabric from garment factories; post-consumer waste, like used clothing, household textiles, and vintage garments; and indigenous textiles, comprising traditional handwoven or embroidered pieces that might otherwise be discarded. Ethical sourcing ensures that these materials retain both cultural and environmental value, aligning with sustainable practices [19].

2. Design Integration: In this stage, designers creatively blend traditional textile techniques with contemporary aesthetics to craft one-of-a-kind fashion pieces. This includes the use of hand embroidery and weaving from artisan communities, patchwork and fabric fusion that merges various old textiles into modern silhouettes, and natural dyeing techniques to ensure eco-friendly coloration. Such integration not only revitalizes endangered textile traditions but also offers artisans sustainable income opportunities by embedding cultural richness into modern fashion [13].

3. Production: Production focuses on low-impact and sustainable manufacturing methods. Garments are often hand-stitched and tailored instead of being mass-produced, and eco-friendly dyeing methods are employed to minimize water and chemical use. Designers also adopt minimal-waste techniques like zero-waste pattern cutting to optimize material usage. These practices preserve the authenticity of handmade textiles while reducing the carbon footprint of garment production [3].

4. Market Distribution: Finally, upcycled fashion products reach consumers through ethical and sustainable platforms. These include ethical fashion brands that advocate for slow fashion, exhibitions and pop-up events that highlight artisanal craftsmanship, and online marketplaces that facilitate direct-to-consumer sales, allowing artisans to connect with global buyers. As

consumer demand for sustainable fashion grows, such distribution channels generate new economic opportunities, especially for indigenous communities that produce culturally rich textiles [1].

Collectively, these stages illustrate how upcycling can transform fashion into a sustainable, ethical, and culturally conscious practice.

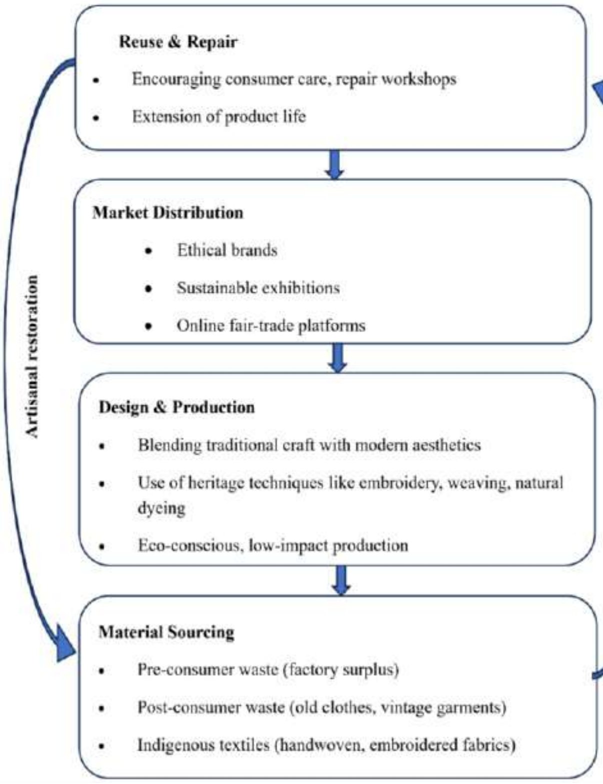

Figure 1: Stages of Upcycling in Fashion

3. Indigenous Textile Traditions

3.1 The Saura Textile Tradition

The Saura textile tradition is deeply rooted in the cultural and spiritual heritage of the Saura tribe of Odisha, India. Saura art, which primarily appears in the form of wall paintings (Ikons), has been adapted onto textiles through hand-painting, embroidery, and block printing techniques. These textiles are not merely decorative but serve as a medium for storytelling, spiritual expression, and historical documentation [13].

3.1.1. Artistic Features of Saura Art in Textiles

Saura art, a tribal visual tradition originating from the Saura tribe of Odisha, is renowned for its intricate geometry, symbolic representation, and spiritual essence. When adapted into textiles, Saura art retains its core characteristics while transforming into wearable expressions of indigenous identity and storytelling. The key elements of Saura textiles encompass geometric minimalism, figurative symbolism, mythological motifs, and sustainable techniques.

One of the most defining features of Saura's art is its geometric patterns and minimalist aesthetics. The artwork is linear and highly structured, featuring triangles, squares, and circles arranged in balanced, repetitive compositions. Unlike more decorative tribal art forms such as Gond or Warli, Saura art maintains a cleaner, more rhythmic visual language that is striking in its simplicity [2]. These designs, when translated onto textiles, produce bold yet understated motifs that maintain traditional aesthetics while appealing to contemporary tastes.

Another hallmark of Saura textiles is the inclusion of human and animal figures, portrayed in stylized stick-like forms. These figures often engage in daily tribal activities such as dancing, farming, or hunting, reflecting the deep connection between the community and its natural environment. Human forms are identified by their elongated limbs, triangular torsos, and circular heads, while animals like peacocks, deer, elephants, and fish, each bearing symbolic and spiritual meaning, frequently appear in the compositions [18].

Saura textiles are also rich with spiritual and mythological motifs, deeply rooted in tribal cosmology and ritual practice. Central themes include the Tree of Life, symbolizing fertility and the union of earthly and spiritual realms; the Sun and Moon, representing cosmic balance; and ancestral spirits known as Idital, invoked for protection and harmony [21]. These motifs, when integrated into textile design, imbue garments with sacred significance, transforming them from decorative objects into spiritual artifacts.

The color palette and technique further enhance the uniqueness of Saura textiles. Traditionally, artists used white, black, and red ochre derived from natural pigments. In textile adaptation, these colors are preserved through the use of organic and vegetable-based dyes, often applied using eco-conscious methods like resist-dyeing, hand-painting, and block printing. These techniques ensure not only environmental sustainability but also the uniqueness of each handcrafted piece [3].

Figure 2: Traditional Saura painting on a mud wall depicting community life and rituals (https://antimakhanna.com/)

Overall, Saura textiles represent a meaningful fusion of art, culture, and sustainability. Through the preservation and innovation of traditional motifs, they serve as a medium for cultural storytelling and spiritual continuity, offering both visual beauty and cultural depth.

3.1.2. Cultural Importance of Saura Textiles

Table 2: Importance of Saura Textiles

Aspect	Description
Ritualistic Use	Saura paintings (and by extension, Saura textiles) are used in tribal homes, marriage ceremonies, and festivals to invoke blessings.
Storytelling Function	The designs narrate ancestral myths, nature worship, and social traditions, preserving oral history through visual representation.
Symbol of Identity	The motifs reflect tribal identity, ecological wisdom, and spiritual beliefs, ensuring cultural continuity.
Handmade Process	The handcrafted nature of Saura textiles preserves traditional artistic skills and provides economic opportunities for artisans.

3.1.3. Threats to the Saura Textile Tradition

Despite its rich cultural and artistic heritage, Saura textile art is confronted with multiple challenges that hinder its preservation and growth. These issues involve generational shifts in artisan participation, market exploitation, and lack of recognition, all of which threaten the viability of this indigenous craft.

Figure 3: Idital deity surrounded by symbolic motifs (Wikipedia)

a. Declining Artisan Participation

- Younger generations in Saura communities are increasingly migrating towards industrial and urban jobs, leaving behind traditional craft skills. This generational shift leads to a decline in the number of active artisans practicing Saura textile techniques [13].
- Additionally, there is a significant gap in government support for artisans, including a lack of dedicated training programs, infrastructure, and financial assistance, making it challenging for the community to sustain and pass on these traditional skills [13].

b. Market Exploitation and Cheap Reproductions

- The commercial success of Saura-inspired designs has led to mass-produced, machine-printed fabrics that mimic Saura's aesthetics. These reproductions, while cheaper, often lack the authenticity, craftsmanship, and cultural significance of the traditional hand-drawn textiles [2].
- Artisans find it difficult to compete with these low-cost, synthetic alternatives that flood the mainstream market, making it harder for traditional Saura textiles to maintain their cultural and economic value [2].

c. Lack of Recognition and Market Integration

- While other Indian textiles such as Banarasi silk, Kanjivaram, and Pashmina are globally recognized and celebrated, Saura textiles have not achieved the same level of recognition in contemporary fashion markets. Their visibility and demand remain limited, which restricts opportunities for artisans to earn a sustainable livelihood [18].
- The absence of formal branding, certification, and structured artisan cooperatives further exacerbates this challenge. Without these elements, Saura textiles are unable to gain recognition within the global sustainable fashion market, and artisans struggle to market their work effectively [18].

These challenges highlight the urgent need for strategic intervention, including targeted government support, market access, and efforts to preserve the authenticity and cultural value of Saura textile art. By addressing these issues, the long-term viability of Saura textiles can be safeguarded, ensuring that this vibrant and meaningful craft continues to thrive for generations to come.

3.2 The Toda Textile Tradition

The Toda textile tradition originates from the Toda tribal community of Tamil Nadu, India, specifically from the Nilgiri Hills. Toda embroidery, locally known as "Pukhoor", is renowned for its intricate hand-stitched geometric motifs in red and black thread on a white fabric base. These textiles, primarily shawls and wraps, hold deep cultural and ritualistic significance, symbolizing Toda identity, heritage, and spirituality.

3.2.1. Distinctive Features of Toda Textiles

Table 3: Features of Toda Textiles

Feature	Description
Geographic Origin	Nilgiri Hills, Tamil Nadu, India.
Embroidery Technique	Hand-stitched geometric motifs often resemble warp and weft weave patterns.
Color Scheme	Predominantly red and black embroidery on an off-white or cream-colored fabric.
Cultural Importance	Traditionally worn during weddings, funerals, and festivals, representing tribal status and identity.
Artisanal Process	Entirely handcrafted by Toda women without the use of drawn patterns, relying on memory and skill.
Threats	Increasing machine-made imitations, lack of artisan incentives, and decline in younger generation participation.

3.2.2. Symbolism and Cultural Importance

Figure 4: The Culture Gully. (2023, May 24)

Toda embroidery is not merely decorative; it is a sacred expression of Toda heritage, deeply embedded with symbolic meaning. The geometric motifs in the embroidery represent natural elements, celestial bodies, and Toda legends, serving as a form of cultural storytelling. These intricate patterns depict mountains, rivers, trees, and celestial symbols like the sun and moon, establishing a connection between the earthly and divine realms. The white fabric base used in Toda embroidery symbolizes purity and spirituality, reflecting the Toda way of life, which emphasizes harmony with nature. Red and black are the prominent colors in the embroidery: red represents sacrifice and strength, while black symbolizes the earth and community bonding, highlighting the interconnectedness of life and the importance of unity within the community. The embroidered shawl, a significant part of Toda attire, is traditionally worn during major life events such as marriages, births, and funerals, marking important milestones and sacred transitions in the lives of Toda people. This intricate art form is thus a powerful cultural artifact, embodying both spiritual beliefs and the rich history of the Toda community.

3.2.3 Upcycling Potential for Toda Textiles

With the increasing demand for sustainable fashion and ethical sourcing globally, Toda textiles have immense potential for upcycling, blending traditional craftsmanship with modern design. Repurposing discarded or surplus Toda fabrics allows artisans and designers to create high-value fashion pieces while preserving the rich cultural heritage of the Toda community [13].

Figure 5: Toda Embroidery (Gupta, G., 2024)

i. Using Toda Embroidery Scraps in High-Fashion Accessories

ii. Leftover or damaged Toda-embroidered fabric pieces can be transformed into unique fashion accessories, such as:

- Bags, wallets, and clutches adorned with Toda motifs, blending tradition with practicality.
- Scarves and belts featuring intricate hand-stitched Toda designs add an artisanal touch to everyday wear.
- Jewellery embellishments, like fabric earrings or embroidered pendants, bring traditional artistry into the realm of fashion accessories.

iii. Reworking Traditional Toda Shawls into Contemporary Sustainable Garments

iv. Upcycled Toda textiles can be integrated into modern fashion, creating both stylish and sustainable garments, including:

- Jackets and coats featuring Toda patchwork, merging traditional designs with contemporary outerwear.
- Fusion wear, where Toda embroidery is combined with modern fabrics like denim, linen, or organic cotton, offers a unique blend of cultures.
- Minimalist dresses and tops that use Toda geometric patterns as accents, adding richness and heritage to simple, sustainable designs.

v. Integrating Toda Designs in International Sustainable Fashion Collaborations

vi. Toda embroidery can gain global recognition through collaborations with:

- Sustainable fashion brands, which can incorporate Toda motifs into their collections, emphasize eco-friendly and handcrafted textiles.

- Luxury brands, introducing Toda designs into exclusive, limited-edition couture collections, are elevating the cultural significance of the craft.
- Fair trade initiatives, ensuring Toda artisans receive fair compensation, promoting ethical sourcing, and supporting the broader movement for sustainable fashion.

By upcycling Toda textiles, designers can create modern, sustainable fashion while keeping Toda heritage alive and providing artisans valuable economic opportunities.

4. Case Studies of Successful Upcycling Initiatives

Indigenous textile upcycling traditions vary across regions, reflecting unique cultural identities while promoting sustainability. The table below provides a comparative analysis of Kantha quilting (West Bengal, India), Native American textile practices, and Godhadi quilting (Maharashtra, India), highlighting their upcycling techniques, cultural significance, and potential applications in sustainable fashion. This structured comparison offers insights into how these traditional crafts can be integrated into modern ethical fashion markets while preserving artisanal heritage.

5. Ethical Challenges and Solutions

While indigenous textile upcycling presents a sustainable and culturally enriching alternative to fast fashion, several challenges must be addressed to ensure ethical and equitable practices. The table below outlines key challenges, their impact on indigenous communities, and potential solutions for sustainable growth.

6. Conclusion

This study highlights the transformative potential of circular fashion in the revival and preservation of indigenous textile traditions, with a particular focus on Saura and Toda embroidery. These rich textile traditions, rooted in the cultural and artistic heritage of Odisha and Tamil Nadu, face numerous challenges, including declining artisan participation, market exploitation, and mass-produced imitations. However, through upcycling and sustainable fashion integration, these textiles can gain renewed relevance in contemporary markets while ensuring fair economic opportunities for artisans.

The upcycling of Saura textiles, with their geometric and spiritual motifs, offers a unique opportunity to integrate traditional storytelling and cultural symbolism into modern apparel and fashion prints. Similarly, Toda embroidery, known for its intricate geometric patterns in red and black, presents immense potential for sustainable fashion accessories and contemporary garments. By repurposing discarded materials and incorporating traditional designs into high-value, sustainable products, artisans can secure better income opportunities while preserving their craft.
However, the expansion of indigenous textile upcycling must be accompanied by ethical considerations and policy interventions. The risks of cultural appropriation, unfair compensation, and unsustainable scalability need to be mitigated through fair-trade certifications, artisan copyrights, and transparent supply chains. Governments, industries, and ethical fashion brands must take proactive steps to support artisan-designer collaborations, ensure fair wages, and promote cultural authenticity in the global market.

Table 4: Case Studies of Upcycling Initiatives

Textile Tradition	Geographic Origin	Upcycling Technique	Cultural Significance	Upcycling Potential in Fashion
Kantha Quilting	West Bengal, India	Hand-stitching old saris into quilts and garments	Represents storytelling, heritage, and women's artistry	Jackets, scarves, dresses, and sustainable fashion collections
Native American Textiles	North America (various tribes)	Reusing woven fabrics, beadwork, and repurposing ceremonial garments	Holds spiritual and tribal significance	Ethical fashion collaborations, beadwork on modern apparel
Godhadi Quilting	Maharashtra, India	Patchwork quilting using fabric scraps	Traditional rural craft promoting sustainability	Patchwork garments, home décor, and fair trade initiatives

Table 5: Challenges and Solutions in Indigenous Textile Upcycling

Challenge	Impact on Indigenous Communities	Proposed Solution
Cultural Appropriation	Loss of artistic ownership and misrepresentation	Fair-trade certifications & artisan copyrights
Scalability Issues	Mass production risks diluting craftsmanship	Artisan-designer collaborations for authenticity
Economic Exploitation	Unfair wages and lack of market access	Transparent payment models & ethical sourcing policies
Sustainability Trade-offs	Risk of unsustainable material sourcing	Ethical sourcing and fair wage policies
Lack of Transparency	Artisans disconnected from global markets	Blockchain-based transparent supply chains

By embracing circular fashion principles, the fashion industry can not only reduce environmental waste but also revitalize endangered textile traditions. This shift towards sustainable, ethical, and culturally respectful fashion offers a viable alternative to fast fashion, ensuring that indigenous textile artisans are recognized, fairly compensated, and empowered to continue their craft for future generations.

References

[1] Bhaduri, S. (2022). Sustainability and cultural heritage in the Indian textile industry: Opportunities and challenges. Sustainability Journal, 14(3), 1124

[2] Bose, P. (2020). Reviving India's tribal art: A case study of Saura painting in contemporary design. Indian Journal of Cultural Studies, 8(2), 67-84

[3] Brydges, T. (2021). Closing the loop on fast fashion: Exploring circular economy practices in the clothing industry. Journal of Cleaner Production, 278, 123882

[4] Bryman, A. (2021). Social research methods (6th Ed.). Oxford University Press

[5] Clark, H. (2020). Slow fashion: A movement for sustainability in clothing production and consumption. Fashion Theory, 24(2), 137-158

[6] Creswell, J. W., & Plano Clark, V. L. (2018). Designing and conducting mixed methods research (3rd Ed.). SAGE Publications

[7] Denzin, N. K., & Lincoln, Y. S. (2018). The SAGE handbook of qualitative research (5th Ed.). SAGE Publications

[8] Ellen MacArthur Foundation. (2020). A new textiles economy: Redesigning fashion's future. Retrieved from https://www.ellenmacarthurfoundation.org

[9] Ellen MacArthur Foundation. (2021). The Circular Economy in Fashion. Retrieved from www.ellenmacarthurfoundation.org

[10] Fletcher, K. (2014). Sustainable fashion and textiles: Design journeys. Routledge

[11] Fletcher, K., & Tham, M. (2019). Earth logic: Fashion action research plan. The J J Charitable Trust

[12] Fletcher, K., & Tham, M. (2019). Sustainable Fashion: Past, Present, and Future. Bloomsbury Publishing

[13] Jain, M. (2021). Preserving India's handloom heritage: Challenges and prospects. Textile Heritage Review, 12(1), 45-60

[14] Jain, R. (2022). Reviving Indian Handlooms through Sustainable Practices. Journal of Textile Research, 48(2), 85-102

[15] Kant, R. (2012). Textile dyeing industry: An environmental hazard. Natural Science, 4(1), 22-26

[16] Khan, M., & Malik, M. (2020). Consumer behavior in sustainable fashion: A market analysis approach. Journal of Fashion Marketing, 14(2), 85-102

[17] Khamis, N., & Njuguna, J. (2020). The impact of globalization on indigenous textile industries in developing countries. Global Fashion Review, 8(2), 88-104

[18] Mahapatra, K. (2019). Saura art and its influence on Odisha's textile industry. Journal of Indian Textile History, 15(1), 98-112

[19] Niinimäki, K., Peters, G., Dahlbo, H., Perry, P., Rissanen, T., & Gwilt, A. (2020). The environmental price of fast fashion. Nature Reviews Earth & Environment, 1(4), 189-200

[20] Pal, R., & Gander, J. (2018). Upcycling and the fashion industry: From waste to value creation. Journal of Fashion Marketing and Management, 22(3), 321-336

[21] Pattanaik, D. (2021). Sacred motifs in Indian tribal art: The spiritual narratives of Saura paintings. Journal of South Asian Arts, 9(2), 34-55

[22] Pink, S. (2021). Doing visual ethnography (3rd Ed.). SAGE Publications

[23] Sandin, G., & Peters, G. M. (2018). Environmental impact of textile recycling: A review. Journal of Cleaner Production, 184, 353-365

[24] Yin, R. K. (2018). Case study research and applications: Design and methods (6th Ed.). SAGE Publications

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Performance Evaluation of Knitted Fire-Retardant Mattress Cover Fabrics Manufactured on Circular Knitting Machine

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Abstract:

Recently, the demand for fire-retardant mattress covers is rising due to increasing safety regulations and growing consumer awareness. This study introduces a cost-effective and scalable approach to manufacturing fire-retardant knitted fabrics using circular knitting technology. Unlike the conventional core-spun yarn technique, which involves complex and expensive manufacturing steps, this research presents a simplified method by directly incorporating modacrylic ring-spun yarn and continuous filament fibreglass yarn into the knitting machine. Three fabric variants with varying GSM (220, 240, and 260) were developed and tested for structural integrity, air and water permeability, flame resistance, tensile and bursting strength, stretch and stretch recovery. Results demonstrate that higher GSM fabrics exhibit improved flame retardancy, mechanical strength, and recovery properties, although with reduced air and water permeability. This method offers a viable, efficient alternative for producing flame-retardant textiles suitable for home furnishing applications.

Keywords: *Circular knitting, Fibreglass yarn, Fire-retardant fabric, Flammability, Home textiles, Modacrylic yarn*

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1. Introduction

The textile industry has witnessed a transforming revolution with rapid developments in science and technology, resulting in innovative materials, extended functional uses, and the development of manufacturing processes. Once limited to fashion and clothing, textiles now cater to various sectors, from life-saving artificial organs to durable geotextile composites, expanding the boundaries of conventional utility. As the field of textiles expands, a requirement to incorporate safety and protection standards, particularly in areas closely related to daily human comfort and well-being [1, 2]. One such critical use is in the field of Hometech and Protech textiles, which is a fire-resistant mattress cover. These custom covers are intended to protect bedding materials from fire risks, performing a critical function in home safety. These fire-retardant mattress covers are generally made of inherently fire-resistant fibres like modacrylic, melamine, FR polyester, FR viscose, and fibreglass. These covers serve as a barrier, causing combustion to be delayed considerably and providing valuable time for escape during fire situations [3, 4].

Among the manufacturing techniques, circular knitting technology is prominent in creating such covers with interlock structures, providing durability, flexibility, and the capability of handling intricate yarn combinations. A commonly used approach involves core-spun yarns, where a continuous filament fibreglass core is wrapped with fire-retardant sheath fibres. The resulting fabric, used in its greige form, offers a fire-protective solution [4, 5]. Considering the combustibility of materials such as polyurethane foam, commonly used in mattresses, the use of fire-resistant covers is not only advisable but, in most areas, a requirement by law. Notably, legislation such as California's Assembly Bill 603 and subsequent national standards imposed by the U.S. Consumer Product Safety Commission have highlighted the significance of open-flame resistance in sleep products. Both the United States and the United Kingdom's statistical data verify that these steps have resulted in a substantial decrease in the number of fires, deaths, and related economic losses. The applicability of fire-retardant mattress covers is also on the rise in India, where the market for mattresses is expanding at a rapid rate. With a market size of mattresses expected to grow to USD 3.48 billion by 2030, driven by new and replacement demand, the scope for embracing fire-safe innovations in local manufacturing is huge [6]. Figure 1 shows the segmentation of the Indian mattress market based on its price.

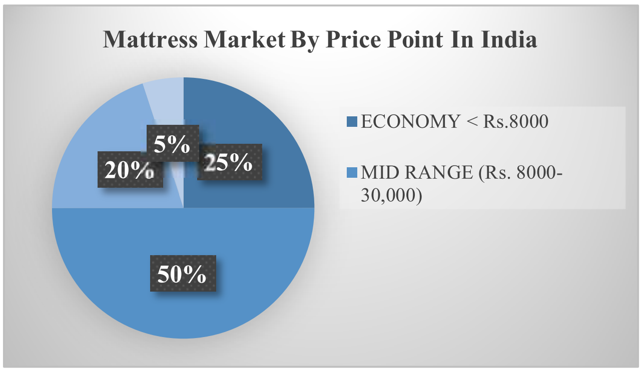

Figure 1 : Segmentation of Indian mattress market by price point [7]

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A commonly used method for producing fire-retardant fabrics with core-spun yarns with filament fibreglass core wrapped with fire-retardant sheath fibres is costly due to the additional manufacturing steps involved, and it requires specialised expertise to ensure effective performance [4]. In contrast, our approach knits both the yarns together by passing them through the same feeder and needle into an interlock structure, which simplifies the process and reduces the production cost.

Looking at the increasing demand for fire-retardant mattress covers, this article introduces an innovative technique for manufacturing such fabrics using circular knitting technology. It emphasises strategic material selection, process optimisation, and comprehensive performance evaluation. The method utilises technical yarns, including modacrylic ring-spun yarn and continuous filament fibreglass, and outlines the necessary modifications to knitting machines to efficiently handle these specialised materials. Apart from this, the study examines the structural, flammability, permeability, and strength characteristics of the fabrics using standardised testing procedures. Samples of different GSMs are considered to study a repeatable, viable, and scalable approach to producing fire-retardant fabrics that meet safety criteria and performance measures for the home furnishings industry.

2. Experimental Section

a. Raw Materials

Two technical yarns were used as raw materials for the development of fire-retardant knitted fabric. A ring-spun Modacrylic yarn of 30s Ne was procured from Hind Synthetics, Kolkata for its inherent flame-retardant properties, and 110 denier continuous filament fibreglass yarn procured from Saint Gobain India, Mumbai, to be used as the charring component.

b. Fabric Sample Preparation

The knitted fabrics were manufactured on a Mayer & Cie OV 3.2 interlock circular knitting machine of 30" diameter, 22 gauge, and 84 feeders. An alternative arrangement of knit and miss cam was set. Modacrylic yarn and continuous filament fibreglass yarn are fed to the Memminger IRO SFE positive feeder alternatively. The IRO feeder processing modacrylic yarn has an in-built tension setting for ring spun yarn, and the IRO feeder processing continuous filament fibreglass yarn has an in-built tension setting for filament yarn for better processability of yarn to the machine feeder. The Memminger IRO SFE positive feeding device has low rounds of yarn storage, due to which processing of continuous filament fibreglass yarn is better, as low bending is involved, and better stability is provided by this feeder for tension. The needles are kept at full clear setting for achieving a loose knit structure [13]. Fabric samples with three different GSM variants were prepared by changing the stitch setting. The sample abbreviation and its description are displayed in Table 1.

Table 1 : Details of the Modacrylic – glass fibre knitted fabric samples

Sample Code	Fabric Description	GSM
M220	Modacrylic–Fibreglass Knit Fabric	220
M240	Modacrylic–Fibreglass Knit Fabric	240
M260	Modacrylic–Fibreglass Knit Fabric	260

a. Testing methods

Random samples of all fabrics were tested after conditioning in standard atmospheric conditions (As per ASTM and IS standards) prior to testing. All tests were performed at Ahmedabad Textile Industry's Research Association (ATIRA), Ahmedabad, a NABL-certified laboratory.

Thread Density: Course-wise and wale-wise thread densities were assessed as per ASTM D3887-96, which is suitable for knitted fabrics.

Flammability Test: Vertical flammability test was performed according to IS 11871 method a, on a 315 mm × 50 mm specimen. A 38 mm luminous flame was used for 12 seconds at 19 mm from the base of the specimen. Specimens were tested and reported for char length, after-flame time, after-glow, and abnormal behaviour. 45° Flammability test was conducted according to IS 11871 Method B with specimens of 150 mm × 50 mm size. A 45° flame was imposed for a period of 1 second, and the flame spread time and ignition characteristic were measured.

Air Permeability: Tested according to ASTM D737, measuring the air flow rate perpendicularly through the fabric at a pressure gradient of 125 Pa.

Water Permeability: Tested with ASTM D4491, in which a water column passes through the fabric, and head changes over time are measured.

Tensile Strength: Tested with ASTM D5034-09. A 100-mm wide fabric sample was clamped and pulled to rupture. Breaking force and elongation were measured in course-wise and wale-wise directions.

Bursting Strength: Test was carried out according to ASTM D3786. Fabric was clamped over a diaphragm and burst through fluid pressure. Burst strength was obtained by subtracting diaphragm pressure from total rupture pressure.

Fabric Stretch and Recovery: Performed according to ASTM D3107. Benchmarks were drawn, and a standard tension was applied. Stretch at loading was measured, and recovery was computed after release of load through intervals of time.

3. Results and Discussion

a. Thread density

The relationship between GSM (grams per square meter) and thread density in both wale-wise and course-wise directions was investigated to understand the structural behaviour of the Modacrylic-Fibreglass knitted fabrics. The results are presented in Table 2 , which represents an increase in wale-wise thread density from 12 to 15 which resulted in a corresponding increase in GSM from 220 to 260 as well relative increase in fabric thickness from 0.84 mm to 1.25 mm. The denser arrangement of vertical threads (wales) leads to more yarn accumulation per unit area, contributing to higher fabric mass [8]. This increase in structural compactness enhances the thermal and physical properties of the fabric, which is essential for fire-retardant textile applications. In coarse direction, almost similar courses per inch were observed [9].

Table 2 : Thread density

Sample Code	GSM	Thickness (mm)	Thread Density	
			Wale/Inch	Couse/Inch
M220	220	0.84	12	28
M240	240	0.95	14	27
M260	260	1.25	15	27

b. Tensile strength

The tensile strength results are graphically represented in . It can be observed that in the wales direction, tensile strength increased with GSM, indicating that fabrics with higher GSM exhibited greater resistance to breaking forces compared to lower GSM samples. This can be attributed to the increased fabric density and yarn content, which contribute to higher mechanical strength [12].

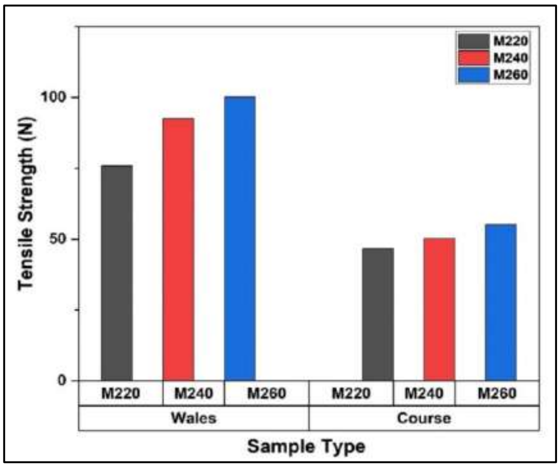

Figure 2 : Tensile strength of knitted fabrics

Similarly, in the course direction, the increase in tensile strength with GSM was relatively low. While higher GSM fabrics still exhibited improved strength, the variation was less pronounced compared to the wale direction. This suggests anisotropic behaviour in tensile properties, which is common in knitted fabrics due to directional yarn alignment and loop formation [12].

c. Fabric stretch and recovery

The fabric stretch and recovery was carried out width wise, the results are illustrated in Table 3. It was observed that the fabric stretch increased significantly as the GSM increased from 220 to 260. Sample M220, having the lowest GSM, showed the least stretch of 120%, as less loops are available for stretching. As the GSM increased to 240 (Sample M240), the fabric stretch rose to around 285%, demonstrating greater extension capacity. The M260 sample exhibited a fabric stretch of approximately 265%, slightly lower than M240 despite having a higher GSM. This non-linear trend in stretch behaviour suggests that while an increase in GSM generally leads to enhanced extensibility, beyond a certain point, the density and compactness of the fabric may begin to restrict the elastic behaviour due to the higher yarn interloping and reduced loop mobility. The fabric with GSM 240 seems to exhibit an optimal balance between yarn tension and loop structure, allowing maximum stretch under the test conditions. It can also be observed that as the GSM increased, the fabric's ability to recover from stretch also improved. This can be attributed to the increased density and structural integrity of the fabric at higher GSM levels. A higher GSM implies a tighter or heavier knit structure, which provides more resistance to deformation and enhances the elastic recovery of the fabric after being stretched .

Table 3 : Stretch and recovery property of knitted fabrics

Sample Type	Fabric stretch after 30 minutes (%)	Fabric recovery after 30 minutes (%)
M220	120.28	69.02
M240	280.09	86.94
M260	263.85	86.48

d. Bursting strength

Results of the bursting strength of modacrylic-fibreglass knitted fabric samples are displayed in Figure 3. It can be observed that as GSM increased, the fabric's ability to resist bursting force improved significantly. This enhancement in bursting strength can be attributed to the denser fabric structure at higher GSMs, which results in a more compact and mechanically robust knit. Increased yarn density contributes to stronger interlocking loops and a greater number of yarns per unit area, distributing applied pressure more effectively across the fabric surface [12].

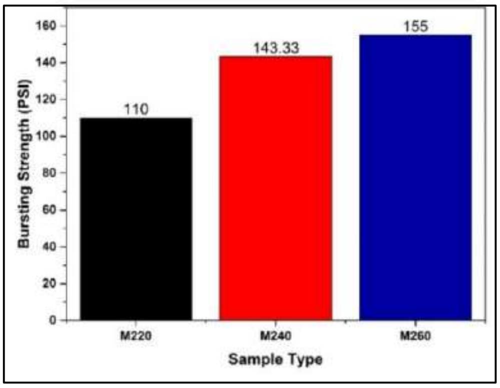

Figure 3 : Bursting strength of knitted fabrics

e. Air permeability

The relationship between GSM and air permeability of fabric is shown in Figure 4 . It can be observed Figure 4 that as the GSM increases from 220 to 260, the air permeability significantly decreases from 588 CFM to 374 CFM. This behaviour can be due to increased yarn content and reduced inter-yarn spacing, as fabrics with higher GSM possess a denser structure. This compactness hinders the passage of air through the fabric, thereby reducing permeability.

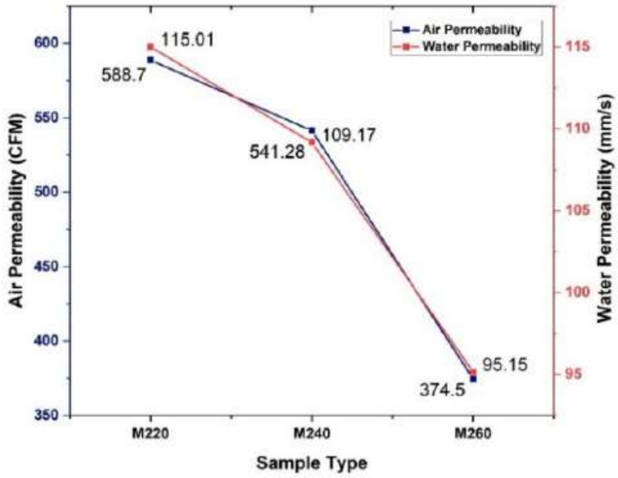

Figure 4 : Air permeability and water permeability of knitted fabrics

These results have important implications for the intended technical applications of the fabric. Higher GSM improves thermal insulation and mechanical strength. Therefore, the focus must be on achieving an optimal balance between protective properties, such as flame retardancy and structural integrity and the specific performance requirements dictated by the intended end-use of the fire-retardant textile [10] .

f. Water permeability

Water permeability determines the rate of water flow through the fabric structure. The relationship between GSM and water permeability is also illustrated in Figure 4. It can be observed that the M220 sample, which has the lowest GSM (220), recorded the highest water permeability (115.01 mm/s), while the M260 sample with the highest GSM (260) exhibited the lowest water permeability (95.15 mm/s). This can be due to a more open knit structure with greater porosity, allowing water to pass through more easily in case of lower GSM fabrics. In contrast, higher GSM fabrics are denser due to increased loop density and yarn content, which results in smaller interstitial spaces.

g. Flammability test

Vertical Flammability

The results of the vertical flammability test indicated that there was no edge or top flaming observed during the test. The samples did not exhibit any flaming or molten debris, and there was no after-flame or after-glow present. These results suggest that the samples possess good flame resistance and stability when exposed to a vertical flame source.

Char length, a key indicator of fabric resistance to flame spread, was measured in both wale and course directions. As shown in Figure 5 , for Wales, char length decreases with increasing GSM. The highest GSM sample (M260) exhibited the shortest char length (16 mm), suggesting better flame resistance. Conversely, the lower GSM samples showed longer char lengths, indicating higher flame susceptibility [11] .

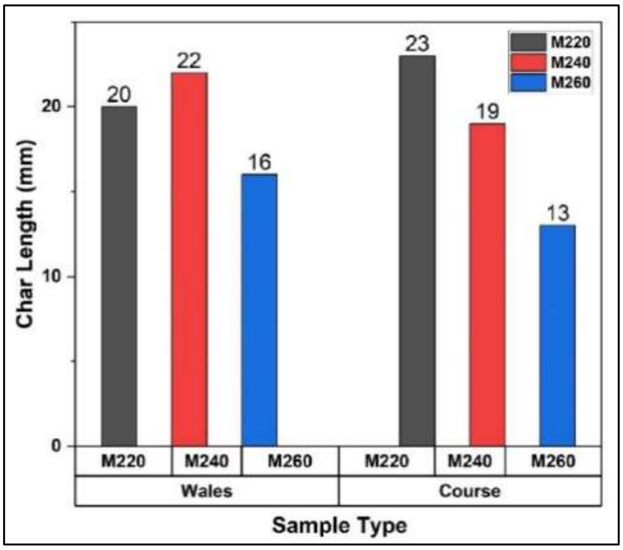

Figure 5 : Char length of knitted fabrics

The course-wise direction follows a similar behaviour. The M260 sample had the lowest course-wise char length (13 mm), while the 220 GSM sample exhibited the longest (23 mm). This inverse relationship confirms that higher GSM fabrics demonstrate improved flame resistance, likely due to denser fabric structure reducing flammability .

h. Flammability

The samples were also tested for 45° flammability, which states that the samples did not ignite.

4. Conclusion

The study successfully demonstrates an alternative method for producing fire-retardant mattress covers via circular knitting by incorporating modacrylic and fibreglass yarns directly into the fabrics. This method simplifies manufacturing, reduces cost, and avoids the additional processes with added complexity needed for core-spun yarns. Among the three fabric variations tested, the 260 GSM fabric had the best overall performance in terms of flame resistance, tensile and bursting strength, and elastic recovery, at the expense of lower air and water permeability. The 240 GSM sample showed the most balanced properties, making it potentially ideal for combining performance and comfort. The results signify that this approach is suitable for commercial processing of protective textiles for home use while expanding the potential for innovation for fire-retardant fabrics.

References

[1] N. D. Yilmaz, "Smart Nanotextiles Applications: A General Overview," in Smart Nanotextiles, John Wiley & Sons, Ltd, (2022) 1-85. Doi: 10.1002/9781119654872.ch1

[2] E. Fiorilli, "Sustainable textile processing: an in-depth analysis of environmental and workers well-being in the fashion industry," (2024) https://www.politesi.polimi.it/handle/10589/222538

[3] S. Nazaré, R. D. Davis, and K. Butler, "Assessment of factors affecting fire performance of mattresses: a review," Fire Sci. Rev., 1/1 (2012), 2, doi: 10.1186/2193-0414-1-2

[4] N. M. Aly, "8 - Fire protective textiles," in Advances in Healthcare and Protective Textiles, S. ul-Islam, A. Majumdar, and B. Butola, Eds., in The Textile Institute Book Series, Woodhead Publishing, (2023) 203-258. doi: 10.1016/B978-0-323-911887.00007-8

[5] Platanus Publishing, "Academic Research and Reviews in Engineering Sciences" (2023), Zenodo. Doi:10.5281/ZENODO.10060775

[6] "Flame Resistant Barriers for Home Furnishings - Alan C. Handermann", (2024) [Online]. Available:https://journals.sagepub.com/doi/abs/10.1177/1528083704039825

[7] A. K. Samanta, "A Review on Fire Protective Functional Finishing of Natural Fibre Based Textiles: Present Perspective,"Curr. Trends Fash. Technol. Text. Eng., 7/1 (2020), doi: 10.19080/CTFTTE.2019.05.555705

[8] S. Mukherjee, "Weft-Knitted Fabrics," in Textile and Clothing Design Technology, CRC Press, (2017)

[9] S. Agnihotri, J. N. Sheikh, S. P. Singh, and B. K. Behera, "Flame-retardant textile structural composites for construction application: a review," J. Mater. Sci., 59/5 (2024) 1788-1818, doi: 10.1007/s10853-023-09312-7

[10] Y. Tian, R. Ding, S. S. Yoon, S. Zhang, J. Yu, and B. Ding, "Recent Advances in Next-Generation Textiles," Adv. Mater.,37/8 p. 2417022, 2025, doi: 10.1002/adma.202417022

[11] A. R. Horrocks, "Fundamentals: Flammability, ignition, and fire spread in polymers," in Analysis of Flame Retardancy in Polymer Science, H. Vahabi, M. R. Saeb, and G. Malucelli, Eds., Elsevier, (2022) 1-72. doi: 10.1016/B978-0-12-824045 8.00001-0

[12] M.-S. Choi and S. P. Ashdown, "Effect of Changes in Knit Structure and Density on the Mechanical and Hand Properties of Weft-Knitted Fabrics for Outerwear," Text. Res. J., 70/12 1033-1045, Dec. 2000, doi: 10.1177/004051750007001201

[13] Priyam Patel and Aadhar Mandot, "Manufacturing of Fire Retardant Fabric Using Circular Knitting Machine" in Proceedings of the International Conference on Recent Advances in (Applied) Sciences & Engineering (RAISE), Faculty of Technology & Engineering, The Maharaja Sayajirao University of Baroda, Apr. 12-13,2023. [13] Priyam Patel and Aadhar Mandot, "Manufacturing of Fire Retardant Fabric Using Circular Knitting Machine" in Proceedings of the International Conference on Recent Advances in (Applied) Sciences & Engineering (RAISE), Faculty of Technology & Engineering, The Maharaja Sayajirao University of Baroda, Apr. 12-13,2023.

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Low Stress Tensile Properties of Needle Punched Nonwovens

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Abstract:

Background: *Even though for many decades, nonwovens have been used as interfacing materials in the form of fusible interlinings and reinforcements for collars and cuffs, in the clothing industry, little is known about their low stress tensile properties. In this study, we aim to explore the tensile performance of needle-punched nonwovens to verify whether they can be utilized as clothing.*

Methodology: *Polyester-viscose blend nonwoven fabrics were manufactured in three blend ratios (20:80, 50:50, 80:20), three mass per unit area values (100, 150, 200 g/m²), and three needle penetration depths (4 mm, 6 mm, 8 mm). The samples were tested for tensile linearity (LT), tensile energy (WT), tensile resilience (RT), and tensile extensibility (EM) in machine and cross directions. Statistical significance was determined by ANOVA.*

Results: *Mass per unit area had a significant effect on LT and WT, with LT increasing -particularly at greater needle penetration—and WT increasing in the machine direction but decreasing in the cross direction. Viscose-rich fabrics showed a greater increase in LT than polyester-rich fabrics. RT was higher in lightweight viscose-rich fabrics but was statistically invariant. EM was higher in the machine direction and was influenced by mass per unit area and needle penetration.*

Conclusion: *Through optimization of blend ratio, mass per unit area, and needle penetration depth, needle-punched nonwoven tensile behaviors including linearity, extensibility, and energy absorption can be optimized to a large extent. These can be successfully optimized through fibre mix and structure design, which further supports their potential application to functional and comfortable fashion garments.*

Keywords: *Blend ratio, Box-Behnken design, low stress mechanical properties, needle-punched nonwovens*

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1. Introduction

Nonwoven fabrics are predominantly used in technical applications such as geo-textiles, medical and healthcare products, agriculture and horticulture, filtration, packaging, and home furnishing [1-3]. Although nonwovens have long served as interfacing materials - particularly as fusible interlinings and reinforcements for collars and cuffs - their use in actual garment production has been minimal. Needle-punched nonwoven fabrics are gaining renewed interest due to their simplicity in processing and unique structural features. After reviewing the literature, it was found that while substantial work has been carried out on the physical and mechanical properties of needle-punched nonwovens made from various synthetic and natural fibres, especially for technical applications, no studies have reported their low-stress tensile properties. In several clothing applications, nonwovens are expected to perform under tensile, bending, shear, and compression loads of low magnitude. Although low-stress mechanical and surface properties of woven and knitted fabrics are well documented, similar investigations on needle-punched fabrics are limited [4-10].

In the present study, the effect of blend composition, mass per unit area and depth of needle penetration on these low-stress tensile properties of needle-punched nonwoven fabrics was investigated using Box-Behnken design.

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2. Material and methods

2.1 Preparation of nonwoven fabrics

Fifteen non-woven needle-punched fabric samples were prepared from polyester and viscose fibres, each having a linear density of 1.5 denier and a staple length of 51 mm. The mechanical properties of the fibres are listed in Table 1.

Table 1: Properties of polyester and viscose fibres

Fibre	Length (mm)	Fineness (denier)	Tenacity (gf/den)	Tensile strain (%)
Polyester	51	1.5	6.61	32.94
Viscose	51	1.5	3.30	21.15

Three factors, namely blend ratio, mass per unit area and depth of needle penetration were selected at three equidistant levels (Table 2). The Box-Behnken experimental design with three levels and three factors was used to prepare the samples.

Table 2: Three levels of factors

Factors	(-1)	(0)	(1)
Blend Ratio (P:V)	20:80	50:50	80:20
Mass per unit area (gsm)	100	150	200
Needle Penetration (mm)	4	6	8

The needle-punched nonwoven samples were produced at DKTE Centre of Excellence in Nonwovens, Ichalkaranji. The fibers were opened and blended by hand, and then fed to the blender for further intense blending. The blended fibers were fed to the Trutzschler card and the webs formed were oriented in a cross-machine direction using a cross-lapper to get the web of the required weight per unit area. The webs were then fed to the Trutzschler needling looms. For the first needling loom the line speed, feed rate, needle depth, and needle density were set to 0.96 m/min, 4.61 mm, 8 mm, and 136 / cm2 respectively. For the second needling loom the line speed, feed rate, and needle density were set to 1.53 m/min, 5.31 mm, and 188 / cm2 respectively. The needle penetration in the second needling loom was changed for each run as shown in Table 3.

Table 3: Parameters for each run

Run number	Fabric Code	Blend ratio (P:V)	Mass per unit area (gsm)	Needle Penetration (mm)
1	A1Y	20:80	100	6
2	C1Y	80:20	100	6
3	A3Y	20:80	200	6
4	C3Y	80:20	200	6
5	A2X	20:80	150	4
6	C2X	80:20	150	4
7	A2Z	20:80	150	8
8	C2Z	80:20	150	8
9	B1X	50:50	100	4
10	B3X	50:50	200	4
11	B1Z	50:50	100	8
12	B3Z	50:50	200	8
13	B2Y	50:50	150	6
14	B2Y	50:50	150	6
15	B2Y	50:50	150	6

P: Polyester, V: Viscose

2.2 Testing of nonwovens

All fabrics produced were conditioned for 24 hours in the standard atmospheric conditions (20±20 C temperature and 65±2 % relative humidity) before tested. Thickness of fabric was measured using Kawabata Evaluation System (KES) FB3 compression tester at 0.5 gf/cm2.

Tensile & shear properties were tested on KES-FB1 instrument. In the tensile mode, the fabric was mounted between two horizontal chucks A and B (one fixed and the other flexible) 5cm apart. The fabric between the chucks had dimensions of 5 x 20 cm. The mobile grip was allowed to move at a speed of 0.2 mm/sec. The sample was made to stretch uni-directionally up to the upper limit force of 500 gf and was thereafter retraced keeping both the rates of extension and recovery constant. The instrument provided results in terms of tensile linearity (LT), tensile energy per unit area (WT), tensile resilience (RT), and tensile elongation (EM).

3. Results and discussion

3.1 Statistical analysis

All the experimental results are listed in Table 4. For statistical analysis of the results, Design Expert software was used. Polyester % in the blend, mass per unit area and depth of needle penetration were fed as input variables and all KES tensile parameters were fed as response variables in the software. The summary of Analysis of Variance (ANOVA) for all low stress tensile properties is provided in Table 5. The parameters having p-values lower than 0.05 have a significant effect on response variables. The regression equations developed by the software for various responses are shown in Table 6. Correlation matrices for low stress tensile properties are reported in Table 7.

Table 4: Experimental test results

Parameter	Unit	A1Y	C1Y	A3Y	C3Y	A2X	C2X	A2Z	C2Z	B1X	B3X	B1Z	B3Z	B2Y
Thickness	mm	2.29	2.3	4.62	4.51	3.81	4.35	3.5	3.8	3.55	4.45	2.81	3.91	4.71
LT - MD	-	0.67	0.76	0.82	0.91	0.84	0.75	0.75	0.9	0.67	0.79	0.69	0.81	0.76
LT - CD	-	0.61	0.63	0.79	0.87	0.76	0.76	0.74	0.76	0.62	0.79	0.67	0.86	0.76
EM - MD	%	31.7	36	29.9	22.3	41.4	39.8	32.7	22.7	39.6	32.9	38.1	31.7	31.5
EM - CD	%	25.9	31.4	13.8	9.97	25	16.6	21.9	14.2	34.6	16.4	21.2	11.4	15.4
WT - MD	$gf.cm/cm^2$	52.7	68.5	60.9	49.7	87.2	74.5	61.3	51.2	66.5	64	66.2	64	59.3
WT - CD	$gf.cm/cm^2$	38.6	49.2	27.2	21.7	47.4	31.7	40.3	27.1	53.8	32.3	35.2	24.8	29.3
RT - MD	%	14.2	8.4	10.4	12.6	6.19	9.8	8.7	13	12.3	9.32	10.5	9.66	11.9
RT - CD	%	14.9	9.11	19.1	14.6	9.01	15.3	12.3	14.4	10.4	10.1	18.5	15.9	15.3

FO: fibre orientation, LT: tensile linearity, WT: tensile energy, RT: tensile resilience, EM: tensile strain

Table 5: Summarized ANOVA (p-values) for quadratic model terms

	Linear terms			Interactive terms			Square terms		
	P	M	D	P * M	P * D	M*D	P * P	M*M	D*D
LT - MD	0.079	0.007	0.555	0.209	0.027	0.381	0.027	0.298	0.86
LT - CD	0.419	0.004	0.135	0.492	0.713	0.693	0.244	0.259	0.46
EM - MD	0.151	0.359	0.006	0.391	0.152	0.126	0.113	0.107	0.682
EM - CD	0.182	0.004	0.081	0.759	0.477	0.309	0.343	0.168	0.599
WT - MD	0.97	0.221	0.076	0.839	0.743	0.609	0.786	0.666	0.81
WT - CD	0.143	0.007	0.084	0.321	0.247	0.443	0.559	0.414	0.194
RT - MD	0.642	0.483	0.761	0.215	0.396	0.885	0.403	0.9	0.995
RT - CD	0.642	0.483	0.761	0.215	0.396	0.885	0.403	0.9	0.995

P: Polyester % in the blend, M: Mass per unit area (gsm), D: Depth of needle penetration (mm)

Table 6: Regression equations and R2 values for LSM parameters

LT - MD	0.812 - 0.00878 P % + 0.00368 M - 0.0818 D+ 0.000067 P %*P % - 0.000009 M*M + 0.00091 D*D- 0.000018 P %*M + 0.000963 P %*D + 0.000180 M*D	0.9058
LT - CD	0.013 + 0.00548 P % + 0.00735 M - 0.0411 D- 0.000040 P %*P % - 0.000014 M*M + 0.00547 D*D- 0.000013 P %*M + 0.000171 P %*D - 0.000110 M*D	0.8712
EM - MD	48.2 + 0.279 P % - 0.196 M + 1.30 D- 0.00241 P %*P % + 0.000887 M*M + 0.123 D*D+ 0.000680 P %*M - 0.0305 P %*D - 0.0199 M*D	0.8889
EM - CD	129.1 - 0.425 P % - 0.697 M - 10.22 D+ 0.00255 P %*P % + 0.001412 M*M + 0.307 D*D- 0.00046 P %*M + 0.0269 P %*D + 0.0238 M*D	0.8872
WT - MD	88.8 - 0.188 P % + 0.009 M - 4.2 D+ 0.00131 P %*P % + 0.00076 M*M + 0.26 D*D- 0.00057 P %*M + 0.0229 P %*D - 0.0216 M*D	0.6066
WT - CD	166.1 - 0.365 P % - 0.508 M - 21.16 D+ 0.00197 P %*P % + 0.00101 M*M + 1.061 D*D- 0.00199 P %*M + 0.0594 P %*D + 0.0226 M*D	0.8713
RT - MD	12.4 + 0.094 P % - 0.070 M + 0.63 D- 0.00146 P %*P % - 0.000076 M*M - 0.002 D*D+ 0.001303 P %*M - 0.0213 P %*D + 0.0021 M*D	0.4824
RT - CD	12.4 + 0.094 P % - 0.070 M + 0.63 D- 0.00146 P %*P % - 0.000076 M*M - 0.002 D*D+ 0.001303 P %*M - 0.0213 P %*D + 0.0021 M*D	0.4824

Table 7: Correlation matrix for low stress tensile properties

	EM	LT	WT
LT	-0.81*		
WT	0.78*	-0.28	
RT	-0.32	-0.07	-0.61**

** = 1% level of significance* *** = 5% level of significance*

3.2 Tensile Linearity (LT)

Tensile linearity (LT) refers to the straightness of the load-extension curve. A value closer to 1 indicates a more linear and less extensible fabric behavior, typically associated with stiffer and more rigid fabrics. LT decreases with increasing non-linearity of the curve. Fabric extensibility in the initial strain range is high when the slope in the initial portion of the stress/strain curve is smaller. In the tested needle-punched nonwoven fabrics, samples such as C3Y and C2Z exhibited relatively higher LT values, indicating a more structured response to applied load.

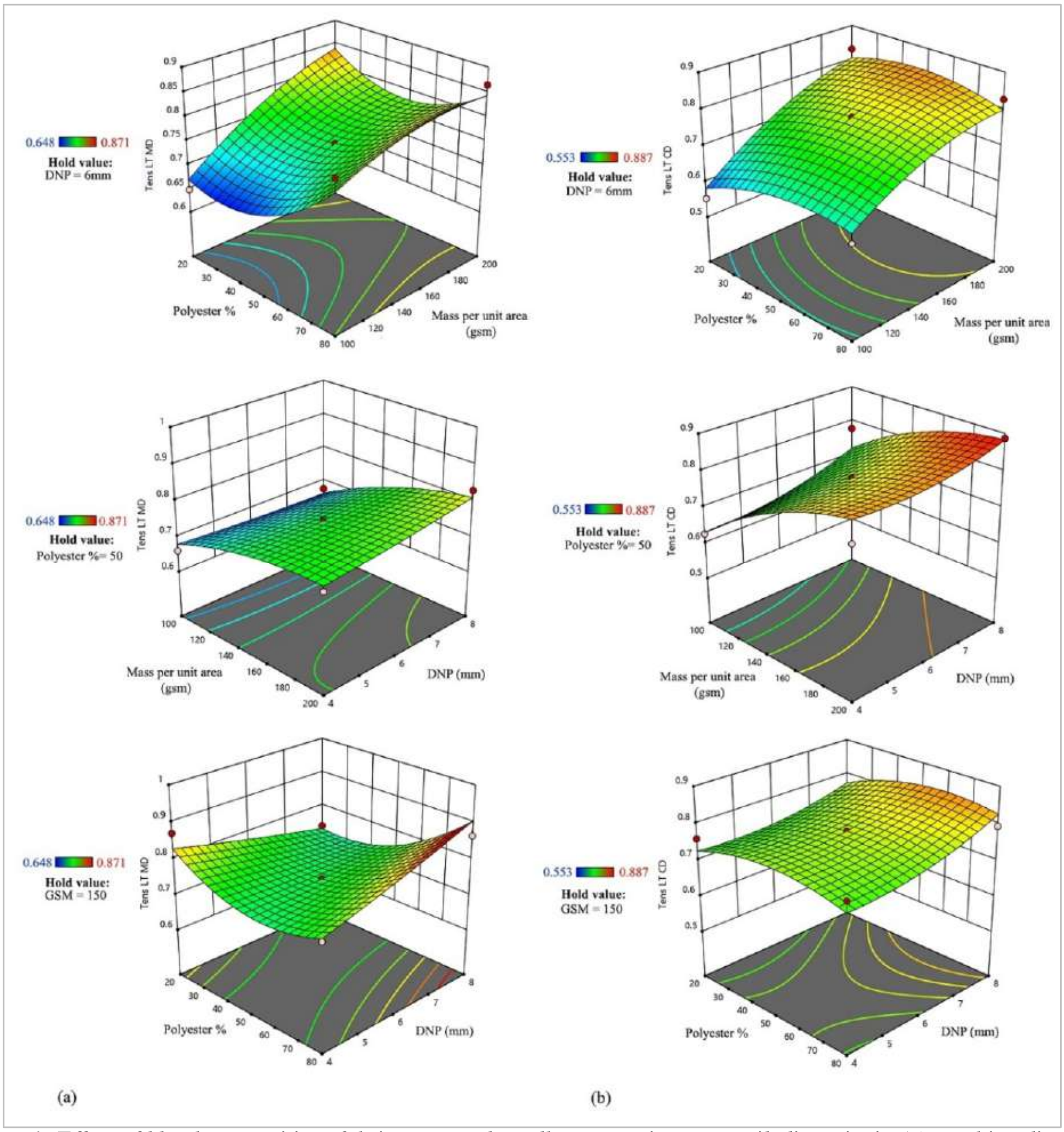

Figure 1: Effect of blend composition, fabric mass and needle penetration on tensile linearity in (a) machine direction and (b) cross direction

The ANOVA findings validate that the mass per unit area (GSM) has a significant influence on LT in machine direction (MD) and cross direction (CD). As shown in Figure 1, LT increases with the rise in the mass per unit area, particularly when combined with greater depths of needle penetration. This trend is due to the increased polyester fibre content at higher GSM, which improves fibre packing density, frictional resistance, and entanglement strength in the fabric. At lower mass per unit area, there are too few fibres to allow proper interlocking and, therefore, fibres under load slip more easily, with the result of lower LT. Higher mass per unit area leads to closer proximity between fibres, which leads to higher inter-fibre friction and a more compact structure and, therefore, better tensile linearity.

Polyester-rich nonwoven fabrics display greater LT values than viscose-rich fabrics at lower mass per unit area. Nonetheless, the increase in LT with mass per unit area is more pronounced in viscose-rich fabrics. It is attributed to the low bending rigidity and high packing density of viscose fibres, enabling more effective consolidation and close entanglement at higher mass per unit area and forming a denser and frictionally cohesive structure.

The depth of needle penetration (DNP) is also important, particularly at higher mass per unit area. With increasing DNP, fibre entanglement is more pronounced, enhancing the interlocking of the fibrous network and leading to increased LT values. There was a strong interaction ($p = 0.027$) between polyester content and DNP in determining LT in the machine direction, whereby greater DNP in polyester-rich samples resulted in a significant increase in LT because of enhanced inter-fibre bonding.

The trend of LT with changing polyester composition is also different in MD and CD. In MD, LT first decreases with an increase in the polyester composition and then increases. This is due to the fact that in cross-laid webs, fibres are mainly aligned in CD and thus exhibit initial slippage in MD when subjected to tensile stress. The structure gets stabilized only after this slippage, which is predominantly non-recoverable. But at very high polyester composition, the polyester resilience and stiffness override the effect of slippage, and LT starts increasing. In CD, the situation is reversed: LT initially increases as a result of improved entanglement but reduces slightly at very high polyester content because of lesser compactness of the structure and possibly less effective interlocking.

3.3 Tensile Energy (WT)

Tensile energy (WT) is the cumulative energy taken up by the fabric prior to breakage under tensile stress. WT is a direct indication of the ability of the fabric to resist load while deforming. Increased values of WT indicate improved mechanical performance and increased toughness of the material.

Experimental data indicate that WT is greater in the machine direction (MD) than in the cross direction (CD). This is a bit counter-intuitive given that fibres are mostly aligned in CD. Nevertheless, the phenomenon is accounted for by fibre reorientation in MD under load. In MD, fewer fibres are initially oriented, therefore when there is an applied tensile load, lots of fibres are reoriented towards the direction of the load, resulting in enhanced energy absorption and thus greater WT.

The mass per unit area has a statistically significant influence

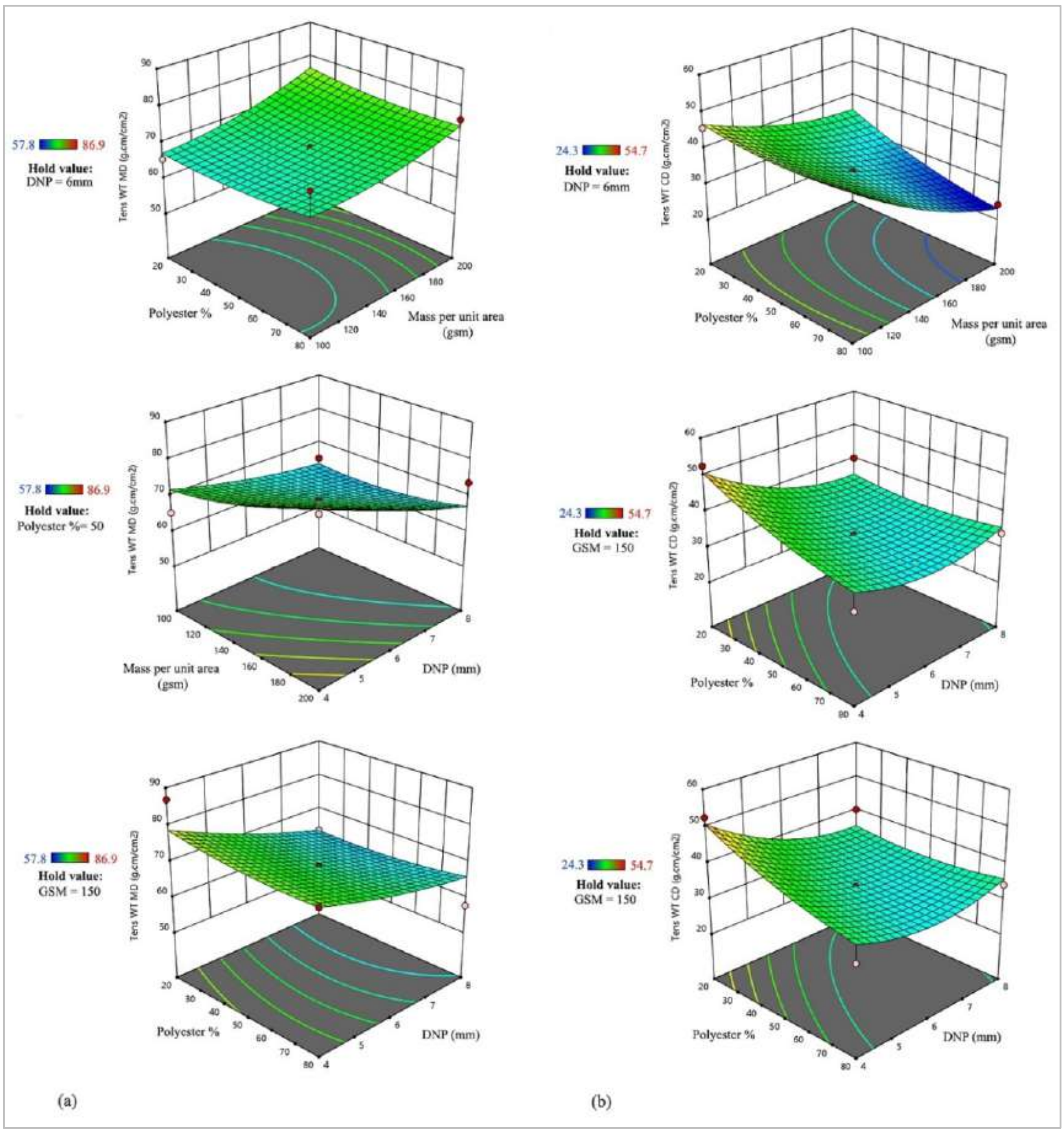

Figure 2: Effect of blend composition, fabric mass and needle penetration on tensile energy in (a) machine direction and (b) cross direction

(p = 0.007) on WT in the cross direction. With mass per unit area increasing, WT in the machine direction increases. This can be attributed to increased fibre reorientation under applied load and increased load-bearing capacity brought about by the higher volume of fibres in the structure. Conversely, WT falls in the cross direction with increased mass per unit area. The decrease can be explained by the tightness brought about by the increased fibre mass, which restricts the freedom and movement of individual fibres. Consequently, the energy absorption capacity of the fabric prior to breakage decreases in the cross direction at increased levels of mass per unit area.

3.4 Tensile Resilience (RT)

Tensile resilience (RT) refers to the capacity of the fabric to regain its original shape and structure after deformation under a tensile load. It is an important parameter in assessing the elastic recovery of fabric, especially relevant for fashion use where garments are subjected to repeat stretching during wear. Figure 3 illustrates effect of polyester content, GSM and DNP on the tensile resilience of needle-punched fabrics in machine and cross direction respectively. It was noted that lightweight viscose-rich fabric enjoys a greater tensile resilience than polyester-rich fabric of the same weight. Statistical analysis, though, reports that none of the factors tested mass per unit area, blend ratio, or depth of needle penetration had a statistically significant influence on RT in either machine or cross direction.

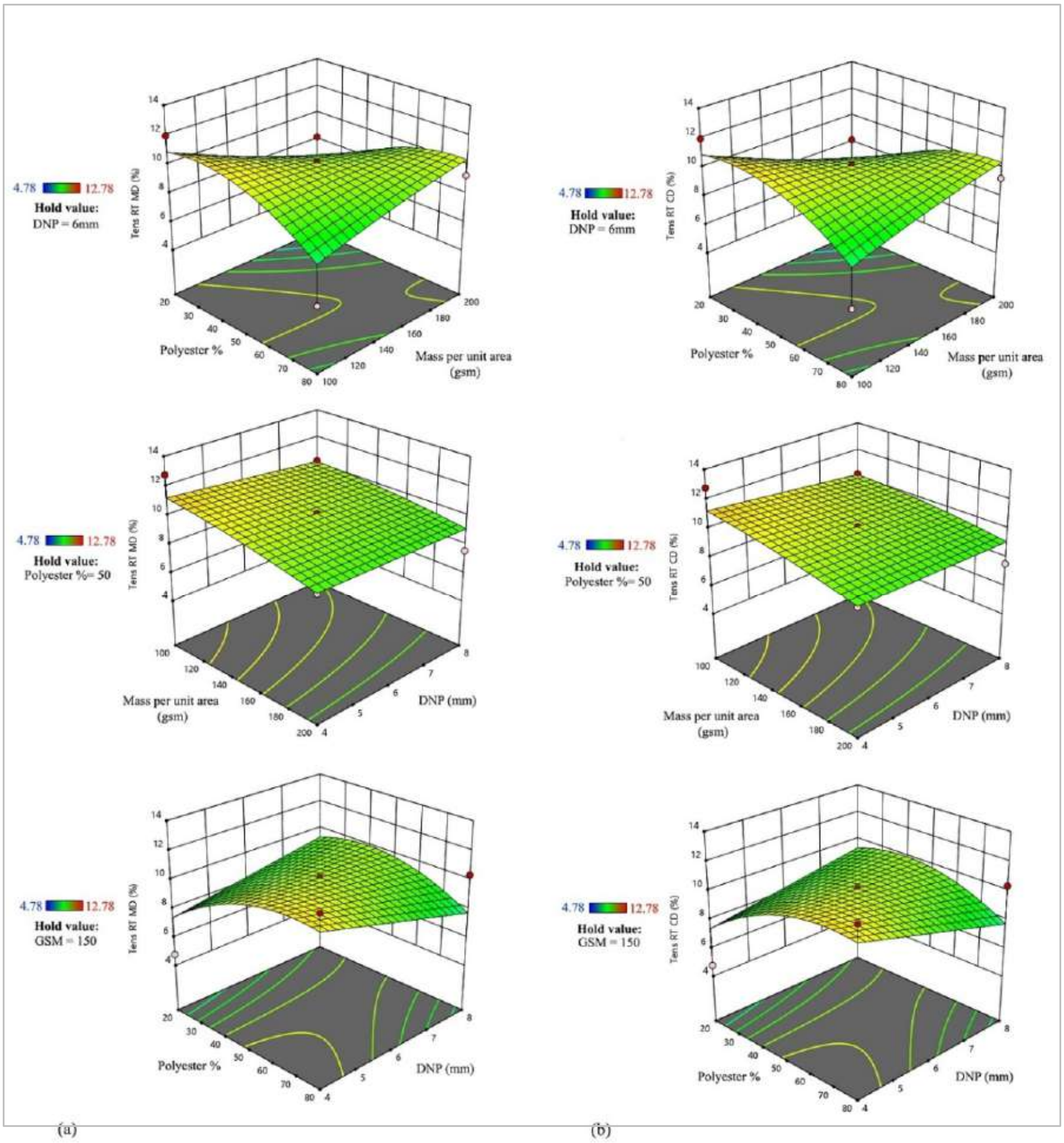

Figure 3: Effect of blend composition, fabric mass and needle penetration on tensile resilience in (a) machine direction and (b) cross direction

3.5 Tensile Extensibility (EM)

Tensile extensibility (EM) is the percentage of strain or extension that a fabric will sustain under tensile stress before it breaks. It is strongly related to WT, and consequently, the trends in EM follow very closely those for tensile energy. EM values tend to be greater in the machine direction compared to the cross direction. This is due to fibre orientation in cross-laid webs. Since the majority of the fibres are in the cross direction, the machine direction has fewer aligned fibres and thus lower cohesive force with easier fibre slippage and movement, which causes higher extensibility in the machine direction.

The statistical analysis demonstrated that depth of needle penetration strongly influences EM in the machine direction ($p = 0.006$), and mass per unit area strongly influences EM in the cross direction ($p = 0.004$). EM has a nonlinear relationship with respect to mass per unit area and polyester content in the machine direction. First, EM drops with increasing mass per unit area, presumably owing to decreased slippage resulting from greater fibre density. Above higher mass per unit area, EM rises as more fibres are present to reorient and become involved when under stress. Likewise, in polyester content, EM first rises because of greater fibre stiffness, then falls as too much polyester restricts flexibility and fibre mobility. In the cross direction, mass per unit area as well as polyester content cause EM to decrease. This is attributed to greater fibre orientation and compactness, which restrict fibre movement and slippage, thereby reducing overall extensibility. At deeper levels of needle penetration, EM values decline owing to greater fibre entanglement that restricts fibre mobility and constrains extension. This effect is more significant at greater mass per unit area, where dense structures already restrict movement.

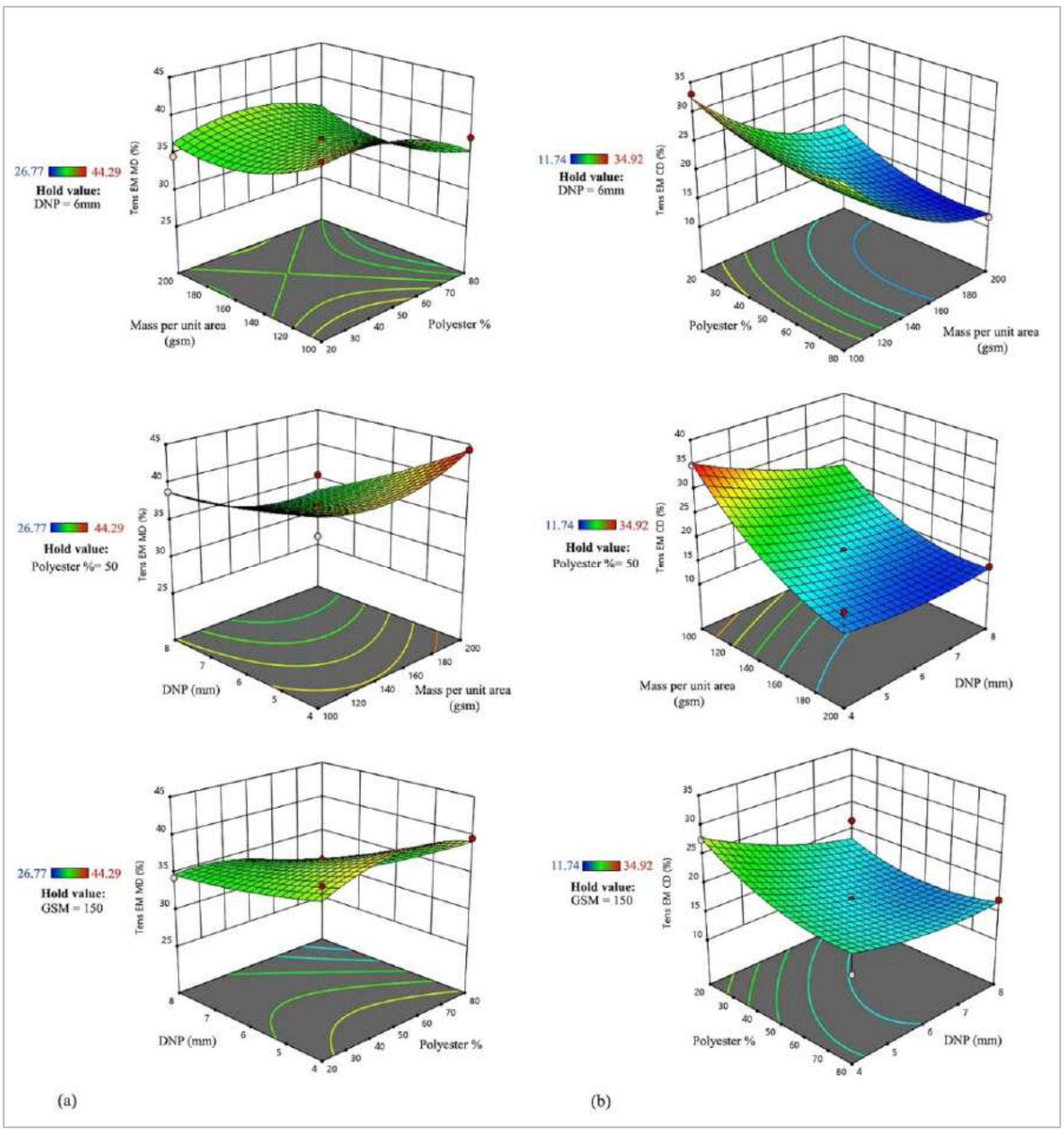

Figure 4: Effect of blend composition, fabric mass and needle penetration on tensile resilience in (a) machine direction and (b) cross direction

4. Conclusion

The research investigated the tensile properties of needle-punched nonwoven fabrics in terms of tensile linearity (LT), tensile energy (WT), tensile resilience (RT), and tensile extensibility (EM). Mass per unit area had a significant effect on LT and WT, with LT rising at higher values because of increased fibre entanglement, and WT exhibiting a directional response—increasing in the machine direction and decreasing in the cross direction. Polyester-dominant materials had increased LT with reduced mass per unit area, whereas viscose-dominant materials had a more pronounced increase in LT. RT was greater in lighter weight viscose-dominant materials but was not influenced significantly by any factor under investigation. EM was greater in the machine direction and was significantly influenced by needle penetration depth and mass per unit area. In total, the findings present that tensile properties of needle-punched nonwovens can be successfully customized by fibre composition and structural parameters, which endorses their viable use in fashion apparel applications.

References

[1] Russell, S. J., Handbook of Nonwovens, 1st ed., Cambridge: Woodhead Publishing Limited, 2007

[2] Batra, S. K., Pourdeyhimi, B., Introduction to Nonwovens Technology, DEStech Publications, Inc, 2012

[3] Chapman, R., Applications of Nonwovens in Technical Textiles, Cambridge: Woodhead Publishing Limited, 2010

[4] Newton, A., Ford, J. E., The production and properties of nonwoven fabrics, Textile Progress, 5 (1973), 1–86

[4] Purdy, A. T., Developments in non-woven fabrics, Textile Progress, 12 (1983), 1–86

[5] Hearle, J. W. S., Purdy, A. T., The structure of needle-punched fabric, Fibre Science and Technology, 4 (1971), 81–100

[6] Debnath, C. R., Needle punching of jute webs, Part III: Tensile properties of various compositions and blends of needle-punched fabrics, Indian Textile Journal, 89 (1978), 137

[7] Sankaran, V., Subramaniam, V., Effect of weave structures on the low stress mechanical properties of woven cotton fabrics, Fibres & Textiles in Eastern Europe, 20 (2012), 56–59

[8] Dhingra, R. C., De Jong, S., Postle, R., The low-stress mechanical properties of wool and wool-blend woven fabrics, Textile Research Journal, 51 (1981), 759–768

[9] Kawabata, S., Niwa, M., Wang, F., Objective hand measurement of nonwoven fabrics: Part I: Development of the equations, Textile Research Journal, 64 (1994), 597–610

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Kalamkari: The Story of Hand-Painted Chintz Fabric from Kalahasti – A Review

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Abstract:

This article is a descriptive narrative of the painted textile tradition of Kalamkari, represented as a religious form of painting depicting Hindu gods and goddesses on cloth. "Kalam" is the Persian word for pen, while "Kari" in Urdu means craftsmanship. This art form was first discovered in the 8th century and later developed under the patronage of the Mughal Empire, gaining popularity for its vibrant vegetable-dyed, hand-painted motifs on cloth created using a reed pen. Kalamkari is majorly produced in small towns of Kalahasti, Machilipatnam, and other interior regions of Andhra Pradesh by rural craftsmen and women and is a household occupation passed from generation to generation as heritage. The Kalahasti style of Kalamkari is based on Hindu mythology themes and has a narrative style constituting a "continuous method "depicting meaningful and connected sequential events taking place through many aspects of time. Created without machines or chemicals, this craft is now struggling to compete with machine-produced cloth. Therefore, this work aims to document the history, methods, and significance of Kalamkari painting, which has endured for centuries and still fascinates art aficionados worldwide.

Keywords: *Artisan, Crafts, Cultural expression, Social Practices, Sustainability, Traditional ecological knowledge*

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1. Introduction

Andhra Pradesh is home to the Kuchipudi dance form, beautiful music, and various crafts, with Kalamkari being among the most important. This art style grew and became established in Sri Kalahasti, a temple town 80 miles north of Chennai, near Tirupati. Kalamkari is a distinctive style of hand-painted or block-printed cotton fabric that originated in India. It is renowned for its elaborate motifs and vivid colors. Kalamkari means painting with a pen, amalgamating two Persian terms, "Kalam" (pen) and "Kari" (craftsmanship), which refer to the primary method of art [1]. These paintings are created on cloth using natural dyes and metallic salts called mordants to fix the dyes onto cotton fabric using a pen crafted from Bamboo or date palm stick with a pointed nib. The art form is closely associated with the temple tradition and was used to create intricate narrative depictions of various gods and goddesses from Hindu epics like The Ramayana, Mahabharata, and Bhagavata Purana art traditions on cloth. Animal shapes, floral motifs, and mehrab designs on textiles are more examples of Kalamkari patterns. Additionally, earthy tones like mustard, green, rust, Indigo, and black predominate in the color pallet [2].

2. History

Kalamkari is traditionally hand-painted with a bamboo pen and has a history that goes back 3000 years. It is believed that

Image: (1) Plan of Sriranganatha Temple, Srirangam Thanjavur, C 1830, British Museum Asia As1962, 1231, 0.13.1, (2) Ramayana canopy 2103-1883(15). Date C. 1881-1882 (Telugu Cyclical Year Vrisha) Artist Panchakalla Pedda Subbarayudu. Provenance: Chirala [2]

painted fabrics have been prevalent since the Indus Valley civilization before the advent of Christ, with archeological evidence claiming the discovery of hand-painted/printed resistive cloth in the 8th century C.E. [3]. Varahamihira, author of the voluminous Hindu text Brihasamhita belonging to the 6th century A.D., describes the dyes and the process of mordanting in fixing colors to cloth. Mordanting is derived from the Latin word Mordere (to bite). This is a process in which a mineral salt like Alum, Tin, or Chrome is applied to the cloth, which "bites" the fibers and makes it receptive to the dye. By this method, a fugitive dye is fixed and forms a color on the fabric, which is fast to wash and light [4, 5].

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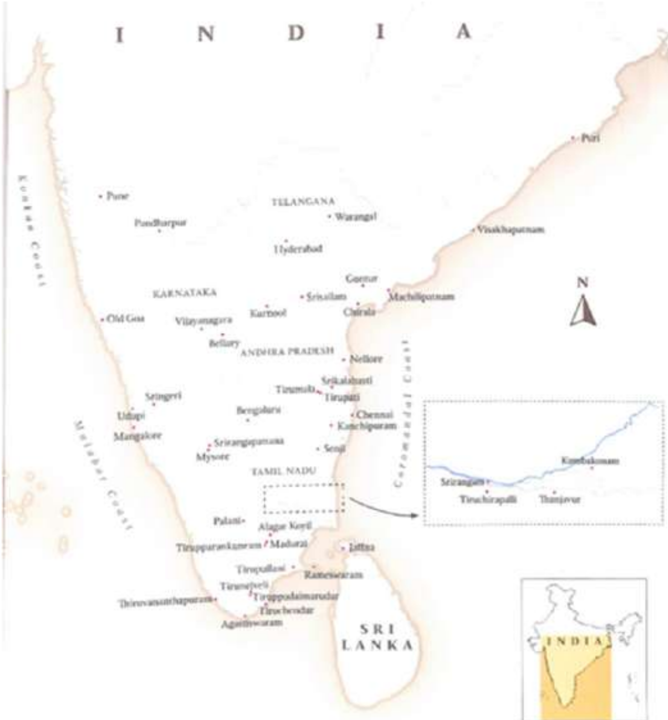

Image 2: Government of India maps with the Surveyor General of India [2]

The art form gained popularity as a temple art in the kingdom of Vijayanagar in the 16th century [6]. This was when Hindu traditions and customs were transferred orally by iterant minstrels, who would paint mythological figures on cloth and spread the name of Hindu gods and goddesses [7]. At the same time, similar painted textile techniques existed in western parts of India, with principal textile printing centers in the 16th and 17th centuries being "Burhanpur in Khandesh, Sironj in Rajputana (now M.P), Agra, Petaboli and Palakollu on the Golconda seaboard and certain towns like Kalahasti in the hinterland of Madras" [7]. The interconnection of the Western and Deccan styles took place in the early 16th century after the Vijayanagar Empire was vanquished by the Mughals when, after being discovered by the sultans of Golconda, it was given the name Kalamkari ("kalam" (pen) and "kari" (art)). It later flourished under the patronage of the Mughal emperors and the Golconda Sultanate. In 1665, while accompanying Emperor "Alamgir" French traveler Francos Bernie wrote about the floral fabrics sourced from Machilipatnam used as material for emperor tents, as noted by Sylvia Houghteling in her book "The Art of Cloth in Mughal India" [8–10]. Bernier appreciated the painted cotton cloths for their naturalism and fineness, attributing their beauty, vividness, and natural colors to the waters from the city "Maslipatam," also known as Masulipatnam and Machilipatnam, which he correctly located elsewhere in the text as the main port of the Deccan sultanate of Golconda [8]. Ancient literature gives substantial reference to kalamkari textiles' production, usage, and trade during the Mughal era, witnessing Persian influence in the technique, motifs, and technology after the Persian encroachment [11]. Chronicles written during that period(late 1640 or early 1640 CE) by Nizamuddin Ahmed, a Persian resident living in Golconda, describe the then reigning Mughal king Shah Jahan's patronage for the same printed cloths described by Bernier as "qalamkārī" in the text [9]. Shah Jahan, during that time, had issued a decree through his trusted minister Mirza Sadeq Qazvini, who went by the nickname "Chishro" from Golconda to Machilipatnam, commissioning the Kalamkari cloth (qalamkārī pārcha)from the artisans [10, 12]. Persian name Chit" or Chintz was the term given to Golconda's painted cloth, particularly Machilipatnam [13, 14]. The main Chintz-producing areas are "Pallakulu, Narsapur, Aramgaon,' Nizampattan, Pulicut, and San-Thome" [13]. The area became renowned for dyeing and painting cloth, calicos, and paintings, and the Chintz produced in this area became famous in England, Holland, and France, resulting in internal and trade exports [15]. The Chay root's easy availability, which enabled color fastness, was one of the reasons for Chintz production in this region, with several Dutch trade factories established there by 1676 [16, 17]. The designs were personalized, such as flowering trees, animals, and scenes of wine drinking and dancing with primary colors used: black, pink, red, violet, yellow, and green. The tools used were simple, such as the "Qalam" or the pencil, and the work depended on the craftsman's skill and the use of colors [18, 19]. The fabric continued to be traded under the Dutch and later the East India Company well into the eighteenth and nineteenth centuries [20, 21].

3. Process

Kalamkari scrolls are inspired by mythological stories, where stories from epics like Mahabharat, Ramayana, and Bhagavata Purana are depicted in a pictorial format. Predominantly used to spread the mythological world of the epics, Kalamkari scrolls are now used as temple cloths to formulate an illustrated narrative background or as visual narrative aid for the Hindu scriptures being retold. Srikalahasti in Andhra Pradesh is home to artisans dedicated to making this craft [22]. Current Kalamkari is not just mythological but takes inspiration from nature and the environment as well. The freestyle drawing using the Kalam with its bold black lines closely resembles the temple murals of the Vijayanagar empire of the 16th century, with its minimal usage of repetitions that were never suitable for block printing [23]. The Kalamkari paintings from this region have a definitive narrative style constituting a "continuous method" where they depict separate events taking place through many aspects of time, having a meaningful and connected sequence and consequence with each depicted event [24]. The pen, or Kalam, is used for freehand drawing and color filling in the Shri Kalahasti form of handcrafted art, with the style of paintings developed around the Hindu epics and inspired by the temples, giving it a sacred identity. This research is a result of an ethnographic study done in Srikalahasti in the months of May-June 2024, where the authors worked with a cluster of Kalamkari artisans (about 50 in number) to document the craft and understand the materials, design process and the artisan's interaction and livelihood with Kalamkari. The Srikalahasti style of Kalamkari follows the following process.

4. Tools

Kalamkari uses some basic tools to create a painting, a time-consuming and cumbersome task consisting of 23 steps [25].

- A cotton cloth wrapped around a bamboo reed to create a "Kalam" or pen
- The burnt branch of the Tamarind tree generates charcoal for sketching
- Cotton fabric for painting
- Buffalo milk for fabric processing and preventing dyes from leaking
- Mordant for fixing dyes, which are Alum
- Handmade dyes from Myrobalan flowers (Karakapuvvu) and buds (Karakapinde) intensify and preserve the colors.
- Water with Jaggery
- Wooden table upholstered in gunny
- Wooden trays for the paste
- Earthen pots, wooden mortars and pestles, and mud pots for the black dye. The 23 elaborate steps for a Kalamkari process are as following-

1. Fabric Selection: Premium silk or cotton fabric is selected.
2. Washing: Thorough cleaning of the fabric to get rid of contaminants.
3. Bleaching: Bleach and cow dung is used to give the fabric an off-white hue.
4. Soaking in Buffalo Milk: To stop colour bleeding, soak the fabric in buffalo milk.
5. Sun drying: It is the process of letting the treated fabric dry in the sun.
6. Stretching the Fabric: The fabric is layered flat at for painting
7. Charcoal Sketching: Tamarind pens or charcoal sticks are used to draw the main outlines.
8. Outlining with Kalam: A Bamboo or date palm pen (kalam) and black ink is used to, trace intricate outlines.
9. Applying Mordant (Alum): Alum solution is applied to areas that will be dyed red or another colour.
10. Drying After Applying Alum: The mordant is given time to set, the fabric air dries for one to two days.
11. Washing Out Extra Alum: The fabric is washed to remove excess alum.
12. Plant-based dyes are used to create red, yellow, green, and other hues is known as "natural coloring."
13. Drying After Dyeing: After every colour application, the fabric is left to air dry.
14. Application of Wax Resist: (in the Machilipatnam style) Applying wax to areas that shouldn't be dyed blue.
15. Indigo dyeing involves soaking the fabric in indigo to turn it blue, then removing the wax with a scraper.
16. Washing After Indigo: The cloth is rinsed to get rid of extra wax and indigo.
17. Milk Treatment (Optional): The fabric is soaked in the milk to stop colour bleeds during the next steps (less common now).
18. Colouring with Other Dyes: Kalam is used to apply other colours.
19. Removing Extra Colour: To remove extra dye, wet cotton is pressed against coloured areas.
20. Final Washing: The fabric is rinsed well to get rid of extra colour and contaminants.
21. Sun Drying: To set the colours, the fabric is dried in the sun.
22. Ironing: It is the process of pressing wrinkles out of fabric.
23. Finishing and Quality Check: Verifying the finished product's quality and getting it ready for retail.

5. Preparation of Cloth

Kalamkari begins with the preparation of the cloth. To remove contaminants, a white cotton fabric is sun-dried in water for a whole night. After another wash, it simmers for around 30 minutes in a container. After removing the Myrobalan seeds and soaking them in water for an entire night, they are filtered, and the juice is combined with raw buffalo milk. The fabric is then immersed in the solution and ground with buffalo milk, flower paste, and myrobalan buds. In addition to cleaning the fabric, this procedure prepares it to absorb the colors and mordants properly. The fabric is triple-washed in running water and sun-dried to get an even off-white color and silky texture.

6. Outlining and Sketching

Charcoal pencils created from burned tamarind branches are used for the initial drawing on the processed cloth. Using a pencil for details, the design is traced using a kalam dipped in "Kasim Kaaram," which is a color solution prepared using rusted iron filings, cane, and palm jaggery and fermented in water within a sealed clay pot for 21days and filtered. The artist delicately presses the cotton ball of Kalam, bringing the dye color into touch with the fabric. When it interacts with a cloth treated with myrobalan, this black color becomes darker. Using a gentle cloth, the artisan removes any extra outline color, after which the fabric is rewashed.

Image 3: Outlining and sketching on fabric. Source: Author Shreya Jhavar & Aastha Ranjan

7. Colour Preparation and Colouring the Designs

The red color is obtained by using Alum as a mordant. To achieve the darker red tones when painting, the "Kasim Kaaram" is necessary; additionally, Alum is applied once for softer red hues. After two days of drying, the painted alum cloth is cleaned under running water. During the boiling process, 300 grams of Suruduchakka, one kilogram of powdered chavalakodi tree root, and half a kilogram of Alum are added to boiling water as natural dyes, which impart the color crimson. The fabric is then washed for three days in water until the cloth is bleached while the colored areas remain the same [25]. Boiling water in an earthen or metal vessel with Myrobalam flowers yields a yellowish-colored dye. The indigo plant's color is used to create the color blue. If set for several days, the yellow solution can turn slightly greenish. Otherwise, green color can be obtained by painting portions with the Myrobalam yellow solution and then treating the same cloth portion with indigo dye. Green is also made by combining myrobalan flower, Kasim karma, and Alum diluted with water [26, 27]. When the black outline dries, the artist applies mordant along with Alum adding red colour to cloth. Once the color dries, the fabric is again washed and dried, and other colors, Indigo and then yellow color, are added to the painting; Orange is created by painting yellow onto red, while Indigo is added onto yellow areas to create green. The fabric is washed after every color application, making it at least twenty times before the final coloring is complete, making Kalamkari dyeing an extremely vigorous and time-consuming process. Kalam with tapered edges is used for color filling. A chisel is used for tapering [26, 28].

8. Themes and Motifs

The Kalahasti style of Kalamkari depicts mythological themes, religious figures, scenes from epics, flora-inspired motifs, animals, and scenes depicting wine, drinking, and dancing [18]. Each Kalamkari is a piece of art reflecting cultural history and symbolizing the spiritual value of the themes [29]. The primary motifs are flowers derived from the Persian and Mughal-styled blossoms [13, 20]. Deities like Ram, Laxmi, Durga, Brahma, Krishna, Parvathi, and Shiva are represented in vibrant colors of yellow and blue, and demons are described in red and green [30]. They are themes taken from the epics where "Dasavathara," the ten incarnations of lord Rama, Vishnu, Krishna, and Arjun, discourse from the epic Mahabharata and the "tree of Life" symbolizing the ancient symbol of life, death, and the afterlife.[31,32]. Hindu goddesses Sita and Lakshmi, the goddess of prosperity, abundance, knowledge, and fortune, are also the prime topics of many Kalamkari works.

Image 4: Filling Colours in Kalamkari Designs, washing, boiling with the next colour, and then drying (Author Shreya Jhavar & Aastha Ranjan)

Image 5: Title (1) "Dasavathara," (2) Krishna Arjun discourse Source:[33] and (3) Rama Seeta painting from Indian epic Ramayana.Artist: Sankaraiah from Srikalahasti, Andhra Pradesh, 1980s. [34]

Image 6: Title (1) Kalamkari Rumal shows scenes of courtly life involving figures in both Persian and Indian dress 1640-50 (Accession Number: 28.159.1), (2) 19th-century Kalamkari Hanging (Accession Number: 08.108.3), (3) Late 18th century Temple cloth celebrating Krishna (Picchavai) (Accession Number: 2019.452.1) at The Metropolitan Museum of Art

9. Current Kalamkari

Indian textiles have garnered considerable appreciation worldwide due to their usage of sustainable materials, eco-friendly dyeing printing, and finishing techniques. Kalamkari is a technique that uses hand skills, organic methods, indigenous tools, and a soulful portrayal of nature and epics embodying organic fashion. The craft is struggling to keep pace with the machine loom and printed fabrics, trying to adapt to the dynamic market orientation [22]. The Kalamkari in Srikalahasti was used to make temple clothes with paintings of Gods and Goddesses, which depicted scenes from Hindu epics. As time passed, the workers had set according to the market's needs as their product ranges varied among the artisans. Using fabrics for products like Apparel, furniture, Wall hangings, home accessories, footwear, handbags, lampshades, etc., enables sales and livelihood for artisans and reservation of art [35]. Color was important in Kalamkari culture, and new colors have been added to the traditional color palette of black, red, blue, yellow, and green. Today, hues like brown, orange, grey, maroon, and pink are also seen. A comparable change is also seen in the way base textiles are used. A wider range of materials, including georgettes, chiffons, crepes, and raw silk, is added to the coarse cotton to expand its potential as a fashion fabric [26].

The Indian government is committed to supporting Kalamkari as an ancient textile and is doing so by GI tagging the craft and supporting artisans through financial aid, recognition, and opportunities through various craft clusters, fairs, and exhibitions [36, 37]. The government also helps the artisans get yarn at concessional rates and offers credit/loans at discounted interest rates to alleviate the craftsman's status and help preserve the craft [38]. Handloom marketing schemes offering insurance coverage and NGOs providing new sales and marketing opportunities are some other platforms for the craftsman [39–41]. One of their most well-known projects is Craftmark, a program designed to identify the most authentic Indian handicrafts made in an ethically conscious manner. Over 80 craft businesses have embraced Craftmark, reaching out to more than 100,000 craftspeople in 23 Indian states [42].

10. Conclusion

Kalamkari is not just a traditional craft but a reflection of India's age-old heritage. Srikalahasti is a flourishing center for hand-painted Kalamkari textiles using natural vegetable dyes, creating an eco-friendly, sustainable, and consumer-friendly textile [6]. Despite competition from chemical-dyed and machine-made printed fabrics, the art has managed to sustain its allure and is sought by designers, textile manufacturers, and brands to create new products in Apparel, furnishing, home accessories, and products with the unique Kalamkari painted on them. The Kalamkari artisans are, hence, trying hard to retain their heritage by nurturing their devotion to the Indian heritage craft in the face of modernity and globalization.

References

[1] C. Sharad, Kalamkari, the Art of Painting with Natural Dyes - The Chitrolekha Journal on Art and Design, Chitrolekha Journal on Art and Design 5 (2015) 1–2. https://chitrolekha.com/kalamkari/ (accessed August 26, 2024)

[2] D. L.Anna, C. Rosemary, C. Devi, Kalamkari Temple Hangings, 1st ed., Mapin Publishing, London, United Kingdom, 2015. https://www.mapinpub.com/products/kalamkari-temple-hangings?variant=43522006843606 (accessed July 29, 2024)

[3] Exotic India, The Art of Kalamkari: Vibrant Hand-Painted Textiles of India | by Exotic India | Medium, Medium.Com (2024) 1–2. https://medium.com/@exoticindiaa/the-art-of-kalamkari-vibrant-hand-painted-textiles-of-india-4263403bd2bf (accessed August 26, 2024)

[4] S.S. V. Panditabhushana, B.R. M.Vidwan, Varahamihira's Brihat Samhita with an English Translation and Notes, V.B.Soobbiah & Sons, Bangalore, 1947. https://www.wisdomlib.org/hinduism/book/brihat-samhita (accessed August 21, 2024)

[5] N.I. Chidambaram, Brihat-Samhita of Varaha-Mihira (Set of Two Volumes), Parimal Publications, Delhi, 2024

[6] G. Meera, The Story of Indian Calico that changed the world, Marasim.Co (2024) 1–2. https://blog.marasim.co/the-story-of-indian-kalamkari/ (accessed August 26, 2024)

[7] S. Maddala, V.R. Chiruvoori, The Ancient Art of Kalamkari: Problems and Prospects with Special Reference to Pedana, Andhra Pradesh, International Journal of Science and Research 9 (2020) 1099–1103. https://www.ijsr.net/getabstract.php?paperid=SR20713172207 (accessed August 26, 2024)

[8] tr I.B. Bernier François, Travels in the Mogul empire, W. Pickering, London, 1826. https://www.loc.gov/item/05007866/ (accessed August 21, 2024)

[9] S. Houghteling, The art of cloth in Mughal India, 1st ed., Princeton University Press, USA, 2022

[10] I.A. Review, Kalamkari and the Fame of Machilipatnam Cloth, Indiaartreview.Com (2022) 1–2. https://indiaartreview.com/stories/book-extract-the-art-of-cloth-in-mughal-india-kalamkari/ (accessed August 26, 2024)

[11] I. Culture, Textiles and Fabrics in Medivial India, Indianculture.Gov.In (2024) 1–2. https://indianculture.gov.in/node/2730143 (accessed August 26, 2024)

[12] U. Desk, Kalamkari: An Ancient Style of Hand Painting, Utsavpedia.Com (2024) 1–2. https://www.utsavpedia.com/motifs-embroideries/kalamkari-art/ (accessed August 28, 2024)

[13] S. Seema, Golconda Chintz: Manufacture and Trade in The 17th Century on JSTOR, Proceedings of the Indian History Congress 49 (1988) 301–305. https://www.jstor.org/stable/44148394 (accessed August 29, 2024)

[14] K.H. Yusuf, Selected Waqai of the Deccan, Central Records Office Hyderabad, Hyderabad, 1953

[15] R. Tapan, Jan Company in Coromandel, 1605-1690: A Study in the Interrelations of European Commerce and Traditional Economies., M. Nijhoff, Netherlands, 1962, https://books.google.co.in/books/about/Jan_Company_in_Coromandel_1605_1690.html?id=cyu6AAAAIAAJ&redir_esc=y (accessed August 29, 2024)

[16] M. Streynsham, The Diaries of Streynsham Master, 1675-1680, and Other Contemporary Papers Relating Thereto, Vol. 1: The Diary, 1675-1677 (Classic Reprint), 2019. https://www.amazon.in/Diaries-Streynsham-1675-1680-Contemporary-Relating/dp/1331894115 (accessed August 29, 2024)

[17] S.R. Burn, S.C. Fawcett, The Travels of the Abbe Carre in India and the Near East, 1672 to 1674 Volume II, 1st ed., Hakluyt Society, India, 2010. https://www.amazon.in/Travels-Abbé-Carré-India-Near/dp/1409414620 (accessed August 29, 2024)

[18] H.M. John Irwin, Indian Painted and Printed Fabrics, Calico Museum of Textiles, Ahmedabad, 1971. https://www.indianculture.gov.in/ebooks/indian-painted-and-printed-fabrics (accessed July 5, 2023)

[19] F.W.S. Company India East, Charles Frederick, Letters received by the East India Company from its servants in the East, S. Low, Marston & Company (Limited), London, 1896. https://archive.org/details/cu31924073059853 (accessed August 30, 2024)

[20] J. van Goor, Trade, Research and Science Under the Dutch in Asia, Revista de Cultura - International Edition (2006) 142–150

[21] G. Das, Linkages between self-congruity, brand familiarity, perceived quality and purchase intention: A study of fashion retail brands, Journal of Global Fashion Marketing 6 (2015) 180–193. https://doi.org/10.1080/20932685.2015.1032316

[22] D.M.C.R. Jyoti Phogat, A Study Of Kalamkari Scroll Paintings In Particular And Temple Murals In Andhra Pradesh- A Structural Analysis, Journal of Pharmaceutical Negative Results 13 (2022) 1823–1831. https://doi.org/https://doi.org/10.47750/pnr.2022.13.S08.219

[23] V. Lotika, South Indian Traditions of Kalamkari, National Institute of Design, Ahmedabad, 1982. https://books.google.co.in/books/about/South_Indian_Traditions_of_Kalamkari.html?id=KkDrAAAAMAAJ (accessed August 27, 2024)
[24] L.P. Hinchman, S. Hinchman, Memory, Identity, Community: The Idea of Narrative in the Human Sciences, 1st ed., State University of New York Press, New York, 1997. https://philpapers.org/rec/HINMIC (accessed August 27, 2024).
[25] A. Chahna, The Process of Kalamkari Explained, Memeraki.Com (2024) 1–2. https://www.memeraki.com/blogs/posts/the-process-of-kalamkari-explained?srsltid=AfmBOorKprzepfpouEUItSAvfGf0kdcNwWWiQC59lz7-4PxOybhxEioR (accessed September 2, 2024)
[26] D.A. Rani, Beautiful Timeless Art: Kalamkari Painting, Journal of Commerce & Trade 16 (2021) 54–57. https://doi.org/10.26703/JCT.v16i2-10
[27] Dr. Samyukta Priti, A Comparative Study of Batik and Kalamkari Paintings-With Special Reference to Telangana and Andhra Pradesh, krishna Publication House, Bhavnagar,Gujrat, 2021. https://books.google.co.in/books?hl=en&lr=&id=8rFuEAAAQBAJ&oi=fnd&pg=PA1&dq=kalamkari+motifs&ots=_k4_4N-CZK&sig=K1dF2QbIrRcScnYXQv2AymuFJ90&redir_esc=y#v=onepage&q=kalamkari motifs&f=false (accessed August 30, 2024)
[28] C. Sharad, Kalamkari, the art of painting with natural dyes, Chitrolekha International Magazine on Art and Design 5 (2015) 82–88. https://books.google.co.in/books?hl=en&lr=&id=GKI5DwAAQBAJ&oi=fnd&pg=PA82&dq=kalamkari&ots=sxw-QlxD9g&sig=0ROqWqms5W5YxOU_xuZYlEr7PCA&redir_esc=y#v=onepage&q=kalamkari&f=false (accessed August 21, 2024)
[29] V. Gite, How The Intricate Motifs Of Karuppur Kalamkari Paintings Transcend Time, Connecting Us To Shared Human History, Forbes India (2023) 1–2. https://www.forbesindia.com/article/lifes/how-the-intricate-motifs-of-karuppur-kalamkari-paintings-transcend-time-connecting-us-to-shared-human-history/88779/1 (accessed September 3, 2024)
[30] W.A.J. Baral Bibhudatta Prof., Susanth C., Kalamkari Painting The Art of Fabric Painting using Natural Links, D'Source (2024) 1–2. https://www.dsource.in/resource/kalamkari-painting/products (accessed September 3, 2024)
[31] T.H. Desk, Tree of Life gives new lease of life for Kalamkari, The Hindu (2016) 1–2. https://www.thehindu.com/news/national/andhra-pradesh/Tree-of-Life-gives-new-lease-of-life-for-Kalamkari/article14583527.ece (accessed September 3, 2024)
[32] T.N.I.E. Desk, Reviving ancient Kalamkari through 'Tree of Life,' The New Indian Express (2018) 1–2. https://www.newindianexpress.com/bengaluru/2018/Apr/24/reviving-ancient-kalamkari-through-tree-of-life-1805927.html (accessed September 3, 2024)
[33] C. Mala, Embark on a Colorful Journey into the Traditional Kalamkari Art of Andhra Pradesh: A Fusion of History, Mythology, and Imagination, Cultureandheritage.Org (2023) 1–2. https://cultureandheritage.org/2023/06/kalamkari-art-of-andhra-pradesh.html (accessed September 3, 2024)
[34] M. Flitsch, A. Isler, P. von. Wyss-Giacosa, Kalamkari : Erzählstoff aus Indien, Völkerkundemuseum der Universität Zürich, 2016. https://www.musethno.uzh.ch/en/Exhibitions/archiv/kalamkari.html (accessed September 3, 2024)
[35] B. Suvarna, D. Anitha, Development of Designs from Sculptures of Amaravathi for Application on Kameez Material, International Journal of Science and Research 8 (2018) 2319–7064. www.ijsr.net
[36] Myscheme.gov.in, National Handloom Development Programme: Concessional Credit/Weaver MUDRA Scheme, Ministry of Textiles (2024) 1–2. https://www.myscheme.gov.in/schemes/nhdpccwms (accessed August 30, 2024)
[37] T. of M. Handlooms Commissioner Development, Home Page National Handloom Development Program, Myhandlooms.Gov.In (2024) 1–2. https://myhandlooms.gov.in/Home/NHDP.aspx (accessed August 30, 2024)
[38] T. of M. Handlooms Commissioner Development, Concessional Credit/Weaver MUDRA Scheme, Myhandlooms.Gov.In (2024) 1–2. https://myhandlooms.gov.in/Home/WeaverMudraLoan.aspx (accessed August 30, 2024)
[39] Ministry of Textiles, Mahatama Gandhi Bunkar Bima Yojana, Myscheme.Gov.In (2024) 1–2. https://www.myscheme.gov.in/schemes/mgbby-odisha (accessed August 30, 2024)
[40] Dastkari Haat Samiti, Dastkari Haat Samiti, Dastkarihaat.Com (2024) 1–2. https://dastkarihaat.com/?srsltid=AfmBOopnzbuYmGL-TEh3JVj4GqD3RXfDubOhO1wMurkNIiAZlj6NYnlr (accessed August 30, 2024)
[41] AIACA, All India Artisans and Craftworkers Welfare Association, All India Artisans and Craftworkers Welfare Association (2024) 1–2. https://www.aiacaonline.org/ (accessed August 30, 2024)
[42] A. Mamidipudi, Crafting innovation, weaving sustainability: Theorizing Indian handloom weaving as sociotechnology, Comparative Studies of South Asia, Africa and the Middle East 39 (2019) 241–248. https://doi.org/10.1215/1089201X-7586764

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Optimized Hybrid Features Enhance ML-Driven Defect Detection and Quality Control in Textiles

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Abstract:

This work aims to investigate the utilization of ML algorithms to detect defects in textile production processes. Traditional textile inspections rely on manual methods, which are time-consuming, inconsistent, and prone to error. The research seeks to develop and evaluate ML algorithms like SVM, CNN, Random Forest, and KNN to detect imperfections, including surface texture, color quality, and structural flaws. Special attention is paid to such factors as texture, color, and edge detection for their contribution to improving the accuracy of defect recognition. It is revealed that a higher accuracy rate of 96.7% is achievable when CNNs are applied with feature extraction methods, and they have better precision, recall, and F1-score measures. It also evaluates the enhancement in the quality control by presenting the difference in the production of defect-free fabric before and after the implementation of the ML-based system, where significant enhancements were observed. This study demonstrates a 10.3% increase in defect-free fabric rate after implementing the hybrid CNN-based ML model. These studies suggested that incorporating machine learning to improve the quality of textiles has the prospect of being a better approach than the traditional methods of detecting defects in textiles.

Keywords: *Convolutional Neural Network, Defect Detection, Edge Detection Feature Extraction, Hybrid Features, Textile Manufacturing*

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1. Introduction

Machine learning-defect detection in being developed to be a strong solution in the textile manufacturing industry as a result of detecting quality defects [1]. Generally, the initial defect examination occurs through human assessment, which is not efficient, subject to deviation, and inconsistent. Machine learning algorithms however offer a much more efficient and accurate approach to the detection, as it automates the whole process which improves its efficacy both in terms of speed and accuracy when it comes to quality control [2]. Largely focusing on numerous amounts of textile data, it is possible to train machine learning algorithms to recognize different sort of defects like surface defects, color discrepancies and structure defects necessary for high level of quality in textile products. These can lead to reduction of cost, reduction in wastage and ensure that only perfect products are produced to come to the market [3].

The integration of machine learning method in the textile inspection also resolves issues that may arise due to the diversified type of textile fabrics, and the complexity of identifying small imperfections that are not visible to the naked eye [4]. The CNN allows to extract the features automatically from the given textile images and identify the defects easily and with higher accuracy. Similarly, support vector machines (SVM), random forests, k-nearest neighbours (KNN) classifiers have also been further developed in the clothing industry for the classification of defects [5]. All these models are unique in a way that they can handle large data as well as the fact that they can be built into different textures for manufacturing.

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While traditional ML models use single features like color or texture alone, this approach often fails to detect complex or subtle defects. By integrating texture, color, and edge-based features, hybrid feature models provide a richer representation of the textile image, leading to improved classification accuracy and reduced false detections.

Figure 1 depicts common defect-free woven fabric structures. Subfigure (a) is a plain weave pattern, identified by its uncomplicated crisscross pattern of warp and weft yarns, creating a closely packed and even texture. Subfigure (b) is a twill weave pattern, identified by its diagonal rib pattern, which is caused by the weft yarn passing over one or more warp yarns in a regular sequence, providing greater flexibility and a softer drape than the plain weave.

One must quantify how machine learning fits into quality control of textile products as a factor in the success of machine learning [6]. Manufacturers can show the level of quality enhancements of their products by measuring the number of defects found before and after training the system. It is specifically in terms of defect percentage and

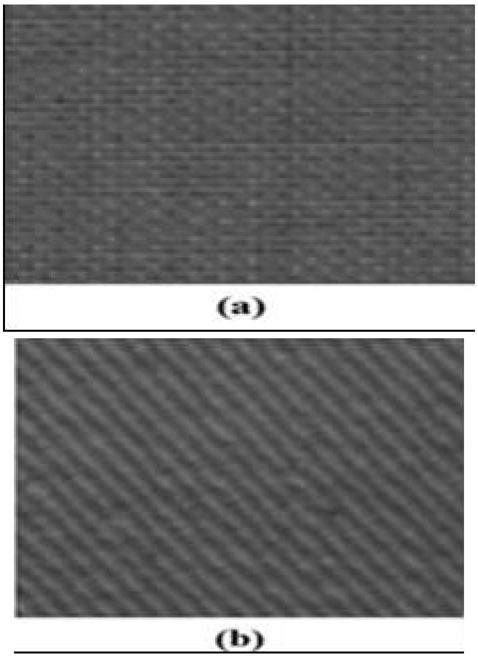

Figure 1: Typical defect-free fabrics (a) plain (b) twill

minimization of false positives or false negatives to highlight the value of machine learning. This review also reveals enhancements in the detail efficacy of the strategies of detecting flaws in addition to the enhancement of the general reduction of textile wastage due to enhanced quality control initiatives [7].

Figure 2 presents comparative photographs of knitted textiles, illustrating structural variations between defected and defect-free specimens. Subfigure (a) illustrates even, defect-free fabric with well-formed loops all over the fabric, which represents proper knitting. For comparison, subfigure (b) illustrates defected fabric in which the patterns of loop distortions are observable, denoted by horizontal lines and distortions that break the normal pattern, representing possible defects during knitting.

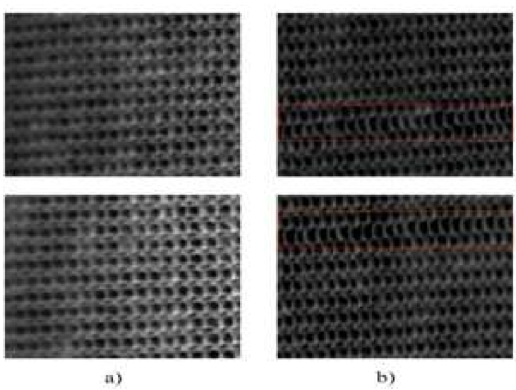

Figure 2: a) defect-free b) defected fabric images

In addition, this quantitative methodology gives textile producers some understanding of the performance of various machine learning models, enabling them to select the most appropriate algorithm according to the particular needs of their production processes [8]. The capacity to optimize machine learning algorithms for different types of textile materials, manufacturing conditions, and types of defects presents a degree of personalization that was not possible with older inspection techniques [9]. With the textile sector further integrating digitalization, applications of machine learning in the areas of defect inspection and quality inspection will soon be the industry benchmark, heralding a new wave of accuracy, efficiency, and sustainability.

Figure 3 presents' two fabric images for defect detection. (A) Defect-Free Fabric Image represents a textile sample without any visible defects, serving as a reference for quality control. (B) Fabric Image shows a textile sample that may contain defects such as surface irregularities, color mismatches, or structural deformations. These images are used in machine learning models for training and evaluation of defect detection algorithms.

A. Research Objectives

The Research Objectives of the Study Are as Follows:

- To develop machine learning models for defect detection in textile manufacturing.
- To evaluate the impact of feature extraction techniques on defect detection accuracy.
- To quantify improvements in quality control by implementing machine learning-based systems.

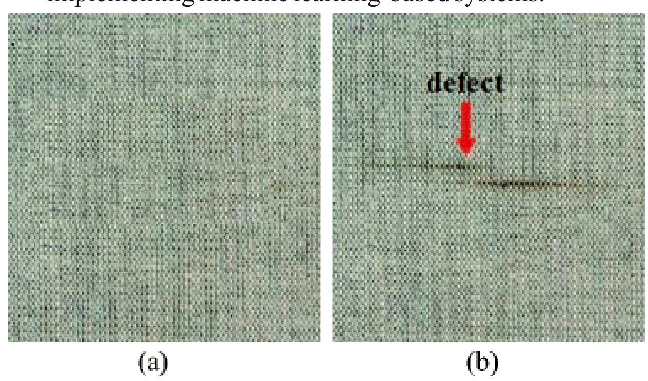

Figure 3: Fabric Images: (A) Defect-Free Fabric Image, (B) Fabric Image

2. Review of Literature

The authors of [8] investigated the use of machine learning techniques for quality control in textile fabric manufacturing. They implemented various ML algorithms to automate the detection of defects and improve the reliability of quality assessment in production settings. Their study demonstrated that integrating supervised learning models significantly reduced manual errors and inspection time, while increasing the consistency of defect classification across different fabric types. The work validated the role of ML in sustainable and smart textile production environments.

The authors of [9] explored the limitations of hand-crafted feature methods and proposed a hybrid deep learning framework for structured defect identification. They found that traditional systems struggled to adapt across varying fabric textures, while CNNs could generalize better when trained with appropriate augmentation.

The authors of [10] investigated the use of deep learning for improving the quality assurance of textiles using a sophisticated fabric defect detection system. The study confirmed the efficiency of deep learning models in automating defect inspection, minimizing the amount of labor required in traditional manual inspections, and overall enhancing the quality control in textile production. They used a convolution neural network (CNN) system for defects inspection, which has been trained for identifying the various types of defects in textiles by using a huge number of images as input.

The authors of [11] researched fabric defect classification and detection by proposing an improved version of the Mask R-CNN model. Their work was in the area of enhancing the object detection models to incorporate effective feature extraction techniques. Regarding holes, stains, and weaving defects of the textiles, the proposed model was as accurate as, or more accurate than, current methods. The analysis showed that the augmented Mask R-CNN model improved the accuracy and recall of the defects compared to conventional methods.

The authors of [12] provided a comprehensive review of feature learning techniques for the classification of defective images in the textile industry. They evaluated models such as CNN, SVM, and ensemble learning using Keras, concluding that deep learning approaches significantly outperform traditional techniques in textile defect detection. However, they also acknowledged the value of low-cost traditional models like SVM and Random Forest for less complex scenarios.

The authors of [13] developed a deep learning-based strategy for detecting financial fraud in e-commerce platforms. Their model integrated convolutional neural networks with behavioural data analysis to identify fraudulent transactions with high precision. Although their work focused on financial security, it demonstrated the effectiveness of deep feature learning in recognizing complex and non-linear patterns, a principle that is similarly applicable to identifying subtle defects in textile manufacturing processes.

The authors of [14] examined an automated inspection of fabrics using deep learning algorithms, focusing on developing a high-efficiency CNN-based model to detect fabric defects.

The authors of [15] proposed a machine learning-based solution for textile defect detection to improve manufacturing quality. Several ML techniques, particularly deep learning architectures, were adopted to enhance accuracy in classification and detection. They emphasized that deep learning outperformed traditional statistical methods, and also highlighted practical challenges such as limited datasets and computational power.

The authors of [16] presented an unsupervised method for fabric defect detection using spatial domain saliency and feature clustering. Their work eliminated the dependency on large labelled datasets by applying clustering algorithms to identify defect patterns, thus reducing annotation costs while improving efficiency.

The authors of [17] designed a hybrid feature aggregation model that demonstrated enhanced performance by combining texture, edge, and spatial pattern analysis. Their work, though applied in the network domain, confirmed that hybrid feature fusion improves model interpretability and precision—an approach applicable to textile inspection as well.

3. Research Methodology

The main purpose of this research is therefore to examine the role of ML techniques [18] in quality control and defect identification in manufacture of textile products. The work uses quantitative research approach based on secondary data and employs different machine learning models for developing, validating and assessing the impact of the developed intelligent and efficient defect detection systems. The remaining sections describe the specific approaches, processes, and methods used in the current research study [19].

A. Data Collection and Pre-processing

No primary data will be collected in this research; therefore, the secondary data can be in textile datasets or synthetic datasets. Such datasets can consist of images or sensor data coming from the textile production systems and including samples of both defective and non-defective products. The TILDA and FabricNet datasets consist of over 3,000 high-resolution textile images annotated with 7 common defect types, such as holes, color inconsistencies, and pattern misalignments. The image resolution is standardized to 256x256 pixels to ensure uniformity during training.

The study utilizes datasets such as TILDA, DAGM, MVTec AD, and Fabric Net, which contain real-world textile defect samples. Additionally, synthetic datasets may be generated using data augmentation techniques to enhance model robustness [20]. These datasets include both defective and non-defective textile samples to ensure balanced model training. Features cleaning, normalization and augmentation activity as a way of improving the quality of data will be

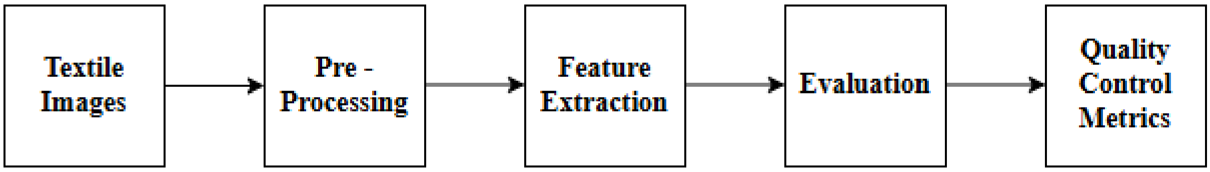

Figure 4: Pipeline for Hybrid Feature-Based ML Defect Detection in Textiles

Table 1: Summary of Feature Extraction Techniques

Feature Type	Methodology	Use Case	Expected Impact on Detection Accuracy
Texture	Haralick Features, LBP	Identifying surface irregularities	High accuracy for patterned textiles
Color	Color Histograms, Moments	Detecting color mismatches	Improved detection for colored defects
Edge Detection	Canny, Sobel	Highlighting structural defects	Helps in detecting boundary issues

carried out on the datasets in a way that they become suitable to feed into a learning model. Splitting the set of input data into training, validation, and test sets will be done to evaluate the separated models.

Use of Feature Extraction Techniques. Feature extraction plays a critical role in improving the accuracy of defect detection models. The following techniques will be employed. Picking up texture details by employing techniques like Haralick features or Local Binary Patterns (LBP) for identifying surface irregularities. Examining color histograms, color moments, and other color-related features to determine color-related defects. Applying edge detection algorithms like the Canny or Sobel operators to emphasize boundaries and structural problems in the textile images.
Features were selected based on experimental testing, model validation scores (accuracy, F1-score), and expert knowledge of textile defect patterns. Combinations showing higher average precision and recall were retained. This approach ensures that the selected features are not only statistically effective but also practically relevant to the types of defects encountered in real-world textile manufacturing [21].

B. Model Development

In the present work, some of the machine learning algorithms will be designed and trained to identify defects in the production of textiles. Some of these include Support Vector Machines (SVM), Scheduler, Convolution Neural Network (CNN), Random Forest and K- Nearest Neighbour (KNN). SVM will be used in binary classification to classify non-defective and defective texts in textiles. CNNs will be applied to extract features automatically from fabric images for an enhanced and more accurate classification of the defects. The chosen algorithm is Random Forests, which is an ensemble method to combine many decision trees to reduce the probability of over fitting the data because the model [22] will be more generalizable. Last, a proximity technique referred to as KNN will sort the defects based on similarities of an image to similar images and can be simple

Table 2: Machine Learning Models for Defect Detection

Model Type	Description	Advantages	Limitations
SVM	Binary classifier using hyperplanes for separation	Good for high-dimensional data	Sensitive to noisy data
CNN	Deep learning for feature extraction from images	High performance on image data	Requires large amounts of data for training
Random Forest	Ensemble method using decision trees for classification	Handles overfitting well	Not as efficient with high-dimensional data
KNN	Classification based on proximity to nearest neighbours	Simple and intuitive	Computationally expensive with large datasets

yet effective in detecting the defects. In general, these models will provide a systematic approach in increasing the defect identification in textile manufacturing.

C. Model Evaluation and Validation

The metrics to be used for the evaluation of the performance of the developed machine learning models include accuracy, precision, recall, and F1 score. In order to have improved models that will perform well in unseen data, cross-validation shall be employed.

- **Accuracy**

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN} \quad (1)$$

- **Precision**

$$Precision = \frac{TP}{TP + FP} \quad (2)$$

- **Recall**

$$Recall = \frac{TP}{TP + FN} \quad (3)$$

- **F1-Score**

$$F1 = 2 \times \frac{Precision \times Recall}{Precision + Recall} \quad (4)$$

D. Algorithm for Defect Detection Model Training

There is a number of steps in the training algorithm of the defect detection model that is peculiar to the training and testing of machine learning models. First, the training and the test set are loaded in the dataset used during the creation of the model. It is then followed by the aspects of normalization and resize of inputs along with feature extraction to boost up the savvy of the model. In this data split, its goal is properly dividing the data into the training and validation and test dataset to avoid the problem of over fitting. This is also the case for all models –SVM, CNN, Random Forest, and KNN as the algorithm goes on to initialize the model, training it with the help of the training data and checking the performance of the model with the help of the validation set. The model realized on the test set as well, then its efficiency measure such as accuracy, precision, recall, and F1-score are calculated. Finally, all the models are evaluated and the selected different model is used for defect detection. Thus, a systematic approach is employed in order to choose the most suitable one in regard to recognition of defects in the production of textiles. The under mentioned pseudocode outlines the processes that need to be followed within the project in order to train the machine learning models for the detection of defects.

Algorithm 1: Model Training for Defect Detection

1. Load the dataset (training and test sets)
2. Pre-process the data (normalize, resize images, and extract features)
3. Split data into training, validation, and test sets
4. For each model
   a. Initialize model (e.g., SVM, CNN, Random Forest, and KNN)
   b. Train model using training data
   c. Validate model using validation set
   d. Evaluate performance using test set
   e. Calculate accuracy, precision, recall, and F1-score
5. Compare performance across models

E. Quantifying Quality Control Improvements

The research will quantify the improvements in quality control by calculating the percentage change in defect-free textiles before and after implementing the machine learning-based defect detection system. This is represented by the following equation:

Improvement = [(Post implementation Quality Matric - Pre implementation Quality Matric) / Pre implementation Quality Matric] x 100 ....(5)

Where:

- Post-Implementation Quality Metric is the percentage of defect-free fabrics once the machine learning system is deployed.
- Pre-Implementation Quality Metric is the percentage of defect-free fabrics prior to the deployment of the machine learning system.

4. Results and Discussion

This phase gives the results of the gadget getting to know-primarily based defect detection fashions and the analysis of the impact of feature extraction strategies, model overall performance, and satisfactory manage upgrades.

a. Feature Extraction and Its Impact on Detection Accuracy

Unlike previous models using single features, this study uniquely combines three complementary featurestexture, color, and edgewithin a CNN framework, resulting in higher performance in real-world fabric defect scenarios.Feature extraction is essential in improving machine learning models' performance for defect detection in textile production. In this research, the three major feature extraction methods texture, color, and edge detection were used in order to extract different aspects of textile defects. Texture characteristics, like Haralick texture features and Local Binary Patterns (LBP), were especially successful in detecting surface irregularities, usually fine and subtle, that need to be analyzed in great detail in texture, hence a good fit for the detection of faults in textured materials. These features helped to greatly enhance the detection accuracy, particularly when it comes to small surface defects which are difficult to detect with simple approaches. The color based features which include histogram and color moments were useful in identifying the area of defect which is common in textile dyeing where the color doesn't match. These characteristics enhanced the ability of the model in segmenting between normal color variation and real defect from the evaluation of color distribution in textile images.

b. Model Performance Evaluation

The main four significant metrics, which are accuracy, precision, recall, and F1-score were adopted to evaluate the accuracy of the machine learning models. In addition to this, they present a general analysis of the correctness of all the models regarding textile manufacturing defects. It is defined by the percentage of total correct predictions produced by each model and it defines the percentage of total true positives among all the defect detections made by it. However, recall estimates the quality of the model in classifying true samples with defective data from the dataset. F1-score is the harmonic mean of precision and recall which gives a balanced outlook about the working of the model. The evaluation of all the four models namely SVM, SVM2, CNN, RF and KNN is afforded in the table below in table 2. This table 3 shows the comparison with respect to the given parameters so as to have an idea that which of the two models is better in terms of the measurement of protecting the quality of the textile items made in the production line.

Table 3: Model Evaluation Results

Model Type	Accuracy (%)	Precision	Recall	F1-Score
SVM	92.5%	0.91	0.93	0.92
CNN	96.7%	0.97	0.96	0.97
Random Forest	94.3%	0.94	0.94	0.94
KNN	89.2%	0.89	0.88	0.88

The evaluation of the proposed model, as presented in Table 3, shows the comparative result of the four types of machine learning algorithm of the four machine learning models analyzed; namely, SVM, CNN, Random Forest, and KNN in identifying defects in textile production. Among all the proposed methods, the highest accuracy was achieved by the CNN model with the values of accuracy, precision, recall, and F1-score being 0.967. This can be seen, in the sense that CNN has the highest specificity; hence it has low false positive and false negative rates when it comes to the identification of the defects. SVM comes second with a very good accuracy rate of 92.5%, while though having relatively lower precision and recall values (0.91 and 0.93, respectively), still maintains an almost balanced F1-score value of 0.92, demonstrating its competency in defect detection processes. Random Forest performs well with 94.3% accuracy, and precision, recall, and F1-score measures of 0.94, indicating that it performs better but marginally lower compared to CNN. KNN, although with 89.2% accuracy, has lower precision (0.89) and recall (0.88), leading to a moderate F1-score of 0.88. This shows that KNN has difficulty with false positives as well as false negatives and hence is the worst-performing model for defect detection in this work.

Compared to traditional rule-based or manual inspection methods, machine learning models significantly reduce misclassification. While traditional methods often rely on subjective visual assessments and lack consistency, CNN-based models provide objective and repeatable evaluations. These models are especially effective at identifying subtle, small-scale defects such as misaligned textures or minor color inconsistencies that are easily missed by human inspectors or simple rule-based systems. The ability to automatically learn complex patterns makes CNNs more suitable for real-time and large-scale textile defect detection.

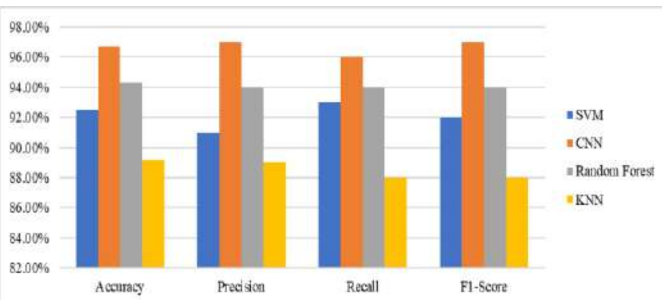

Figure 5: Graphical Representation of Model Evaluation Results

Figure 5 compares model evaluation performance, illustrating four machine learning model performances Support Vector Machines (SVM), Convolutional Neural Networks (CNN), Random Forest, and K-Nearest Neighbours (KNN) in detecting defects in textiles.

The CNN model performs better than all other models with the greatest accuracy of 96.7%, accompanied by very high precision, recall, and F1-score values of 0.97, 0.96, and 0.97, respectively. This means that CNN efficiently identifies defects with high reliability for both defect detection and non-detection cases. The Random Forest model is next in line with good performance, recording an accuracy of 94.3% and balanced precision and recall of 0.94, indicating that it is also very reliable when it comes to defect detection. SVM's accuracy of 92.5 % ranked high on scale of performance that is supported further by its precision of 0.91 and recall of 0.93 indicates that the correct marking of defect is comprehensive and at the same time controlling the false positives. KNN is, however, the least effective with an accuracy of 89.2% and giving less precision and recall values with 0.89 and 0.88 respectively which shows the worse performance of KNN in identifying the defects of textiles than the above models. Figure 5 indicates the same results where CNN outperforms all the other techniques in terms of defect detection; nonetheless, Random Forest and SVM represent satisfactory approaches as well.

c. Impact of Feature Extraction Techniques on CNN Performance

To investigate the effect of feature extraction methods on the CNN model, various combinations of three features including texture, color, and edge were applied. In the following table 4, the results demonstrate how the application of each of these features with the CNN model increases the detection ratio when used individually or in combination. The evaluation process involved using the individual features such as texture, colour and edges OK It also included using combinations of the various features to see the performance of the model when such features were used. Including the features one by one in the model entails that the approach resulted in enhanced performance for each added feature where there is equal improvement in both accuracies, precisely, recall and the F1 score. Hence, the following sections for feature extraction are regarded vital in improving the CNN model for defect identification in textiles, wherein texture, color, and edge feature detection are most potent.

Table 4: Impact of Feature Extraction on CNN Performance

Feature Type	Accuracy (%)	Precision	Recall	F1-Score
Texture	94.2%	0.95	0.94	0.94
Color	95.1%	0.96	0.95	0.95
Edge Detection	95.7%	0.97	0.96	0.96
Texture + Color	96.3%	0.97	0.96	0.97
Texture + Color + Edge	96.7%	0.97	0.96	0.97

The best performance was achieved using all three features together, demonstrating that hybrid feature integration significantly improves the CNN's defect recognition accuracy.The extraction results shown in Table 4, it can be observed that the performance comparison of the CNN model with different features gradually improves as the types of features are gradually added. When used independently, features based on texture came to 94.2% accuracy, precision of 0.95, and recall of 0.94 and F1-score of 0.94, meaning that the proposed CNN-model can recognize irregular texture successfully. When color features were integrated into the model, the accuracy reached 95.1%, and the measures of precision and the recall increased to 0.96 and 0.95, respectively, the F1-score was also higher and made 0.95. However, applying edge detection methods improved the score of identifying structural issues of the model providing a good accuracy of 95.7%, the precision and recall measures being 0.97 and 0.96, respectively while the F1-score = 0), When the features of texture and color combination were used, it slightly increased the overall classification accuracy to 96.3% while at the same time having high values of precision, recall, and F1-score.

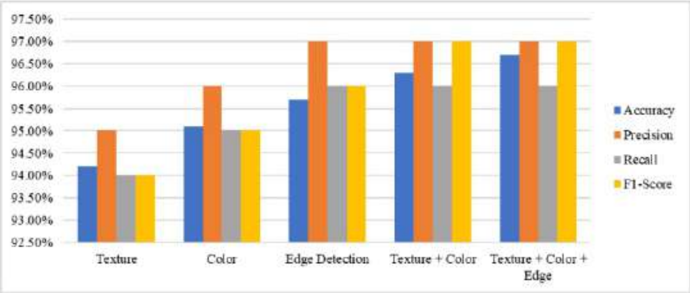

Figure 6: Graphical Representation of Impact of Feature Extraction on CNN Performance

The results from Figure 6 highlight the efficacy of various features extractions on a CNN model performance to identify defects in textiles. The results indicate that using a combination of features enhances model performance (i.e. accuracy, precision, recall, F1 score); specifically, the performance of each feature shows that edge detection had the overall top accuracy (95. 7%) relative to texture (94.2%) and color (95.1%), supporting its effectiveness in detecting defects within the textile material's structure. But using different features led to the best performance. The combination of color and texture resulted in a performance of 96.3% accuracy, which shows a combination of color information and texture improve performance with classification defects. The most accurate results came from using the combination of all three features all together (texture, color and edge detection) achieving 96.7% accuracy, and highest precision, recall and F1 scores of 0.97, and 0.96 and 0.97, respectively. These findings suggest that a wholistic feature extraction methods enhance accuracy for defect detection, by allowing the CNN model to learn more nuanced details within textile patterns. Figure 6 summarizes the findings and indicates the value of a multi-feature extraction methodology to optimize CNN models for defects detection within textiles for quality control.

- **Quantification of Quality Control Improvements**

To evaluate the influence of machine learning enabled defect detection of textile products on textile manufacturing quality control; the rate of defect-free textiles was recorded before and after the implementation of the system. The chart in Figure 4 shows defect-free rates that were recorded over two periods, demonstrating the effectiveness of integrating a machine learning system into the inspection process. The system aimed to reduce human error and enhance the reliability of quality assessment, through automation of defect detection. The observed increase in the defect-free rate demonstrates that machine learning enabled process can be utilized more optimally in textile manufacturing. Notably, the machine learning enabled defect detection of textile products provides an increased product quality consistency and a reduction of defect presence. This analysis highlights the relevance of artificial intelligence enabled inspection systems that are capable of transforming quality control in textile manufacturing.

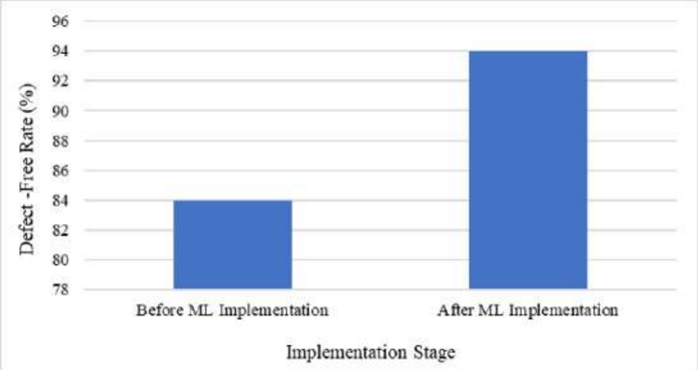

Figure 7: Quality Control Improvement Before and After Machine Learning Implementation

The results shown in figure 7 demonstrate a significant enhancement in quality control in textile manufacturing with the adoption of machine learning based defect detection. Prior to the adoption of machine learning, the defect free-rate was at 84%, indicating a prevalence of defective textiles during the produce process. With the introduction of the machine learning system, the defect-free rate increased to 94%, representing a very noticeable 10% improvement. This is demonstrative of the power of machine learning algorithms to successfully detect defects with image data and to eliminate the errors that can be inadvertently introduced by human inspectors. The greater defect-free percentage indicates that machine learning algorithms, with more sophisticated image processing and pattern detection features, have the ability to accurately spot defects and enhance quality control processes. By minimizing defects and promoting greater product uniformity, this technology helps save costs, minimize material waste, and improve customer satisfaction.

- **Comparison of Model Performance in Quality Control Enhancement**

Comparative analysis was undertaken to assess quality control improvements on various machine learning models. The outcomes reflect the ratio of defect-free textiles prior to and following implementation of each model. Table 5 compares performance of models in improving quality control on textile production. It shows the ratio of defect-free textiles before and after adopting each machine learning model. The information indicates the pre-deployment baseline rate of defect-free products and the improvements from the point of deployment onward. The percentage of improvement per model of quality control can also be found in the table, indicating the extent of improvement in textiles attributed to each model. This comparison demonstrates the capacity for machine learning models to improve defect detection and the quality control process in any textile production process.

Table 5: Comparison of Model Performance in Quality Control

Model Type	Pre-Implementation Defect-Free (%)	Post-Implementation Defect-Free (%)	Improvement (%)
SVM	84.5%	92.1%	7.6%
CNN	84.5%	94.8%	10.3%
Random Forest	84.5%	93.2%	8.7%
KNN	84.5%	91.4%	6.9%

Table 5 highlights a comparative in-depth examination of the model's efficacy in improving quality control in textile manufacturing. The table compares the defect-free percentage of textiles before and after implementing any of the model's machine learning algorithms: Support Vector Machines (SVM), convolutional neural networks (CNN), random forest, and K-nearest neighbours (KNN). The model indicated that the defect-free percentages across all models were consistent at 84.5% before the models were implemented. Following application, all models experienced a defect-free increase. The most significant improvement was depicted from CNN at 10.3%, resulting in a 94.8% defect-free rate. This was followed by SVM at 7.6%, resulting in 92.1% defect-free textiles understanding random forest and KNN with improvements of 8.7% and 6.9%, respectively. These positive results depict the efficiency of machine learning toward improved textile quality control, with CNN demonstrating greater improvements in terms of defect detection.

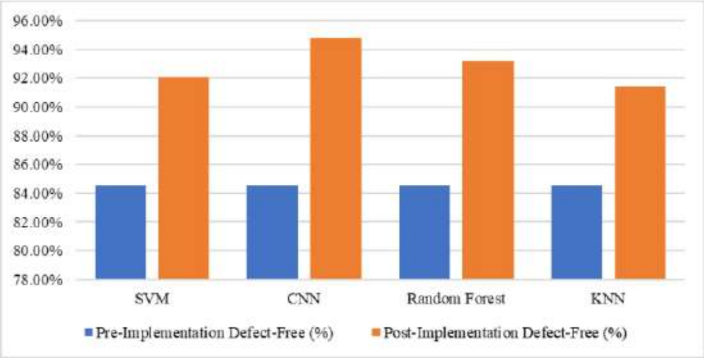

Figure 8: Graphical Representation of Comparison of Model Performance in Quality Control

A graphical demonstration of the performance levels of machine learning models to improve quality control in textile manufacturing is presented in Figure 8. The results demonstrate all models improved the defect-free rate, thus validating success in defect detection using machine learning. All models had a baseline defect-free rate of 84.5% prior to implementation, providing a comparable baseline. Of all models, Convolution Neural Networks (CNN) demonstrated the highest increase in defect-free rate at 94.8%, due to the ability of the CNN to extract features and classify defects. Random Forest also displayed a significant increase in defect-free rate at 93.2%, utilizing ensemble learning techniques to accurately detect defects. The support vector machine (SVM) was second best with a defect-free rate of 92.1%. SVM saw success as a well-known classification algorithm. The K-nearest neighbours (KNN) model saw the least improvement from pre-implementation to post-implementation, with a defect-free rate of 91.4%. KNN may have decreased the defect-free rate due to computational efficiency and sensitivity to noise within the dataset. Overall, these results illustrate that CNN performs best in a textile quality control model, followed by Random Forest and SVM. Figure 8 graphically depicts the variations in these differences, affirming the role of machine learning in improving quality control procedures in textile production.

- **Computational Efficiency of Machine Learning Models**

The models' performance in terms of computational performance was measured by looking at the time for training and prediction. The timing measurement is critical in determining possibilities of use of these models in an actual real-time environment in textile production. In Table 6, various machine learning models, Support Vector Machines, Convoluted Neural Networks, Random Forest, and K-Nearest Neighbours are chronologically arranged showing the training and prediction time. The training times listed are given in hours showing the necessary training time for each model based on the dataset used, while the prediction times are listed in milliseconds per image or based on the time taken to predict each image based on the training time.

Table 6: Computational Efficiency of Machine Learning Models

Model Type	Training Time (hours)	Prediction Time (ms per image)
SVM	1.5	20
CNN	12	100
Random Forest	3.5	15
KNN	2.5	40

In Table 6, the computational efficiency of SVM, CNN, Random Forest, and KNN are discussed in terms of training time and prediction time. It can be seen in the results that SVM is the most computationally efficient in training time, as it only requires 1.5 hours, compared to CNN which takes the longest at 12 hours to train. In prediction time, SVM is also the most efficient at only 20 milliseconds per image, with Random Forest the next fastest prediction time of 15 milliseconds per image. While CNN had demonstrated relatively low accuracy performance, it was also the slowest prediction time at 100 milliseconds per image. KNN presented the second slowest, at 40 milliseconds. These findings all exemplify the direct trade-off between computational efficiency and model complexity, in that while CNN was designed to give the best accuracy performance, the computational costs of training and prediction makes it more challenging to operationalize a machine learning model in a real-time application for textile manufacturing.

5. Conclusion

This study highlights the potential for machine learning models to advance defect detection and quality control in the textiles industry. The research demonstrates how advanced feature extraction techniquesspecifically texture, color, and edge detectionsignificantly enhance model accuracy and robustness. Among the models evaluated, Convolutional Neural Networks (CNN) consistently outperformed Support Vector Machines (SVM), Random Forest, and K-Nearest Neighbours (KNN), particularly when integrated with hybrid feature inputs. The findings confirm CNN's superior ability to detect minor flaws and structural inconsistencies in textile products, resulting in measurable improvements in quality control. Despite these promising outcomes, the study acknowledges certain limitations, primarily the high computational cost and training time associated with CNN, as well as its dependence on large, well-annotated datasets. Future research may address these challenges by incorporating Generative Adversarial Networks (GANs) for synthetic data generation, exploring lightweight CNN architectures suitable for real-time deployment, and developing adaptive learning frameworks capable of handling diverse textile textures. The practical implications of this work are substantial, as the proposed model holds strong potential for integration into automated quality inspection systems within textile production lines, reducing reliance on manual inspection, minimizing human error, and enhancing overall manufacturing efficiency.

References:

[1] Ahmad, H. M., & Rahimi, A. (2022). Deep learning methods for object detection in smart manufacturing: ASurvey. Journal of Manufacturing Systems, 64, 181-196

[2] Arshad, S. R., & Shahzad, M. K. (2024). Deep Learning Based Fabric Defect Detection. Research Reports on ComputerScience, 1-11

[3] Bai, J., Wu, D., Shelley, T., Schubel, P., Twine, D., Russell, J., & Zhang, J. (2024). A comprehensive survey onMachine learning driven material defect detection: Challenges, solutions, and future prospects. arXiv preprintArXiv: 2406.07880

[4] Dlamini, S., Kao, C. Y., Su, S. L., & Jeffrey Kuo, C. F. (2022). Development of a real-time machine vision system forfunctional textile fabric defect detection using a deep YOLOv4 model. Textile Research Journal, 92(5-6), 675-690

[5] Gapon, N., Voronin, V., Zhdanova, M., Sizyakin, R., Semenishchev, E., &Ilyukhin, Y. (2023, August). Deep learning-based image defect detection and removal in manufacturing. In Digital Optical Technologies 2023 (Vol. 12624, pp. 295303). SPIE

[8] Ismail, M., Mostafa, N. A., & El-Assal, A. (2022). Quality monitoring in multistage manufacturing systems by usingmachine learning techniques. Journal of Intelligent Manufacturing, 33(8), 2471-2486

[6] Guo, P., Liu, Y., Wu, Y., Gong, R. H., & Li, Y. (2024). Intelligent quality control of surface defects in fabrics: Acomprehensive research progress. IEEE Access

[7] Hariharan, V., &Sivaraman, K. (2024, July). Machine learning techniques for quality control in textile fabricmanufacturing. In 2024 2nd International Conference on Sustainable Computing and Smart Systems (ICSCSS) (pp. 902907). IEEE

[9] Mir, T. A., Banerjee, D., Malhotra, S., &Devliyal, S. (2024, July). Advancements in Quality Control: IntegratingMachine Learning for Defect Prediction. In 2024 2nd World Conference on Communication & Computing (WCONF) (pp. 16). IEEE

[10] Rahman, S., Tista, S. C., &NazmulHoq, M. (2024, January). Enhancing Textile Quality Assurance: An Advanced DeepLearning Approach for Efficient Fabric Defect Detection. In International Conference on Communication andComputational Technologies (pp. 29-41). Singapore: Springer Nature Singapore

[11] Revathy, G., &Kalaivani, R. (2024). Fabric defect detection and classification via deep learning-based improved MaskRCNN. Signal, Image and Video Processing, 18(3), 2183-2193

[12] Shahrabadi, S., Castilla, Y., Guevara, M., Magalhães, L. G., Gonzalez, D., &Adão, T. (2022, April). Defect detection inthe textile industry using image-based machine learning methods: a brief review. In Journal of Physics: ConferenceSeries (Vol. 2224, No. 1, p. 012010). IOP Publishing

[13] Sharma, Aditi. Phani, S., Tiwari, Vipin. , Kumar, Pradeep. , Parvathaneni, Deepak. , Patel, Mukta. Revolutionizing E-Commerce Security: Unveiling an Innovative Deep Learning-Based Strategy for Detecting Financial Fraud. Fusion: Practiceand Applications, vol.17, no.2, 2025, pp. 366-376. DOI: https://doi.org/10.54216/FPA.170227

[14] Voronin, V., Sizyakin, R., Zhdanova, M., Semenishchev, E., Bezuglov, D., &Zelemskii, A. (2021, June). Automatedvisual inspection of fabric image using deep learning approach for defect detection. In Automated Visual Inspection andMachine Vision IV (Vol. 11787, pp. 174-180). SPIE

[15] Yashini, P., Karthika, G., Sunitha, T., & Berlin Magthalin, R. (2024, October). Machine Learning-Based Textile FabricDefect Detection Network. In 2024 4th International Conference on Sustainable Expert Systems (ICSES) (pp. 1470-1477).IEEE

[16] Zhao, S., Zhong, R. Y., Wang, J., Xu, C., & Zhang, J. (2023). Unsupervised fabric defects detection based on spatialdomain saliency and features clustering. Computers & Industrial Engineering, 185, 109681

[17] Biyyapu, N., Veerapaneni, E. J., Surapaneni, P. P., Vellela, S. S., &Vatambeti, R. (2024). Designing a modified featureaggregation model with hybrid sampling techniques for network intrusion detection. Cluster Computing, 27(5), 5913-5931

[18] S Phani Praveen et al., " Enhanced Predictive Modeling for Alzheimer's disease: Integrating_Cluster-Based Boosting and Gradient Techniques with Optimized Feature Selection ", Journal of Theoretical and Applied Information Technology, vol. 103, no. 8, 30th April 2025

[19] N Mohana Priya et al., "Revolutionizing Healthcare with Large Language Models: Advancements, Challenges, and Future Prospects in Ai-Driven Diagnostics and Decision Support", Journal of Theoretical and Applied Information Technology, vol. 103, no. 9, May 2025

[20] S Phani Praveen et al., "AI- Powered Diagnosis: Revolutionizing Healthcare with Neural Networks", Journal of Theoretical and Applied Information Technology, vol. 103, no. 3, 15th February 2025

[21] S, S., Raju, K. B., Praveen, S. P., Ramesh, J. V. N., Shariff, V., & Tirumanadham, N. S. K. M. K. (2025c). Optimizing Diabetes Diagnosis: HFM with Tree-Structured Parzen Estimator for Enhanced Predictive Performance and Interpretability. Fusion Practice and Applications, 19(1), 57–74. https://doi.org/10.54216/fpa.190106

[22] S. P. Praveen, P. Chaitanya, A. Mohan, V. Shariff, J. V. N. Ramesh and J. Sunkavalli, "Big Mart Sales using Hybrid Learning Framework with Data Analysis," 2023 2nd International Conference on Automation, Computing and Renewable Systems (ICACRS), Pudukkottai, India, 2023, pp. 471-477, doi: 10.1109/ICACRS58579.2023.10404941.

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Setting up an Automatic Reeling Unit for Silk Yarn Manufacturing in the Maharashtra: A Case Study

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Abstract:

This case study examines the feasibility of establishing an Automatic Reeling Machine (ARM) unit in Maharashtra, which contributes 10% of India's mulberry cocoon production yet has only two operational ARM units. Through primary data collection involving field visits, stakeholder consultations, and questionnaires, the study evaluates site selection criteria, financial viability, government support schemes, market potential, products and properties. Findings reveal that a 400-end ARM unit requires an initial investment of Rs. 32 million, with government subsidies covering up to Rs. 13.5 million. The unit is projected to achieve growing profitability from Rs. 7.99 million in Year-1 to Rs.10.1 million in Year-5 at a selling price of Rs.3,500/kg, supported by 95% capacity utilization by Year-3 and additional revenue from by-products like silk waste and pupae. Key challenges include cocoon price fluctuations and dependence on skilled migrant labour. However, strategic measures such as workforce upskilling, optimized procurement, and ideal site selection (soft water access, non-residential zoning) can mitigate risks. The unit's potential is further enhanced by strong domestic demand from Pathani's saree-weaving clusters and export opportunities via Bangalore's Silk Exchange. By aligning with India's Silk Samagra-2 mission, this initiative promises economic returns while strengthening Maharashtra's silk industry, reducing import dependence, and generating rural employment. The ARM unit will produce high-quality raw silk (2/20D–6/20D) for luxury textiles, ensuring sustainable growth through diversified revenue streams and optimal resource utilization.

Keywords: *Automatic Reeling Machine, Financial Feasibility, Government policies, Mulberry Silk. silk yarn manufacturing*

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1. Introduction

India is the only country in the world that produces all varieties of silk. It is the second-largest producer of Mulberry raw silk globally, after China, and the sole producer of Muga silk. India's silk industry is unique, producing all four varieties of silk Mulberry, Tasar, Muga, and Eri [1]. Traditional states in India involved in the mulberry silk production are Karnataka, Andhra Pradesh, Tamil Nadu, West Bengal and Jammu & Kashmir. Among the varieties of silk produced in 2022-23, Mulberry accounted for 75.60% (27,654 MT), Tasar, 3.60% (1,318 MT), Eri 20.09% (7,349 MT) and Muga 0.71% (261MT) of the total raw silk production of 36,582 MT [2]. Further India has the mulberry acreage of 223926 hectares, producing 161684 tons of mulberry cocoons, which are used to produce 22066 tons of mulberry raw silk.

In the Maharashtra state, 13872 acres were under mulberry cultivation in the year 2022-23. According to the Central Silk Board survey report for the year 2022-23, Maharashtra is ranked eighth in the country in mulberry silk production and first among non-traditional states. Due to the favourable climate in the state and the increasing demand for silk yarn, there is good scope for the growth of the industry in the state. Paithan, Yeola, Solapur, Bhandara are traditional places for textile production in the state. There is a huge demand for silk cloth in the global market and at present, the raw silk required for domestic textile production must be imported from foreign countries to meet the demand. Therefore, there is huge scope for increasing the silk business in the Maharashtra state [3].

However, the state's silk yarn production remains limited, with most raw silk being imported from Karnataka. The establishment of the Automatic Reeling Machine (ARM) units in Maharashtra can bridge this gap, enabling local production of high-quality silk yarn and reducing dependency on external markets. The study highlights the economic viability of ARM units, their role in supporting the silk industry, and their potential to create value-added products from silk waste. Maharashtra's current cocoon production (4,905 MT annually) and existing infrastructure gaps—only six ARM units, with limited operational efficiency highlight untapped potential for localized, high-quality silk yarn production.

Strategic opportunities lie in vertical integration (weaving, garment manufacturing) and innovative waste utilization (sericin extraction, pupae-based fertilizers). The unit's success could reduce Maharashtra's dependency on Karnataka-supplied yarn, strengthen domestic silk value chains, and position the state as a hub for premium silk production.

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2. Silk Reeling Process

Silk reeling is the process of unwinding filaments from cocoons to produce silk yarn. This process is critical in determining the quality of the final product. ARM units automate this process, ensuring consistent quality and higher productivity compared to traditional methods. A 400-end ARM unit can process 500 kg of cocoons per 8-hour shift, producing approximately 60 kg of silk yarn daily. The production of silk yarn from cocoons involves several critical steps such as drying, sorting, mixing, cooking, reeling, permeation, re-reeling and finishing. To understand the process, a field visit was carried out to the working ARM unit in the Maharashtra state.

In the first stage of the ARM process, cocoons were hot air dried within a temperature range of 55°-115° C to harden the sericin uniformly which kills the pupa and removes moisture [6]. In the next step, cocoons are sorted out and defective cocoons like double, flimsy, melted, uzi infected, urinated or malformed are removed [4]. In the mixing process, the cocoons were mixed based on single cocoon filament denier and reliability. Only lots with similar characteristics were combined to maintain consistency. After mixing, cocoons are allowed to cook using a three-pan method or a pressurized cooking machine. After that, they were cooled down with cold water and brushed at 75-80°C before transferring to the reeling basin.

In the ARM machine, cocoons were reeled on a multi-end reeling machine with reel speed of 100-120 meters/minute, croissure length 8-10 cm, reeling basin water temperature 40°C and reeling button size 250-350 microns. Water used in reeling was colourless, odourless, and had pH-7.0, total hardness- <75 ppm and total alkalinity- <50 ppm [5]. Once the small skeins are formed, then they are sent to the reel permeation process. Silk on small reels was soaked in a permeation chamber under low pressure (up to 400 mm Hg) with a wetting agent to facilitate unwinding. After that material was transferred to standard-size skeins at 150-180 meters/minute. Drying was done using steam pipes at 35-40°C and 40-45% relative humidity to prevent gum spots. In the last stage of finishing of Silk, the skeins were laced at six places with cotton thread to prevent entanglement. During the process, gum spots and impurities were gently removed by hand. Silk material was folded and twisted into five spirals on a skeining machine. This streamlined process ensured the production of superior-grade raw silk yarn, ready for use in textile manufacturing.

3. Research gap and Methodology

After understanding the ARM process, a detailed questionnaire was prepared and circulated to the farmers, traders, silk yarn producers with the objective of to prepare guidelines in form of case study for setting Up an Automatic Reeling Unit (ARM) in the Maharashtra state.

4. Site selection for ARM Unit

The ARM unit can be established anywhere in Maharashtra with good transport connectivity. Mulberry cocoons, being a high-value crop, can be transported economically from across the state. For instance, the ARM unit in Bhandara district of Maharashtra state operates successfully despite limited local mulberry cultivation. Alternatively, cocoons can be sourced from markets in Beed and Jalna or through local mulberry cultivation.

When selecting a site for construction, key considerations include ensuring a structurally stable foundation to support shade infrastructure, as well as prioritizing locations with robust road connectivity to facilitate seamless transportation logistics. A consistent and reliable electric supply is essential to maintain uninterrupted operations. Additionally, access to a dependable source of soft water is critical, as water quality directly influences the integrity and consistency of yarn production. To address environmental and community concerns, the site should ideally be situated away from residential zones to minimize potential odour disturbances caused by reeling waste and decomposing pupae. These criteria collectively ensure operational efficiency, product quality, and harmonious coexistence with surrounding areas.

5. Financial Overview of an ARM unit

5.1 Financial projections

The ARM unit requires a total capital investment of Rs. 27.5 million, comprising Rs.8 million for construction (15,000 sq. ft. facility), Rs.15 million for the ARM unit (including auxiliary machinery and GST), Rs. 0.5 million for installation, and Rs.4 million as working capital. Operational assumptions outline a production schedule of 300 days annually with two daily 8-hour shifts, targeting an annual output of 36,000 kg of silk yarn at 85% capacity utilization. To achieve this, the unit will require 500 kg of cocoons per shift, with a renditta of 6.5 kg of cocoons per kg of yarn, translating to a raw material cost of Rs.440/kg. The selling price of raw silk is conservatively set at Rs.3, 500/kg (below the current market rate of Rs.4, 200/kg), and labour needs include 36 workers per shift. The working capital cycle accounts for 15 days of raw material inventory, 3 days of work-in-process, 7 days of finished goods storage, and 15 days of bills receivable, culminating in a total working capital requirement of Rs.15.54 million at full capacity to ensure smooth cash flow and operational continuity.

Table 1- The financial projections of an ARM Unit

I	Product	Silk Yarn
II	**Installed Capacity**	
1	Machinery (No. of ends)	400
2	Production (kgs/annum)	36000
III	**Operating efficiency**	
IV	**Purchase / Selling Price**	
1	Purchase price (cocoons) (Rs/kg)	440
2	Selling price (raw silk) (Rs/kg)	3500

I	Product	Silk Yarn
V	**Project Cost**	**(Rs)**
1	Building	80,00,000
2	Machinery (incl. 18% GST)	1,51,27,600
3	Contingencies	23,12,760
4	Miscellaneous Fixed Assets	13,00,000
5	Prelim. & Pre-operative Expenses	12,21,000
6	Working capital margin	40,26,708
7	**Total**	**3,19,88,068**
VI	**Means of Finance for Project**	
1	Financial institution	1,34,54,520
1	Promoter	89,18,548
2	Subsidy on machinery	96,15,000
3	**Total**	**3,19,88,068**
VII	**Working Capital**	
1	Cycle (Days)	40
2	Raw material	43,75,800
3	Working expenses	6,45,525
4	Work in process	9,60,273
5	Finished goods	22,87,770
6	Bills receivable	49,40,615
7	**Total**	**1,32,09,983**
VIII	**Means of Finance for Working Capital**	
1	Bank borrowing	9183276
2	Promoter's contribution	4026708
3	**Total**	**1,32,09,983**
IX	**Profitability**	
1	Sales	11,09,15,055
2	Net Profit (NPAT)	79,88,335
3	Net Profit/sales	7.20

Table 2- Details of Operational Expenses

Sr. No.	Details	Value (% / Rs)	Basis
1	Repairs & maintenance	9,00,000	per annum
2	Taxes	25,000	per annum
3	Establishment expenses	1,80,000	per annum
4	Interest on Term Loan	14.00%	per annum
5	Interest on WC Loan	14.00%	per annum
6	Packing Expenses	1,08,000	per annum
7	Selling Expenses	7,65,000	per annum
8	Fuel & water & Power	42,00,000	Of Cost
9	Subsidy (M/c)	75.00%	Of Cost

5.2 Operational Expenses

Operational expenses include repairs & maintenance at Rs. 0.9 million, establishment expenses at Rs. 0.18 million, and taxes at Rs. 0.025 million annually. Packing and selling expenses amount to Rs. 0.108 million and Rs.0.765 million, respectively, while fuel, water, and power constitute a significant annual outlay of Rs. 4.2 million. Financing costs feature a 14% interest rate on both term loans and working capital (WC) loans. The miscellaneous fixed assets total Rs.1.3 million, comprising office equipment (Rs. 0.2 million), vehicles (Rs.1 million), and miscellaneous assets (Rs. 0.1 million). These figures collectively outline key fixed and variable costs critical to financial planning and operational budgeting.

Table 3- Preliminary & preoperative expenses

Details	Amount (Rs)
Preliminary Expenses	100000
Pre-Operative Expenses	
Insurance, clearing, incidentals, etc.	321000
Municipal permission, tax, etc.	200000
Interest, etc.	500000
Others expenses	100000
Total	1221000

The total pre-commissioning costs amount to Rs.1.2 million, covering preliminary expenses (Rs. 0.1 million), insurance, clearing, and incidentals (Rs. 0.32 million), municipal permissions and taxes (Rs. 0.2 million), interest during setup (Rs. 0.5 million), and other miscellaneous costs (Rs. 0.1 million). These expenses encompass regulatory compliance, administrative groundwork, and preparatory financial obligations essential for project initiation.

Table 4- Details of Employee required for an ARM Unit

Sr. No.	Designation	Number	No. of Shifts
A	**In plant Workers**		
1	Cocoon drying	2	2
2	Cocoon sorting	4	2
3	Cocoon cooking & vacuum permeating	2	2
4	Silk reeling	8	2
5	Cocoon brushing & feeding	2	2
6	Silk re-reeling & lacing	2	2
7	Reel humidifier	1	2
8	Skein making	2	2
9	Silk rewinder	1	2
10	Bisu treatment	2	2
11	Mechanics & Electrician	2	2
12	Maintenance	2	2
13	Helpers	2	2
	Total	**32**	
B	**Administrative workers**		
1	Manager	1	2
2	Accountant	1	1
3	Driver	1	2
4	Security	1	3
	Total	**4**	
	Grand total	**36**	

Table 5- Profitability statement of an ARM Unit for next 5 years

Sr. No.	Details	Unit	I Year	II Year	III Year	IV Year	V Year
1	Installed Capacity	Kg	36000	36000	36000	36000	36000
2	Capacity Utilisation	%	85%	90%	95%	95%	95%
3	Actual Production	Kg	30600	32400	34200	34200	34200
4	Selling Price	Rs	3500	3500	3500	3500	3500
5	Sales	Rs	110915055	117439470	123963885	123963885	123963885
	Cost of Production						
A	**Production Cost**						
1	Raw Material	Rs	87516000	92664000	97812000	97812000	97812000
1	Power	Rs	566100	599400	632700	632700	632700
2	Fuel & water	Rs	3008400	3185365	3362329	3362329	3362329
3	Repairs & Maintenance	Rs	900000	900000	900000	900000	900000
4	Wages	Rs	4080000	4536000	5027400	5027400	5027400
5	Taxes	Rs	25000	25000	25000	25000	25000
5	Depreciation	Rs	1710129	1710129	1710129	1710129	1710129
6	Packing Expenses	Rs	91800	97200	102600	102600	102600
	Sub Total		97897429	103717094	109572158	109572158	109572158
B	**Administrative Expenses**						
7	Establishment Expenses	Rs	180000	180000	180000	180000	180000
8	Salaries	Rs	915000	960750	1008788	1059227	1112188
	Sub Total	Rs	1095000	1140750	1188788	1239227	1292188
C	Financial Expenses						
9	Interest on Term Loan	Rs	1883633	1883633	1506906	1130180	753453
10	Interest on WC Loan	Rs	1285659	1361286	1436913	1436913	1436913
	Sub Total		3169291	3244918	2943819	2567092	2190366
D	**Marketing Expenses**						
11	Selling expenses	Rs	765000	765000	765000	765000	765000
	Sub Total	Rs	765000	765000	765000	765000	765000
	Total Cost of Production	Rs	102926720	108867762	114469765	114143478	113819712
E	**Profit Analysis**						
1	Net Profit (NPAT)	Rs	7988335	8571708	9494120	9820407	10144173
2	Net Profit/sales	%	7.20	7.30	7.66	7.92	8.18
3	Cash Accruals (NPAT+Dep)	Rs	9698464	10281837	11204249	11530537	11854302

5.3 Five-year profitability projections

The unit maintains a consistent installed capacity of 36,000 kg annually, with capacity utilization rising from 85% (30,600 kg) in Year-1 to 95% (34,200 kg) by Year-3, sustaining this level through Year-5. Despite a fixed selling price of Rs.3, 500/kg, sales grew from Rs.1109 million in Year-1 to Rs.1239 million annually from Year-3 onward, driven by higher production. Total production costs rise steadily due to increasing raw material expenses (Rs.87.5 million to Rs.97.8 million) and wage inflation (Rs.4.08 million to Rs.5.03 million). However, declining interest costs on term loans (Rs.1.88 million to Rs.0.75 million) and controlled administrative/marketing expenses help stabilize margins. Net profit grew from Rs.7.99 million (7.2% of sales) in Year-11 to Rs.10.1 million (8.18% of sales) by Year-5, reflecting improved efficiency. Cash accruals (profit + depreciation) rise consistently from Rs.9.69 million to Rs.11.8 million, demonstrating strengthening liquidity. The projection highlights scalability, cost management, and stable profitability despite fixed pricing.

6. Different yarn with properties produced by ARM

Silk yarn produced by ARM is known for its high quality, uniformity, and strength. The type of silk yarn produced depends on the machine parameters and the reeling process. Below are the types of silk yarn, machine parameters, and yarn properties associated with ARM-produced silk.

6.1 Types of Silk Yarn Produced by ARM Machines

ARM machines typically produce the Raw Silk (Mulberry Silk) 2/20D, 3/20D, 4/20D, 5/20D, 6/20D of types of silk yarn which are used in high-end fabrics like sarees, dress materials, and luxury textiles. The Reeled Silk (Thrown Silk) Produced by twisting multiple raw silk threads together (e.g., 20/22D doubled into 40/44D) and used in weaving, embroidery, and knitting. The Tram Silk, which is a lightly twisted silk yarn, softer than organize and used as weft yarn in weaving.

Table 6- Machine Parameters Influencing Silk Yarn Quality

Parameter	Range/Setting	Impact on Yarn
Reeling Speed	80-120 rpm	Higher speed ? higher productivity but may reduce uniformity
Cocoon Cooking Time	2-5 minutes (steam/boiling)	Affects filament extraction efficiency
Number of Ends	5-10 cocoons per thread	More ends ? thicker yarn (e.g., 6/20D).
Twist Level (TPI)	0-30 twists per inch (TPI)	Higher twist ? stronger but less lustrous yarn
Temperature Control	80-95°C (water bath)	Ensures proper gum (sericin) softening
Tension Control	Adjustable brakes	Prevents breakage and ensures uniform winding

Table 7- Properties of ARM-Produced Silk Yarn

Property	Characteristics
Denier (Fineness)	13D to 30D (standard: 20/22D)
Tenacity (Strength)	| 3.5-5.0 g/denier
Elongation	15-25%
Lustre	High (depends on degumming)
Uniformity	Very high (due to automated control)
Moisture Regain	11%
Thermal Stability	Good (up to 140°C)

6.2 Application of ARM produced silk yarn

ARM-produced silk yarn is widely used in various high-end applications due to its superior quality, strength, and lustre. It is a preferred choice for luxury fabrics, including traditional sarees, elegant suits, and delicate scarves, where its smooth texture and natural sheen enhance the fabric's appeal. The medical textiles also use ARM silk yarn, particularly in surgical sutures. Additionally, this yarn is extensively used in knitted and woven apparels, offering durability and a luxurious feel in garments like dresses, blouses, and formal wear. Beyond fashion and medicine, ARM silk yarn finds application in home textiles, such as premium silk bedding, curtains, and upholstery.

7. Government Support Schemes

The Indian government's Silk Samagra-2 scheme offers significant financial incentives to support the establishment of ARM (Automatic Reeling Machine) units. Open-category beneficiaries are eligible for a 75% subsidy on the ARM unit cost (excluding GST), while SC/ST beneficiaries receive an enhanced subsidy of 90%. Additionally, the scheme provides a 50% subsidy (capped at Rs.4 million) for the construction of reeling sheds. To further promote quality production, an incentive of Rs.150 per kilogram is extended for reeled yarn graded 2A or higher. These measures aim to reduce upfront capital burdens, encourage inclusivity, and incentivize high-quality silk yarn manufacturing under the initiative.

8. Market Analysis

Table 8- Market Details

Sr. No	Name of the product	Selling price per unit (Rs/kg)	Sales Realisation (Rs)
1	Raw Silk	3500	10,71,00,000
2	Silk waste	600	18,36,000
3	Defective Cocoons	175	17,40,375
4	Pupae	2	2,38,680
	Annual Sales		**11,09,15,055**

The product portfolio generates annual sales of Rs.110.9 million, driven primarily by raw silk priced at Rs.3, 500/kg, contributing Rs.107.1 million (96.5% of total revenue). Secondary revenue streams include silk waste (Rs.1.836 million at Rs.600/kg), defective cocoons (Rs.1.74 million at Rs.175/kg), and pupae (Rs. 0.239 million at Rs.2/kg). This diversified sales structure leverages both premium-grade silk and by-products, ensuring optimal utilization of raw materials while capitalizing on varying market demands.

India consumes all the silk it produces and imports an additional 3,500 metric tons annually from China. The demand for silk goods, particularly sarees, is steadily increasing due to population growth and rising consumer purchasing power. Maharashtra's Paithan region, a hub for silk saree manufacturing, relies heavily on silk yarn imported from Karnataka. Targeting these weavers can create a significant local market for ARM-produced yarn. Currently, Maharashtra has only six ARM units, with 2-3 operating efficiently. Examples include RSM Silk in Sangli and Bhandara Silk Udyog in Bhandara. The limited number of operational units presents an opportunity for new entrants to capture market share. Silk yarn can also be traded through the Silk Exchange in Bangalore, which serves as a major trading hub. Additionally, West Bengal offers a robust market for silk yarn.

9. Risks and Challenges

The quality of silk yarn depends heavily on the skill of machine operators. Currently, most ARM units in Maharashtra rely on skilled labour from West Bengal. Training local workers is essential to ensure consistent product quality.

Cocoon prices fluctuate significantly, ranging from Rs.400 to Rs.900 per kg. ARM unit owners must maintain sufficient working capital to purchase cocoons during low-price periods and hold inventory until market prices rise [4].

10. Potential and Future Prospects

ARM units serve as the backbone of the silk industry, akin to spinning units in the cotton sector. Successful operation of an ARM unit can pave the way for forward integration into weaving, processing, and garment manufacturing. Additionally, advancements in waste utilization, such as sericin extraction, silk sheet production, and pupae-based fertilizer or fish feed, offer opportunities to convert silk industry waste into valuable products.

11. ARM unit registration process

i. Visit the concerned District sericulture office and get Silk Samagra-2 application form for Purva Sammati for ARM

ii. Fill up the form, annex all the documents given by the office (NOC from the Local body is one of the important documents)

iii. The District Sericulture officer will write a letter to the Central Silk Board to carry out the site inspection feasibility report

iv. Feasibility report inspection visit by CSB officials (check availability of three phase electricity connection, water supply and road connectivity as well as check the availability of silk cocoons and skilled manpower)

v. Once the feasibility report is completed, the proposal will be put in front of the Project Monitoring Committee (PMC) headed by Director Sericulture.

vi. PMC will evaluate the proposal and call the candidate for interview to check his prior experience in Textiles, whether he is financially strong enough and check his entrepreneurial capabilities. Then they give pre sanction (purva sammati).

vii. PMC will also give him a letter to open an ESCROW account at the national bank and ask the applicant to deposit his share (25 % for open/OBC candidate, 10% for SC/ST candidate).

viii. The certificate by the bank must be submitted by the beneficiary to PMC.

ix. If funds available with the Directorate of Sericulture, then give final approval or funds not available with DoS, the beneficiary can start purchasing the machine by utilising their own funds (later on they can recover the funds from the government once available with them.)

x. Once funds are available with DoS, they will allow the beneficiary to initiate the process of procurement of machineries. (A tripartite agreement has to be made between DoS, Machine Manufacturer and beneficiary describing the legal clauses and nature of instalment releases)

xi. The last instalment to the machine manufacturer will be released after successful run of the machine.

12. Conclusion

Establishing a 400-end ARM unit in Maharashtra presents a financially viable and strategically critical opportunity to bolster the state's silk industry. By leveraging government subsidies (up to Rs.13.5 million for ARM units) and addressing domestic demand particularly from Pathani's saree-weaving hub—the project can achieve stable profitability (8.18% net margin by Year-5) while mitigating import reliance. Key success factors include local workforce upskilling to address labour shortages, strategic cocoon procurement during price dips, and adherence to stringent site selection criteria (soft water access, non-residential zoning). The unit's scalability is underscored by export potential through Bangalore's Silk Exchange and West Bengal's market. Forward integration into value-added processes (weaving, waste-to-product innovations) and advancements in automation could further enhance competitiveness. By aligning with India's Silk Samagra-2 objectives, this initiative not only promises economic returns but also positions Maharashtra as a self-reliant contributor to the national silk ecosystem, fostering rural employment and sustainable industrial growth. ARM machines typically produce the Raw Silk (Mulberry Silk) 2/20D, 3/20D, 4/20D, 5/20D, 6/20D of types of silk yarn which are used in used in high-end fabrics like sarees, dress materials, and luxury textiles. Silk yarn produced by ARM is known for its high quality, uniformity, and strength. The product generates annual sales primarily by raw silk, secondary revenue streams include silk waste and pupae. This diversified sales structure leverages both premium-grade silk and by-products, ensuring optimal utilization of raw materials while capitalizing on varying market demands.

References

[1] Ministry of Textiles (2024). Annual Report 2023-2024, https://texmin.nic.in/sites/default/files/MOT%20Annual%20Report%20English%20%2807.11.2024%29.pdf

[2] Central Silk Board (2023). Functioning of Central Silk Board & Performance of Indian Silk Industry. Ministry of Textiles, Government of India. 1 April 2023. https://texmin.nic.in/sites/default/files/NoteOnSericulture-April_2023%20English.pdf

[3] Panda, A (2023). Directorate of Sericulture Nagpur, Government of Maharashtra, Annual Report 2022-23. https://cdnbbsr.s3waas.gov.in/s3959ef477884b6ac2241b19ee4fb776ae/uploads /2024/07/202407311239572998.pdf

[4] Kumar, N., & Singh, M. K. (2016). Silk industry in India: Growth, challenges and opportunities. Journal of Textile and Apparel, Technology and Management, 9(3), 1–15

[5] Sivaprasad, V., et al. (2019). Adoption of automatic reeling machines in India: Economic viability and impact on silk quality. Journal of Natural Fibers, 16(6), 789–801

[6] Zhang, Y., et al. (2020). Automation in silk reeling: A review of modern reeling technologies. Textile Research Journal, 90(5–6), 567–580. https://doi.org/10.1177/0040517519883952

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Statistical Optimisation of Dyeing Conditions for Colouration of Soya-Bean Based Bio-Cationized Cotton with Catechu

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Abstract:

This present study focuses on the statistical optimisation of dyeing parameters for eco-friendly dyeing of waste soybean seeds-based bio-cationized cotton using Catechu (an anionic natural dye) and potash-alum (fitkari) as an eco-friendly mineral-based bio-mordant. Cotton cellulose was modified using acid-hydrolysed extracts from de-oiled waste soybean seeds to enhance dye affinity, enabling salt-free dyeing. Six independent input dyeing process variables were optimised considering mordant concentration, dye concentration, pH of the dye bath, material-to-liquor ratio (MLR), dyeing time, and dyeing temperature. Initial experiments showed that an optimum K/S value of 6.75 and ΔE value of 10.12 can be achieved using 10% bio-cationized cotton, pre-mordanted with 10% potash alum and dyed with 30% catechu. Further statistical optimisation and ANOVA analysis revealed improved results of K/S value up to 6.95 and ΔE value of 10.22 under optimised conditions, i.e. dye bath pH 5, 60 minutes dyeing time, 70°C dyeing temperature, and an MLR of 1:20, without the use of salt.

Keywords: *Bio-Mordant, Bio-cationization, Box-Behnken design, Catechu, Soyabean*

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1. Introduction

In recent years, interest in plant-based dyes for colouring natural fibre-based materials has grown due to their biodegradability, non-toxicity, hypoallergenic nature, and minimal environmental impact. Natural dye extraction and dyeing are still done in very old traditional techniques [1] and involve several challenges, including low dye uptake, poor colour fastness, and lack of standardised dyeing methods [2]. These issues can be addressed by optimising extraction and dyeing conditions. Another alternative is to modify natural fibres like cotton through bio-cationization to create affinity for anionic natural dyes like catechu, allowing for salt-free dyeing for improved dye uptake and colour fastness. Traditional natural dyeing mostly depends on metallic mordants, which may not always be eco-friendly [3-6]. So, the use of plant-based bio-mordants rich in tannins and the use of natural mineral salts like potash alum (Fitkari) [6, 7] applied in combination as dual-bio-mordanting is a very new/novel approach studied. Hence, the present work involves modifying cotton cellulose with acid-hydrolysed waste soybean seed extract following our earlier reported work of bio-cationization of cotton with chitosan [7], followed by catechu dyeing. Moreover, catechu, obtained from the Acacia catechu wild tree, commonly known as "Katha" or "Cutch" in India, is well known for producing ayurvedic medicinal products [8] known as ayur-vastra, hence use of catechu dyed bio-cationised modified cotton may also be used as medical textiles with antimicrobial properties.

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Therefore, the present study is considered important in promoting salt-free, eco-friendly bio-dyeing of soya protein-based bio-cationized cotton (SB-Cotton) using catechu, a natural dye known for its medicinal and antimicrobial properties [9]. The major aim of this work is to develop coloured bio-medical textiles like surgical gowns that enhance colour depth and colour fastness, and microbial protective wellness criteria of the wearer. As a continuation of the said work series, this part of the study aimed to optimise each dyeing condition to maximise colour strength (K/S value) using the Box-Behnken design model under response surface methodology (RSM).

2. Materials and Methods

2.1 Fabrics

Plain woven, bleached 100% cotton shirting fabric with ends/ inch 84 (Ends/ dm- 200) and picks/ inch 74 (Picks/ dm – 190) having warp count 9.8 Tex (60 Ne), weft count 10.7 Tex (55 Ne) with thickness of 0.25 mm and areal density of 145 g/m2 was used for all the experiments.

2.2 Chemicals

Analytical Reagent (AR) grade Acetic acid (CH_3COOH), Sodium Acetate (CH_3COONa) and buffer of Sodium Acetate + Acetic acid for maintaining pH at 4-5, AR grade Sodium hydroxide (NaOH) and Hydrochloric acid (HCl), and Potash-alum (K-alum or $K.Al(SO_4)_2, 12\ H_2O$), all were procured from a reputed local chemical supplier.

2.3 Natural Dye (Catechu) and its extraction

Catechu, also known as Katha (derived from Senegalia catechu or Acacia catechu), is a natural brown dye primarily contains 22%–30% of flevo-tannin (catechu-tannic acid), 10%–12% catechin, along with catechu red (catechol), quercetin, epi-catechin, saponin, and traces of other components. To prepare the catechu dye extract, the powdered raw material was heated in water at 50 °C for 60 minutes at pH 10, using a material-to-liquor ratio (MLR) of 1:30, with 1% NaOH added [10] and filtered after cooling. The filtrate was subsequently neutralised to pH 5 using acetic acid to obtain a 30% catechu extract on a bone-dry weight basis.

Further purification of this extract was carried out using Soxhlet extraction and distillation with a 1:1 ethanol + benzene mixture over 10 cycles for 6 hours. 30 g of raw catechu powder produced 3 g of purified dye powder, confirming a 3% yield of purified solid colourant content.

2.4 Extraction of amino acid from de-oiled waste soybean seeds

Dehydrated soybean seeds waste (de-oiled) was crushed using a grinding machine, and soaked in dilute 10% HCl for around 24 hrs. for hydrolysis, followed by neutralisation. Later, the results of LC-MS analysis of the said filtrate confirmed the presence of a total of 20.01% of different amino acid mixtures.

2.5 Pre-oxidation of cellulose of cotton fabric

Cotton cellulose was pre-oxidised to develop some aldehyde (-CHO) groups in cellulose by treating it with 1% K2S2O8 solution as a mild oxidising agent for 30 min at room temperature (30 °C), batched for 1 h with MLR 1:20.

2.6 Bio-cationization of cotton cellulose with waste Soya bean seed extract

Scoured and bleached cotton and pre-oxidised cotton fabric samples were dipped in 5-20% acid hydrolysed waste soya-bean seed extract and batched for a few min, followed by padding (2-dips-2-nips) with a laboratory padder and then oven dried for 5 min at 100 ºC and curing at 120ºC for 3-4 min.

2.7 Potash-Alum pre-mordanting before catechu dyeing

The soyabean seed-based bio-cationized cotton fabrics were pre-mordanted with varying % (5- 20%) of potash alum using MLR 1:30 for 30 min at 60 ºC temperature, followed by air drying without washing to make ready for dyeing with pre-fixed or varying % of catechu dye extract at different dyeing conditions to optimise it statistically.

2.8 Dyeing of acid-hydrolysed soya bean seed-based bio-cationized (bio-modified) cotton cellulose after further pre-mordanting with and without potash alum

Our previous study [11] indicate a standard dyeing conditions for cotton cellulose using catechu dye using two bio-mordants (potash alum and gallnut), identifying optimal dyeing parameters as: 30% catechu dye extract, pH 4–4.5, material-to-liquor ratio of 1:20, dyeing time of 60 min., dyeing temperature of 70 °C, with low salt (5 g/L) or no salt addition. However, since the current study focuses on dyeing modified, bio-cationized cotton, specifically using a soya-protein-based treatment, the dyeing conditions are expected to differ and require separate optimisation.

So, a separate set of dyeing of soya-modified SB-cotton was carried out to study the influence of varying dyeing parameters—K-alum concentration, catechu dye concentration, dye bath pH, material-to-liquor ratio (MLR), dyeing time, and temperature (keeping Other dyeing parameter constant)—on K/S value (colour strength) for statistical optimisation of dyeing process conditions, aiming at maximum colour yield and better colour fastness.

After dyeing, the dyed SB-cotton fabrics were rinsed with tap water, followed by soap washing using 1–2 g/L neutral surfactant at 50–60 °C for 10–15 minutes to remove any unfixed surface dye, and then air-dried.

2.9 Methods of Testing

2.9.1 Estimation of tensile properties

Both warp and weft way tensile strength properties were evaluated by the ASTM D 5034 method [12].

2.9.2 Estimation of colour parameters

K/S value (colour strength) was measured by using the following Kubelka-Munk equation [13].

$$\frac{K}{S} = \frac{(1-R_{\lambda max})^2}{2R_{\lambda max}} = \alpha\, C_D$$

Where K denotes the absorption coefficient and S denotes the scattering coefficient, $R_{\lambda max}$ is reflectance (R) at a wavelength at maximum absorbance (λmax), CD is dye concentration, and α is an empirical constant as applicable.

All other colour parameters were measured using CIE-1976 [13] standard equations for each parameter. Colour difference index (CDI) represented by a single value, considering the differences of hue, chroma, Total colour differences and metamerism index, was calculated by following an empirical formula [14] irrespective of their sign.

$$\text{Colour Difference Index (CDI)} = \frac{\Delta E \ X \ \Delta H}{\Delta C \ X \ MI}$$

2.9.3 Estimation of colour fastness criteria

Colour fastness to washing was tested as per ISO-II (IS: 3361-1979) method, and colour fastness to rubbing was evaluated as per IS M766-1988 method and colour fastness to light was tested as per IS: 2454: 1985 method [15].

2.9.4 Statistical optimisation using the Box and Behnken Statistical design model

The "Central Composite Response Surface Design" [16] is the best-fitted tool for predicting best output results using statistically optimised independent input variables. Among different statistical models, the "Box-Behnken design model" [BBDM] is most efficient as it requires fewer experimental combinations for optimisation [17]. BBDM requires at least three input variables with three levels (-1,0, +1) for each input variable. It also requires a central value (mid-level) for each input variable to determine the coded regression coefficient for generating a second-order (quadratic) regression equation, as shown below, using the MiniTab 20.4 trial version software.

$$Y_i = \beta_0 + \sum_{i=1}^{i=k} \beta_i x_i + \sum_{i=1}^{i=k} \beta_{ii} x_i^2 + \sum_{i=1}^{i=k}\sum_{j=1}^{j=k} \beta_{ij} x_i x_j \quad \text{(Regression Equation)}$$

Where Y_i is the resultant output variable, i to k is the range of variation, where x_i represents any three chosen input variables as x_1, x_2 and x_3. β_0 denotes a constant, and β_i, β_{ii} and β_{ij} are regression coefficients (RC), where β_i is for linear first-order interaction, β_{ii} is for square quadratic interactions, and β_{ij} is for cross multiplication interactions [18].

Based on our earlier communicated experimental results reported elsewhere [19], mid, low and high ranges of six dyeing conditions were selected as independent input variables for optimising the K/S value (colour strength). These six input variables were divided into two sets: 1st Set included mordant concentration (x_1), concentration of dye (x_2) and pH of dye liquor (x_3); 2nd Set included dyeing time (x_4), dyeing temperature (x_5) and MLR (x_6).

Although the BBDM can address all 6 input variables simultaneously with 46 experimental runs, it posed difficulty to handle and explain, due to complex interactions and superimposition effects. So, an alternate approach was adopted here, i.e. analysing these six parameters in two sets separately, where each set consisted of three input variables together, to simplify the interpretation of its results and to avoid compound interaction effect.

3 Results and Discussion

3.1 Results of test of tensile properties test before and after treatments

Table 1 presents the tensile properties of untreated, pre-oxidised, and soya-based bio-cationized cotton fabrics before and after treatment. The results showed that treatment with 1% potassium persulfate ($K_2S_2O_8$) results in a weight loss of 2.22%, with fabric tenacity recorded at 2.82 cN/tex in the warp direction and 2.34 cN/tex in the weft direction, along with a slight increase in elongation in both directions. Subsequent soya-based bio-cationization of the pre-oxidised fabric leads to a higher weight loss of 5.01%, and a further reduction in tenacity to 2.33 cN/tex (warp) and 1.85 cN/tex (weft), accompanied by some further increase in elongation in both directions.

3.2 Preliminary results of standardisation of the dyeing process

The colourimetric summary data of that preliminary work for the untreated bleached control fabric, 1% K2S2O8 Oxidised control cotton fabric and optimum Catechu dyed fabric are shown in Table 2.

Table 1: Results of tensile properties of cotton fabrics before and after treatments

Sr. No.	Sample	Wt. gain (+) or loss (-) %	Tensile Strength (fabric tenacity in cN/tex)		Elongation (%)	
			Warp	Weft	Warp	Weft
1	Scoured & Bleached cotton	-	3.22	2.84	8.66	10.76
2	Scoured & bleached and 1% K2S2O8 pre-oxidized cotton	- 2.22	2.82	2.34	9.32	11.30
3	10% Soya-based bio-cationization on K2S2O8 pre-oxidised cotton	- 5.01	2.33 (82.62%) *	1.85 (83.33%)	10.34	12.72

**Data within parentheses indicate, % retention of fabric tenacity with respect to results obtained for Srl 2*

Table 2: Colourimetric data to study the effect of identified independent variables

Sr. No.	Sample/ Treatment	K/S	? E*	? L*	? a*	? b*	? c*	CDI
1.	Scoured/ Bleached control cotton fabric	0.02	---	---	---	---	---	---
2.	1% $K_2S_2O_8$ treated pre-oxidised **(oxy-cotton)** cotton fabric (No dyeing)	0.23	---	---	---	---	---	---
3.	10% soyabean-seed based bio-cationization of **oxy Cotton** + -30% Catechu dyeing* (No salt)	4.77	4.06	-2.49	1.66	2.75	9.59	1.50
4.	10% K-ALUM pre-mordanting on **oxy Cotton (NO SOYA)** + -30% Catechu dyeing* (No salt)	4.78	4.22	-2,08	1.67	2.53	10.90	1.37
5.	10% soybean-seed based bio-cationization of **oxy-cotton** +10% K-alum pre-mordanting and + -30% catechu dyeing* (No salt)	6.75	10.12	-5.95	6.09	5.82	12.98	1.61

**[Balanced dyeing result is found at pH 5, dyeing time 60 min, dyeing temperature 70 ºC and MLR 1:20.] [19]*

Table 3: Three levels of experimental range of selected important input variables chosen

Process Conditions (1st SET)		Assigning a 3-Level of data with a central mid-value		
		Minimum or Low (-1)	Medium (0)	Maximum or High (+1)
Mordant (K-alum) concentration (%)	(x_1)	5	10	15
Concentration of catechu dye (%)	(x_2)	20	30	40
pH of dye liquor	(x_3)	4	5	6
Dyeing time (min)	(x_4)	30	60	90
Dyeing temperature (ºC)	(x_5)	50	70	90
MLR (Substrate to Liquor ratio)	(x_6)	10	20	30

3.3 Statistical Optimisation of dyeing process conditions for both 1st Set and 2nd SET

In Set-1, the first three independent input variables selected are mordant concentration (%), dye concentration (%), and pH and for Set-2, three independent input variables selected are dyeing time, dyeing temperature, and MLR, which are selected based on the dyeing results of our earlier preliminary study [11 and corresponding CDI values as shown in Table 2..The mid, high and low limits of each parameter were finalised and are detailed in Table 3.

As per the BBDM design, 15 actual experimental results for selected independent input dyeing process variables and the dependent output variable (K/S value) for both the 1st set and the 2nd set are shown in Table 4.

Table 4: Experimental sets/ runs as per Box-Behnken Design for 3 chosen independent variables and chosen outputs/ response variable [1st and 2nd set]

Code	Results of 1st set of varying dyeing conditions					Results of the 2nd set of varying dyeing conditions			
	1st set of independent input variables			Output variable*		2nd set of independent input variables			Output variable*
	Concentr-ation of Mordant (potash-alum) (%)	Concentr-ation of catechu dye (%)	pH of dye liquor	K/S		Time of dyeing (min)	Temperature (ºC) of dyeing	MLR	K/S
	x_1	x_2	x_3	Y_1		x_4	x_5	x_6	Y_2
S1	15 (+1)	20 (-1)	5 (0)	5.02		90 (+1)	50 (-1)	20 (0)	5.45
S2	10 (0)	40 (+1)	4 (-1)	6.75		60 (0)	90 (+1)	10 (-1)	6.25
S3	5 (-1)	30 (0)	6 (+1)	4.95		30(-1)	70 (0)	30 (+1)	4.35
S4	5 (-1)	40 (+1)	5 (0)	4.98		30 (-1)	90 (+1)	20 (0)	4.50
S5	10 (0)	40 (+1)	6 (+1)	5.20		60 (0)	90 (+1)	30 (+1)	5.62
S6	10 (0)	20 (-1)	6 (+1)	4.98		60 (0)	50 (-1)	30 (+1)	6.98
S7	5 (-1)	30 (0)	4 (-1)	6.76		30 (-1)	70 (0)	10 (-1)	4.01
S8	5 (-1)	20 (-1)	5 (0)	6.29		30 (-1)	50 (-1)	20 (0)	4.67
S9	15 (+1)	30 (0)	4 (-1)	5.07		90(+1)	70 (0)	10 (-1)	4.40
S10	15 (+1)	30 (0)	6 (+1)	6.74		90 (+1)	70 (0)	30 (+1)	6.10
S11	10 (0)	20 (-1)	4 (-1)	5.42		60 (0)	50 (-1)	10 (-1)	4.10
S12	15 (+1)	40 (+1)	5 (0)	6.10		90 (+1)	90 (+1)	20 (0)	6.57
S13	10 (0)	30 (0)	5 (0)	6.76		60 (0)	70 (0)	20 (0)	6.75
S14	10 (0)	30 (0)	5 (0)	6.75		60 (0)	70 (0)	20 (0)	6.75
S15	10 (0)	30 (0)	5 (0)	6.75		60 (0)	70 (0)	20 (0)	6.75

** All the results for K/S and Δ E displayed here indicate the corresponding actual experimental data*

3.3.1 Response surface effect analysis to maximise K/S values for 1st SET

The results of ANOVA for 1st SET of varying dyeing conditions are shown in Table 5, the model summary is given in Table -6 and corresponding regression coefficient values with standard errors are given in Table 7.

Table 5: ANOVA analysis for Response Surface effect of K/S against mordant and dye concentration and pH

Results of ANOVA				
Type and source of relevant input parameters	**Df**	**f- Value**	**p-Value**	**Remarks**
Model	9	33596.67	0.000	As the tabulated P-value is much lower than the charted value for DF-9, the model is Significant.
Linear interaction:	3	51266.76	0.000	
K-alum Mordant Concentration (%)	1	15262.94	0.000	
Catechu Dye Concentration (%)	1	13203.97	0.000	
pH of dye liquor	1	125333.38	0.000	
Square interaction:	3	45797.08	0.000	
Mordant Concentration (%) X Mordant Concentration (%)	1	64235.86	0.000	
Dye Concentration (%) X Dye Concentration (%)	1	82277.13	0.000	
pH X pH	1	5454.32	0.000	
2-Way Interaction:	3	3726.18	0.000	
Mordant Concentration (%) X Dye Concentration (%)	1	9543.53	0.000	
Mordant Concentration (%) X pH	1	3.53	0.119	
Dye Concentration (%) X pH	1	1631.47	0.000	

Table 6: Model summary report [1st SET]

Model Summary	**Std deviation** 0.005323	**R-Square** 100.00%	**R-Square (Adjusted):** 100.00%	**R-Square (Predicted)** 99.98%

Table 7: Regression coefficients for interactive effects of input variables of K/S against variation of 1st set of 3 independent dyeing variables, i.e., mordant concentration, dye concentration and pH. [1st SET]

1st Set of Process Conditions varied as independent input variables	CC	RC.	SEC	t-value	p-value
Term					
Constant	β_0	3.585	0.003	2198.5 9	0.000
Linear interaction:					
Mordant Concentration (%)	β_1	0.447	0.002	123.54	0.000
Dye Concentration (%)	β_2	0.500	0.002	114.91	0.000
pH	β_3	1.692	0.002	354.02	0.000
Square interaction:					
Mordant Concentration (%) X Mordant Concentration (%)	$\beta_{1,1}$	-0.028	0.003	-253.45	0.000
Dye Concentration (%) X Dye Concentration (%)	$\beta_{2,2}$	-0.008	0.003	-286.84	0.000
pH X pH	$\beta_{3,3}$	-0.205	0.003	-73.85	0.000
2-way Interaction:					
Mordant Concentration (%) X Dye Concentration (%)	$\beta_{1,2}$	0.005	0.003	97.69	0.000
Mordant Concentration (%) X pH	$\beta_{1,3}$	0.001	0.003	1.88	0.119
Dye Concentration (%) X pH	$\beta_{2,3}$	-0.108	0.003	-40.39	0.000
CC - Coaded Coefficient, RC-Regression coefficient, SEC -Std. Error Coefficient					

On analysis of ANOVA (Table- 5), it is observed that the calculated p-value (Probability value) for "Model" as well as all the other parameters are lower than the charted value for degree of freedom 9 implying "Model" and all other parameters have significant contribution on 'K/S' value. The model summary report (Table 6) also shows a low standard deviation (S), a high R-square value (indicating strong explanatory power), and a small difference (less than 0.2) between the predicted and adjusted R-square values, confirming that the model is well fitted [20].

From the regression coefficient values shown in Table 7, it is observed that all the parameters are correlated (positively or negatively) with the response parameter, as well as indicating that each independent input variable has a significant effect on the output response variable as a whole, showing the model as significant. By putting the values of the respective regression constants (RC) in the said quadratic regression equation for K/S values,

The predicted K/S value stands as follows:

K/S (Y1) = 3.585+ 0.447 * Mordant Concentration + 0.500 * Dye Concentration + 1.692 * pH – 0.028 * Mordant Concentration * Mordant Concentration – 0.008 * Dye Concentration * Dye Concentration – 0.205 * pH * pH + 0.005 * Mordant Concentration * Dye Concentration + 0.001 * Mordant Concentration * pH – 0.108 * Dye Concentration * pH.

By replacing the values of the three independent input variables (Mordant Concentration, Dye Concentration and pH) in the above regression equation, the calculated response variable i.e., K/S (Y1) becomes 6.95, whereas an actual experimental value of 'K/S' for the identical condition is found 6.75, which is very close to calculated/predicted value, indicating the efficacy of this model.

With the help of graphical displays for BBDM statistical analysis, 3D surface plots and 2D contour plots for interactive effects are obtained using the same Minitab 20.4 software and are shown in Figure 1(a) and Figure 1(b). Figure 1(a) shows a 3D surface plot illustrating the effect of Mordant concentration and Dye concentration on the colour strength (K/S). It shows that as both mordant and dye concentrations increase, the K/S value also increases, reaching a peak at a critical point. This indicates a direct relationship between these input variables and the output variable up to this optimal level. Beyond this point, further increases in either variable result in a decline in K/S, suggesting an inverse relationship beyond the optimal range.

Figure 1(b), the corresponding 2D contour plot, represents the same data. In this diagram, the x- and y-axes denote mordant and dye concentrations, respectively, while the z-axis represents the K/S value. The contour plot indicates that an optimal K/S value of approximately 6.75+ can be achieved when the mordant concentration is around 10% and the catechu dye concentration is approximately 30%.

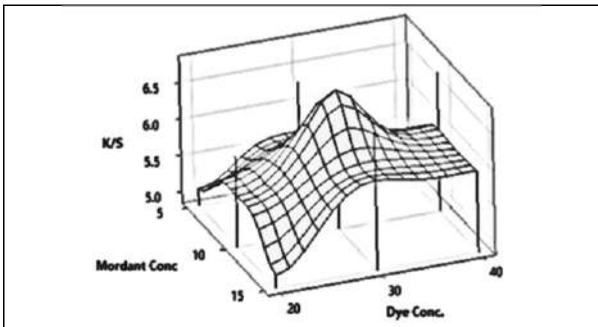

Figure 1(a) - 3D Surface plot for the effect of Mordant concentration and Dye concentration on K/S

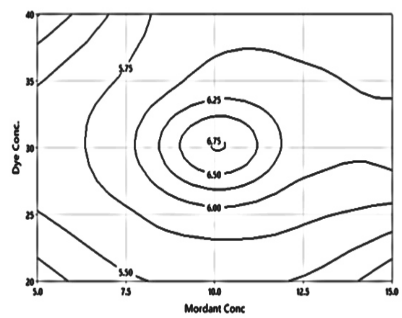

Figure 1(b) - 2D Contour diagram for the effect of Mordant concentration and Dye concentration on K/S

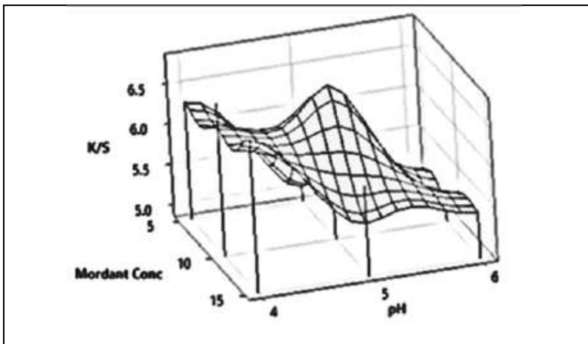

Figure 2(a) - 3D Surface plot for the effect of Mordant concentration and pH on K/S

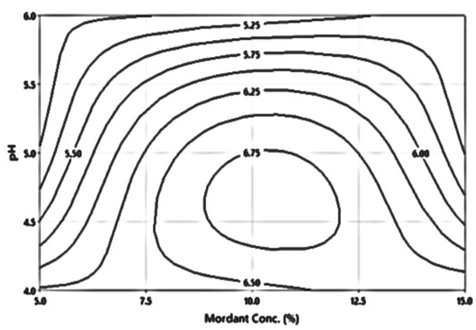

Figure 2(b)- 2D Contour diagram for the effect of Mordant concentration and pH on K/S

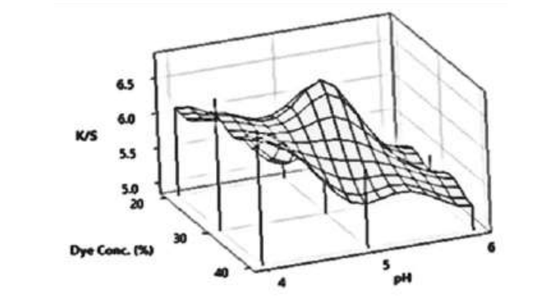

Figure 3(a) - 3D Surface plot for the effect of Dye concentration and pH on K/S

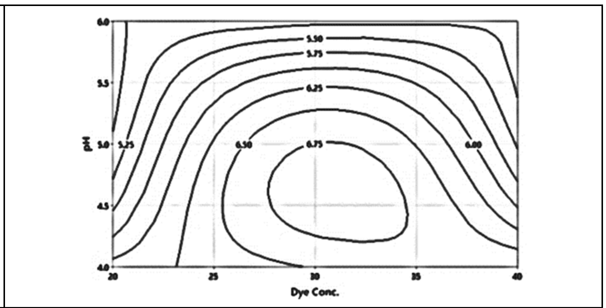

Figure 3(b) - 2D Contour diagram for the effect of Dye concentration and pH on K/S

Figure 2(a) and Figure 2(b) are 3D surface plots and 2D contour diagrams for the effect of Mordant concentration (%) and pH of dye bath on K/S value. Figure 2(a) shows an upside-down peak indicating the optimum K/S value.

The 2D contour diagram in Figure 2(b) represents the surface diagram of the x-axis and y-axis as 2 independent input variables, i.e. Mordant concentration (%) and pH, and the Z-axis represents the output variable of K/S value. From this contour plot, it is observed that the optimum value for K/S of 6.75+ could be achieved in approximately. 9- 12 % of mordant concentration and nearing 4.25 - 5 pH of dye liquor.

Figure 3(a) and Figure 3(b) are 3D surface plots and 2D contour diagrams for the effect of dye concentration (%) and pH of dye liquor on the K/S value. An upside-down peak in this surface plot indicates an optimum value for the K/S value.

The 2D contour diagram in Figure 3(b) represents the surface plots of the x-axis and y-axis as the independent input variables of dye concentration (%) and pH of dye liquor, and the Z-axis represents the output variable of K/S value. From this contour plot, it is observed that the optimum value for K/S of 6.75+ could be achieved using 28- 34% dye concentration and pH. 4.3- 5.0 in dye liquor.

3.3.2 Response surface effect analysis to maximise K/S values for 2nd SET

The results of ANOVA for the 2nd SET of varying dyeing conditions are shown in Table 8, the model summary is given in Table -9 and corresponding regression coefficient values with standard errors are given in Table 10.

On analysis of ANOVA (Table- 8), it is observed that the calculated p-value (Probability value) for “Model” as well as all the other parameters are lower than the charted value for degree of freedom 9 implying “Model” and all other parameters have significant contribution on 'K/S' value. The model summary report (Table 9) also shows a low standard deviation (S), a high R-square value (indicating strong explanatory power), and a small difference (less than 0.2) between the predicted and adjusted R-square values, confirming that the model is well-fitted.

From the regression coefficient values shown in Table 10, it is observed that all the parameters are correlated (positively or negatively) with the response parameter, as well as indicating that each input variable has a significant effect on the output response variable, showing the model as significant.

By putting the values of the corresponding regression coefficients and constants in the regression equation, the calculated 'K/S' value stands as follows:

Table 8: ANOVA analysis for Response Surface effect of K/S against variation of dyeing time, dyeing temperature and MLR. [2nd SET]

Results of ANOVA				
Type and Sources of data for input variables	**Df**	**f- Value**	**p-Value**	**Remarks**
Model	9	133.65	0.000	As the tabulated P-value is much lower than the charted value for DF-9, the model is Significant.
Linear interaction:	3	134.58	0.000	
Dyeing time (min)	1	216.98	0.000	
Dyeing Temperature (ºC)	1	26.38	0.004	
MLR	1	160.37	0.000	
Square Interaction:	3	174.38	0.000	
Dyeing time (min) X Dyeing time (min)	1	394.17	0.000	
Dyeing Temperature (ºC) X Dyeing Temperature (ºC)	1	11.90	0.018	
MLR X MLR	1	163.70	0.000	
2-Way Interaction:	3	91.98	0.000	
Dyeing time (min) X Dyeing Temperature (ºC)	1	29.00	0.003	
Dyeing time (min) X MLR	1	32.23	0.002	
Dyeing Temperature (ºC) X MLR	1	214.71	0.000	

Table 9: Model summary report [2nd SET]

Model Summary	Std deviation	R-Square	R-Square (Adjusted):	R-Square (Predicted)
	0.01198	99.59%	99.84%	93.38%

Table 10: Regression coefficients for the interactive effect of input variables of K/S against variation of dyeing time, dyeing temperature and MLR [2nd SET]

Dyeing Process conditions varied [as independent process variables]	CC	RC	SEC	t-Value	p-value
Term					
Constant	β_0	-11.25	0.069	-97.61	0.000
Linear Interaction:					
Dyeing time (min)	β_1	0.126	0.042	14.73	0.000
Dyeing Temperature (º C)	β_2	0.142	0.042	5.14	0.004
MLR	β_3	0.612	0.042	12.66	0.000
Square Interaction:					
Dyeing time (min) X Dyeing time (min)	$\beta_{1,1}$	-0.001	0.062	-19.85	0.000
Dyeing Temperature (º C) X Dyeing Temperature (º C)	$\beta_{2,2}$	-0.0005	0.062	-3.45	0.018
MLR X MLR	$\beta_{3,3}$	-0.008	0.062	-12.79	0.000
2-way Interaction:					
Dyeing time (min) X Dyeing Temperature (ºC)	$\beta_{1,2}$	0.0005	0.060	5.39	0.003
Dyeing time (min) X MLR	$\beta_{1,3}$	0.001	0.060	5.68	0.002
Dyeing Temperature (ºC) X MLR	$\beta_{2,3}$	-0.004	0.060	-14.65	0.000
CC- Coefficient Coefficients, RC-Regression coefficient, SEC -Std. error coefficient,					

K/S (Y2) = –11.25+ 0.126 * Dyeing time (min) + 0.142* Dyeing Temperature (º C) + 0.612 * MLR – 0.001 * Dyeing time (min) * Dyeing time (min) – 0.0005 * Dyeing Temperature (º C) * Dyeing Temperature (º C) – 0.008* MLR * MLR + 0.0005 * Dyeing time (min) * Dyeing Temperature (º C) + 0.001 * Dyeing time (min) * MLR – 0.004 * Dyeing Temperature (º C) * MLR

By replacing the values of 3 input variables (dyeing time, dyeing temperature and MLR) in the above-mentioned regression equation, the calculated response variable of K/S (Y2) value becomes 6.94 against actual experimental value of 'K/S' for the identical condition is found as 6.75, which is thus very close to the calculated value.

Using Minitab 20.4, a statistical design software, generated a 3D surface plot and a 2D contour diagram to analyse the interactive effects of dyeing time and dyeing temperature on the colour strength (K/S value), as shown in Figures 4(a) and 4(b). The 3D surface plot (Figure 4(a)) illustrates that as both dyeing time and temperature increase, the K/S value also rises, reaching a peak, indicating the optimal combination for maximum colour yield. This reflected a direct relationship between the input and the output variables. Beyond this point, further increases in either dyeing time or temperature led to a decline in the K/S value, demonstrating an inverse relationship between these inputs and the output variables. The 2D contour diagram (Figure 4(b)) further confirms these observed trends.

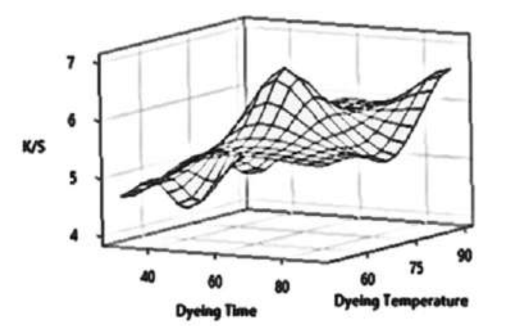

Figure 4(a) - 3D Surface plot for the effect of Dyeing time and Dyeing temperature on K/S

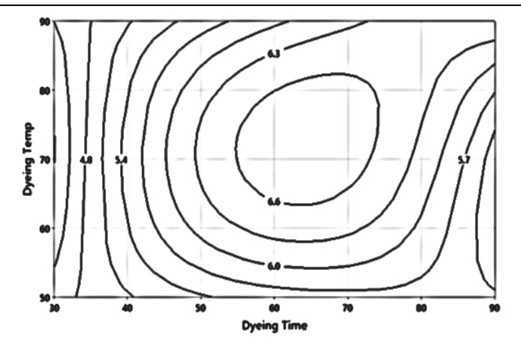

Figure 4(b) - 2D Contour diagram for the effect of Dyeing time and Dyeing temperature on K/S

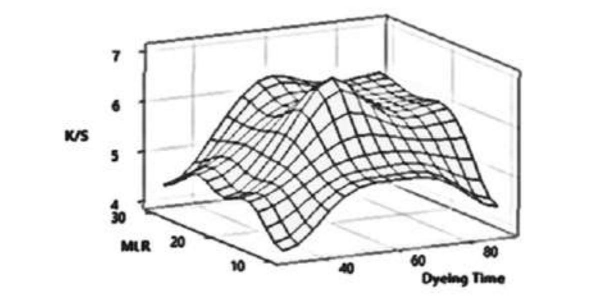

Figure 5(a) - 3D Surface plot for the effect of Dyeing time and MLR on K/S

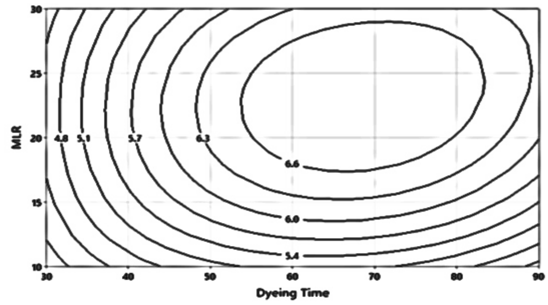

Figure 5(b) - 2D Contour diagram for the effect of Dyeing time and MLR on K/S

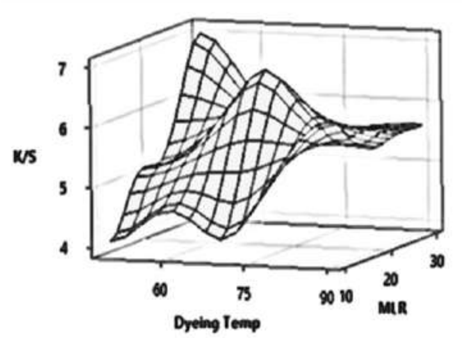

Figure 6(a): 3D Surface plot for the effect of Dyeing temperature and MLR on K/S

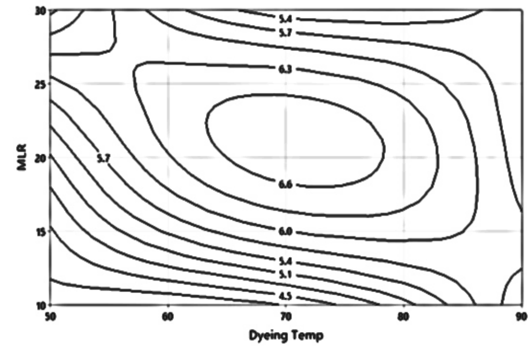

Figure 6(b): 2D Contour diagram for the effect of Dyeing temperature and MLR on K/S

The contour diagram (Figure 4 (b)) is the 2D surface plot of the x-axis and y-axis representing the chosen two independent input variables, i.e., dyeing time and dyeing temperature, and the Z-axis represents the chosen output variable of K/S value. From this contour plot, it is observed that the optimum value for K/S up to 6.6+ could be achieved in between 58 - 75 min of dyeing time and in between approx. 65 - 70 ºC of dyeing temperature.

Figure 5(a) and Figure 5(b) are 3D surface plots and 2D contour diagrams for the effect of dyeing time and MLR on K/S value, showing an upside-down peak in the surface plot showing maximum K/S value as optimum.

The contour diagram (Figure 5 (b)) is the 2D representation of the surface plot of the x-axis and y-axis representing the independent input variables of dyeing time and Substrate to liquor ratio (MLR), and the Z-axis represents the output variable of K/S value. From this contour plot, it is observed that the optimum value for K/S of 6.6+ could be achieved in between 55- 80 min of dyeing time and in between 18- 28 MLR.

Figure 6(a) and Figure 6(b) are the 3D surface plot and the 2D contour diagram for the effect of dyeing temperature and MLR on 'K/S' value, showing an upside-down peak indicating maximised K/S value.

Figure 6(b) represents a 2D contour plot illustrating the relationship between two input variables—dyeing temperature (x-axis) and material-to-liquor ratio (MLR) (y-axis)—with the K/S value as the output variable on the Z-axis. The plot reveals that a K/S value exceeding 6.6 can be optimally obtained when the dyeing temperature ranges between 65- 75 ºC and the MLR falls within the range of 18-23.

3.3.3 Analysis of results of colour fastness to wash, light and rubbing

The colour fastness to wash, light and rubbing for 10% soya extract-based bio-cationized SB-cotton after pre-mordanting with and without 10% K-alum and dyed with 30% catechu bio-dye, is also shown in Table 11.

Table 11: Colour fastness data for catechu dyed SB-Cotton without and with K-alum pre-mordanting

Description of Samples	Wash fastness		Light Fastness	Rubbing fastness	
	Change in shade	Staining		Dry	Wet
SOYA-10% on oxy cotton + Catechu 30% (without K-alum pre-mordanting)	3-4	3-4	3	3-4	2
SOYA-10% on oxy cotton + 10% K-alum (with mordant) + Catechu 30% (No Salt)	4	4	4	4	3-4

From Table 11, it was observed that application of K-alum (natural metallic mordant) on Cotton rendered to noticeable improvement in dye fastness properties. There was approximately. 1/2 grade enhancement of wash fastness, 1 grade improvement of light fastness and 1 to 1.5 grade increase in wet rubbing fastness. These enhancements may be viewed as due to strong ionic interaction between the negatively charged Catechu dye molecule and cationic soya-based bio-cationized Cotton. Additionally, Phenolic -OH groups of Catechin donated electrons to the aluminium ions of K-alum, facilitating the formation of a giant [Fibre-Soya-cation-K-alum mordant-catechu dye] complex formation [19], enhancing dye fixation and improving overall colour fastness.

4. Conclusion

This study demonstrated that pre-oxidised, soya-based bio-cationized cotton fabric could be effectively dyed with natural catechu dye using potash alum as a bio-mordant, achieving high colour yield and good colour fastness under salt-free, acidic conditions (pH 5). Initial experimental results showed a maximum standardised colour strength (K/S) value of 6.75 and a corresponding ΔE value of 10.12.

Further statistical optimisation using the Box-Behnken Design model and ANOVA analysis identified precise dyeing conditions that enhanced the K/S value up to 6.95 and ΔE up to 10.22. The optimal parameters were determined as: 10% potash alum bio-mordanting on 10% soya-based bio-cationized cotton, dyed with 30% catechu extract at pH 5, at a dyeing temperature of 70 °C for 60 minutes, using a material-to-liquor ratio (MLR) of 1:20. This statistically optimized process provides a reliable and practical guideline for industrial dyeing, enabling commercial application of this eco-friendly system to achieve superior color yield and improved fastness to washing, light, and rubbing.

References

[1] Bhouri N., Ltaief S., Bhouri B. & Abdessalem S. B., "Optimisation of a green dyeing process using natural dyes extracted from Corchorus Olitorius leaves", Journal of Natural Fibres, 20 (2023) 2170946, https://doi.org/10.1080/15440478.2023.2170946

[2] Lee Y. H. "Dyeing fastness and deodorising properties of Cotton, Silk and wool fabrics dyed with coffee sludge (Coffea Arabica L.) Extract", Journal of Applied Polymer Science, 103 (2007) 251- 257, https://doi.org/10.1002/app.25221

[3] Vankar P. S., "Chemistry of Natural Dyes", Resonance, 5 (2000) 73- 80

[4] Bechtold T., Turcanu A., Ganglberger E. & Geissler S., "Natural dyes in modern textile dyehouse- how to combine the experience of two centuries to meet the demand of the future", Journal of Cleaner Production, 11 (2003), 499- 599, https://doi.org/10.1016/S0959-6526(02)00077-X

[5] Rovira J., Nadal M., Schuhmacher M. & Domingo J. L., "Human exposure to trace elements through the skin by direct contact with clothing: Risk assessment" Environmental Research, 140 (2015) 308- 316, https://doi.org/10.1016/j.envres.2015.03.032

[6] Manian A. P., Paul R. & Bectold T., "Metal mordanting in dyeing with natural colourants" Colouration Technology, 132 (2016) 107- 113, https://doi.org/10.1111/cote.12199

[7] Samanta P., Mukhopadhyay A. & Konar A., "Development of Naturally Coloured Cotton Fabric Based Bio-Medical Textiles for Human Wellness Behaviour Using Chitosan, Catechu and Eucalyptus Leaves as Natural Bio-Chemical Agents", African Journal of Bio-Medical Research, 27(4s) (Nov-Dec-2024), https://doi.org/10.53555/AJBR.v27i4S.6461

[8] Nair A., Chattopadhyay D. & Saha B., "Plant-Derived Immunomodulators", in a book on 'New Look to Phytomedicine' (eds.: Khan M. S. A., Ahmad I., Chattopadhyay D...) Academic Press, London, 435-499 (2019), https://doi.org/10.1016/B978-0-12-814619-4.00018-5

[9] Khan M. I., Ahmad A., Khan S. A., Yusuf M., Shahid M., Manzoor N. & Mohammad F., "Assessment of antimicrobial activity of Catechu and its dyed substrate", Journal of Cleaner Production, 19 (2011) 1385-1394, https://doi.org/10.1016/j.jclepro.2011.03.013

[10] Khatun M. H., Akhtar A., Kadri H. J. & Mostafa M. G., "Optimisation of alkaline extraction of natural dye from Acacia Catechu and its dyeing on silk fabrics", Journal of Environmental Science, 6 (2017) 111- 117

[11] Samanta P., Mukhopadhyay A. & Konar A., "Eco-friendly dyeing and finishing for improving colour fastness and wellness properties of cotton", in Functional Textiles & Clothing-2023, (Springer, Singapore). Springer Proceedings in Materials, 42 (2024) 113- 145, https://doi.org/10.1007/978-981-99-9983-5_9

[12] Annual Book of ASTM Standards, Part 32E 23.02 (American Society for Testing and Materials, Philadelphia, Pennsylvania, USA), 1976, 219

[13] Shimo S. S. & Smriti S. A., "Colour coordinates and relative colour strength of reactive dye influenced by fabric GSM and dye concentration", International Journal of Research in Engineering and Technology, 4 (2015) 192- 197

[14] Samanta A.K., Agarwal P., Singhee D. & Dutta S., "Application of single and mixtures of red sandalwood and other natural dyes for dyeing of jute fabric: Studies on colour parameters/colour fastness and compatibility" Journal of the Textile Institute, 100 (7) (2009) 565-587

[15] ISI (BIS): Handbook of Textile Testing SP: 15-1981. 1st edn. 1982, Bureau of Indian Standards, New Delhi, 1-4 (1982) 221-280

[16] Aslan N., "Application of response surface methodology and central composite rotatable design for modelling and optimisation of a multi-gravity separator for chromite concentration" Powder Technology, 185 (2008) 80- 86, https://doi.org/10.1016/j.powtec.2007.10.002

[17] Ferreira S. L. C., Bruns R. E., Ferreira H. S., Matos G. D., David J. M., Brandao G. C., Silva E. G. P., Portugal L. A., Reis P. S., Souza A. S. & Santos W. N. L., "An alternative for the optimization of analytical methods" Analytica Chimica Acta, 597 (2007) 179- 186, https://doi.org/10.1016/j.aca.2007.07.011

[18] Yetilmezsoy K., Demirel S. & Vanderbei R. J., "Response surface modelling of Pb (II) removal from aqueous solution by Pistacia Vera L.: Box–Behnken experimental design" Journal of Hazardous Materials, 171 (2009) 551- 562, https://doi.org/10.1016/j.jhazmat.2009.06.035

[19] Samanta P., Mukhopadhyay A. & Konar A., "Bio-Cationization of cotton fabric using de-oiled Soya-bean waste and chitosan for salt-free dyeing with anionic catechu natural dye without and with natural Potash-Alum pre-mordanting", Communicated to Fibres and Polymers under Review

[20] Hussain H. N., Imtiaz F., Sajid A., Younas U., Manzoor Q., Mnif W., Nazir A., Al-Mijalli S. H., Iqbal M. & Ehsan N., "Response surface optimized green approach for silk and cotton dyeing using Beta vulgaris peels extracts as a dye and pomegranate rind as bio-mordant waste to craft", Journal of Engineered Fibers and Fabrics, 19 (2024) 01- 15, https://doi.org/10.1177/15589250241309010

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Textile Application of Natural Dye Extracted from Myrobalan (Terminalia chebula): Process Optimisation using RSM

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Abstract:

*Myrobalan is a natural dye extracted from the fruits of Terminalia chebula, a medicinal plant widely used in Ayurveda. Myrobalan has been used in textile dyeing since ancient times, as it imparts a yellowish-brown colour. It is also used as a mordant, enhancing the fixation, colour fastness, and hue of other natural dyes. Despite being the most widely used bio-mordant for dyeing with natural dyes, inconsistency in terms of dyeing method and uniform colour uptake have been a major problem in commercial dyeing using myrobalan. In this study, response surface methodology (RSM) has been used to compare the application of myrobalan on 100% cotton cambric fabric by three techniques, viz. exhaustion technique, padding technique and soaking technique. The factors studied were dye concentration, dyeing temperature, and dyeing duration. The responses measured were uniformity of colour uptake, colour strength (K/S), colour coordinates (L*a*b*), and fastness properties (washing and rubbing). The results show that the optimal technique for uniform dyeing using myrobalan is the padding technique, employing 3 nip-dips of 20% owf dye liquor, at a dyeing temperature of 50oC. This technique produces the desired colour, while reducing dyeing time and water consumption, as compared to the conventional exhaustion technique. The optimized technique of myrobalan dyeing is promising for sustainable natural dyeing in commercial sector.*

Keywords: *Harad, Myrobalan, Natural dye, RSM, tannin, Terminalia chebula*

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1. Introduction

The art of colouration of textiles is age old, which employed natural dyes extracted from plants, animals, and minerals. The textile industry is increasingly seeking more sustainable and eco-friendly practices. Therefore, natural dyes are gaining prominence due to their biodegradability, non-toxic nature, and alignment with eco-friendly practices. However, most of the natural dyes are only adjective in nature and do not possess direct affinity for textile fibres [1]. Therefore, the application of natural dyes often requires treating the fabric with mordants which act as a bridging complex between the fibre and the dye molecules. This facilitates the dyeing process. Myrobalan, or harad is one of the most widely used bio-mordant for the application of natural dyes in various traditional textile crafts of India [2, 3].

Myrobalan is a natural dye extracted from the dried fruits of Terminalia chebula, a medicinal plant widely used in Ayurveda (Figure 1) [4]. Myrobalan has been used as a dyeing agent for cotton fabrics since ancient times, as it imparts a yellowish-brown colour. It also acts as a mordant, as it can bind to both fibres and dyes, enhancing the colour uptake, value and fastness of several other natural dyes such as madder, turmeric, indigo, kasim, pomegranate, cutch, and lac [5, 6].

Figure 1: Myrobalan fruits (dried nuts)

The phytochemical profiling of myrobalan reveals the presence of several phenolic compounds, primarily hydrolysable tannins such as chebulic acid, chebulinic acid, chebulagic acid, ellagic acid, and gallic acid. The tannin content can make upto 20-50% of the total phytochemical constituency of myrobalan. In addition to tannins, myrobalan also contains a range of phenolic compounds (like phenol and propenoic acid), terpenoids (like arjunic acid and terminolic acid), flavonoids (like quercetin and rutin), and sterols (like daucosterol) (Figure 2) [7, 8].

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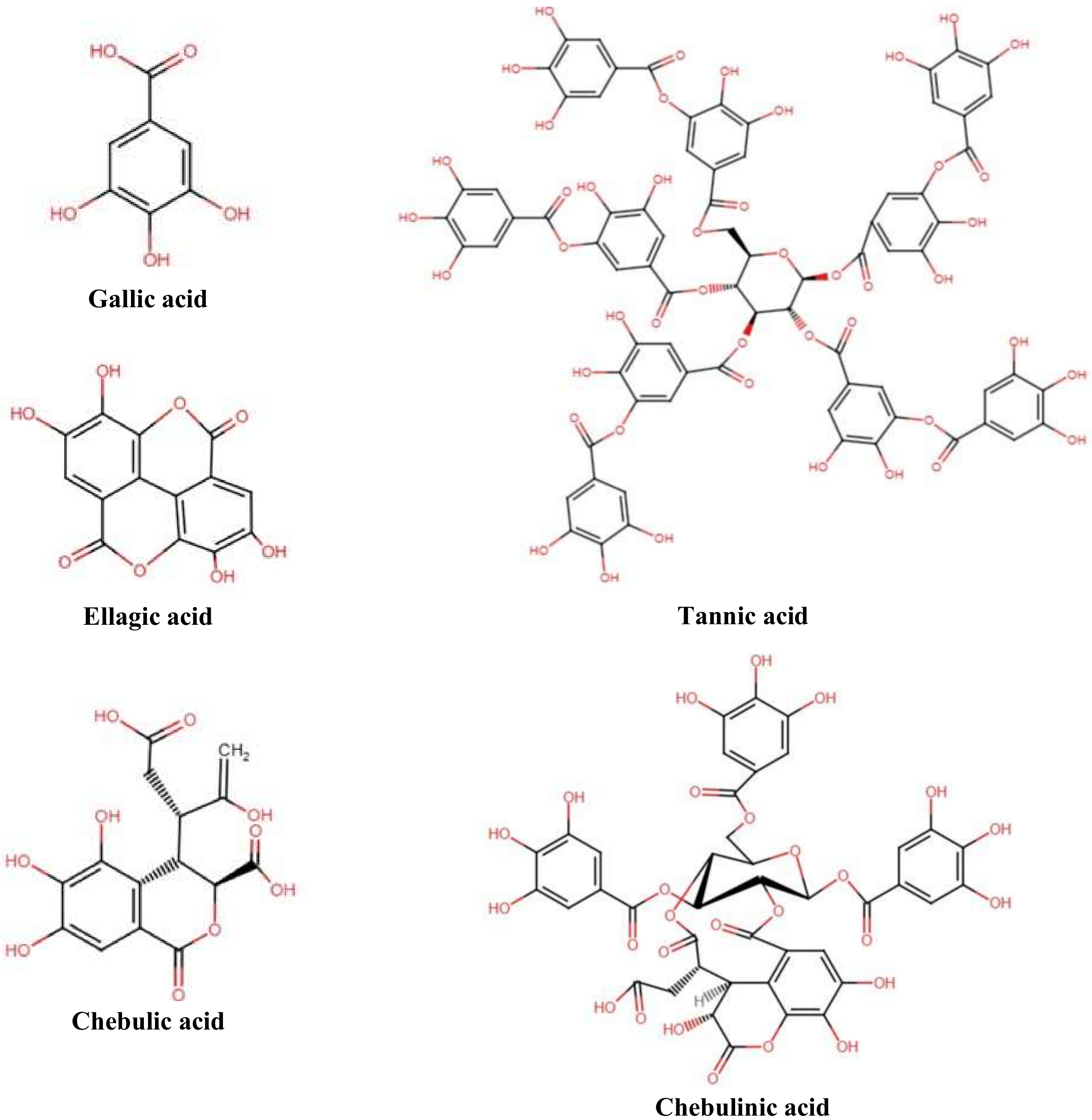


Figure 2: Structure of major hydrolysable tannins present in myrobalan (Terminalia chebula) [7, 8]

These compounds contribute to its ability to act as a mordant and dye, providing a range of colour tones from golden yellow to deep brown, depending on the dyeing process and the use of other mordants. Its versatility and the range of shades it can make with other natural dyes make myrobalan a valuable resource for textile colouration. When myrobalan treated fabric is topped with ferrous sulphate, the fabric develops a deep green-grey colour. Similarly, when it is applied alongside indigo, it produces teal hue, and a grey-black hue with kasim [9, 10]. In addition to this, the high tannin content in myrobalan also imparts functional properties to the fabric, such as antimicrobial properties, UV protection properties, and antioxidant properties [11, 12].

Despite the demonstrated versatility and benefits of myrobalan as a natural dye and bio-mordant, its application remains limited the traditional textile dyeing sector. The traditional process involves soaking myrobalan fruits in water for 24 hours, boiling the soaked fruits for 2–3 hours in large vats. This is followed by immersing and pounding the fabric in the filtered extract for 4-5 hours and subsequently drying the fabric in open width under the Sun. This process is repeated 2-3 times until the desired colour intensity has been obtained [13].

However, this dyeing procedure is not commercially viable. The application of natural dyes on textile material, especially tannin-rich natural dyes, shows higher incidences of uneven dyeing. This is because in exhaust dyeing, when the textile material is added to the heated dye bath, the dye molecules rush into the fibre system. This results in higher colour uptake in some regions of the fabric. Moreover, any folds or creases in the fabric during the dyeing process cause accumulation of the colourant in those regions. These factors lead to dyeing faults and non-uniform colouration of textile materials [14].

Traditional techniques of myrobalan dyeing are labour-intensive, time-consuming, and water intensive. This prevents any attempts at adopting the traditional method of application in existing commercial set up. This, in turn, restricts the usage of natural dyes in commercial textile dyeing despite the global sensitisation towards natural dyeing practices. To address these challenges and optimize the myrobalan dyeing process, this study employs factorial model under response surface methodology (RSM) to optimize the dyeing parameters for cotton fabric using Myrobalan powder. RSM is a statistical tool used for designing experiments to study the response of interest, i.e. the dyeing efficiency and uniformity. RSM allows for the exploration of interactions between multiple variables – such as dye concentration, temperature, and dyeing time enabling the identification of optimal conditions for achieving desired colour properties. By integrating traditional knowledge with contemporary statistical techniques, this research aims to enhance the industrial applicability of myrobalan [15, 16].

This study compares three primary dyeing techniques:

i. Exhaustion: Heat energy is applied to 'exhaust' the dye from dye liquor and carry the dye molecules for fixation onto the substrate. It is used for the application of most natural dyes (like madder, safflower, turmeric, etc.) as well as synthetic dyes (reactive, direct, acid, etc.). The dyeing temperature, dye concentration, material to liquor ratio (MLR), and addition of auxiliaries, affect the substantivity of a dye towards the substrate. They also govern the depth of colour obtained, as well as its uniformity. [17, 18]

ii. Padding: It consists of two processes- dipping and nipping. The fabric is first dipped in the required solution, in this case the myrobalan dye solution. This ensures that the fabric gets thoroughly saturated with the dye liquor. Following immersion, the fabric is passed through a pair of squeeze rollers of the padding mangle, known as nips, which apply pressure to remove excess dye solution from the fabric. This controlled squeezing, or nipping, adjusts the dye pickup and ensures that the dye is evenly distributed across the fabric. This process is termed as a single nip and dip [19, 20].

iii. Soaking: Soaking is a traditional dyeing technique, predominantly used with natural dyes. This involves immersing textile material in the dye bath for an extended period, typically overnight, to ensure thorough absorption of the dye into the fibres. The long duration of immersion in the dye solution encourages better absorption of the dye molecules inside the fibre system [21, 22].

The present study presents a systematic optimisation of the dyeing process using myrobalan powder on cotton fabric, through response surface methodology. This provides a comprehensive understanding of the factors affecting dye uptake and colour fastness. This study seeks to advance the application of natural dyes, like myrobalan, in commercial textile colouration, paving the way for more sustainable and eco-friendly practices in the industry.

2. Materials and Methods

2.1 Materials

The application of myrobalan was studied on 100% cotton RFD cambric fabric with a thread count of 212 x 216, sourced from Kotla Market, New Delhi. Myrobalan, or harad (Terminalia chebula), was obtained in powder form of the dried fruits (nuts) from Isha Agro Developers Pvt. Ltd.

2.2 Methods

2.2.1 Design of Experiment (DoE) for optimisation of application of Myrobalan

This study compares and evaluates three techniques for application of myrobalan: 1- Exhaustion technique, 2- Soaking technique, and 3- Padding technique. Response surface methodology (RSM) was followed to determine the optimal dyeing procedure. The evaluation of quality of dyed textile material was done by measuring responses. The factors considered and responses measured in this study are given in Figure 3.

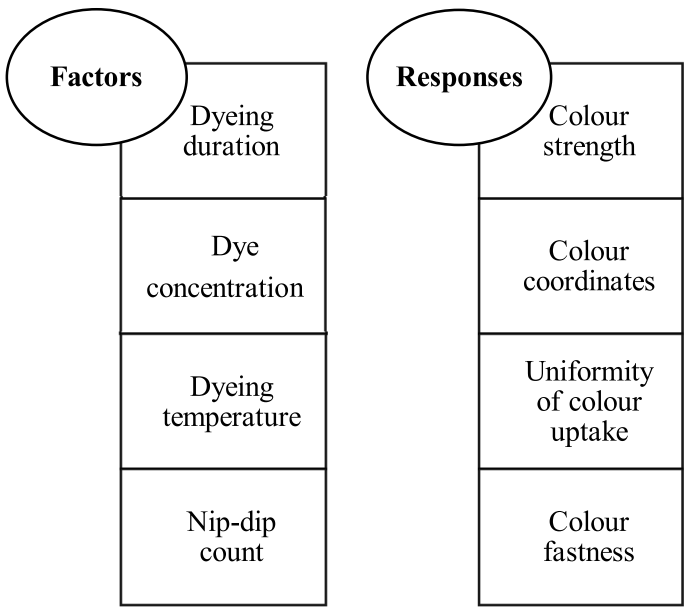


Figure 3: Factors and responses studied under RSM for optimization of myrobalan application

Under the RSM model, a combination of two-level and three-level factorial method was employed. The dye concentration was studied by employing the three-level factoring method to ensure coverage of a wider range for optimization. [23] . This independent variable consisted of three values- a lower, an intermediary, and a higher value, coded as -1, 0, and +1 respectively in Table 1. The dye concentration is depicted as a percentage on weight of fabric (% owf).

The other factors were studied using two-level factoring. It was inferred, based on the review of literature that the optimum lies within the proposed two-level factoring design of experiment. Therefore, adoption of two-level factoring reduces the number of experiments while giving optimized results. However, in case the preliminary test results had indicated that the optimum lies outside these factors, then an expanded factorial design would have been conducted [24, 25]. These independent variables have been coded as 0 and +1, as given in Table 1.

Table 1: Independent variables for optimization of myrobalan application

Sl. No.	Factors (independent variables)	-1	0	+1
1.	Dye Concentration	10%	20%	30%
2.	Dyeing duration (Exhaustion)	-	30 minutes	60 minutes
3.	Dyeing duration (Soaking)	-	12 hours	24 hours
4.	Number of nips and dips (Padding)	-	2 nips and dips	3 nips and dips
5.	Dyeing temperature (Exhaustion)	-	50°C	80°C

The design of experiment was thus formulated to study the efficiency of dyeing using three methods of application of myrobalan – exhaustion technique, padding technique, and soaking technique. This is shown in Figure 4 below.

2.2.2 Extraction of Dye

The extraction of dye from myrobalan was done in aqueous medium, by heating myrobalan powder (10%, 20%, and 30%, as per the DoE), in MLR of 1:40 water at simmer for 30 minutes. The liquor volume was maintained by covering the beaker during extraction. After extraction, the liquor is sieved to obtain the required dye liquor for further application on fabric using different techniques.

2.2.3 Application of Myrobalan on cotton fabric

a. Exhaustion technique

The dyeing parameters (independent variables) for exhaust dyeing were studied as follows:

a) Dyeing temperature- 50°C and 80°C
b) Dyeing duration- 30 minutes and 60 minutes
c) Dye concentration (% owf)- 10%, 20%, and 30%
d) MLR- 1:40 (constant)

A combination of these parameters was studied in accordance with the DoE, as depicted in Figure 2 above. The fabric was manually stirred every five minutes, while the dye liquor was heated up to the pre-determined temperature on simmer. The dyed fabric was squeezed and dried at room temperature.

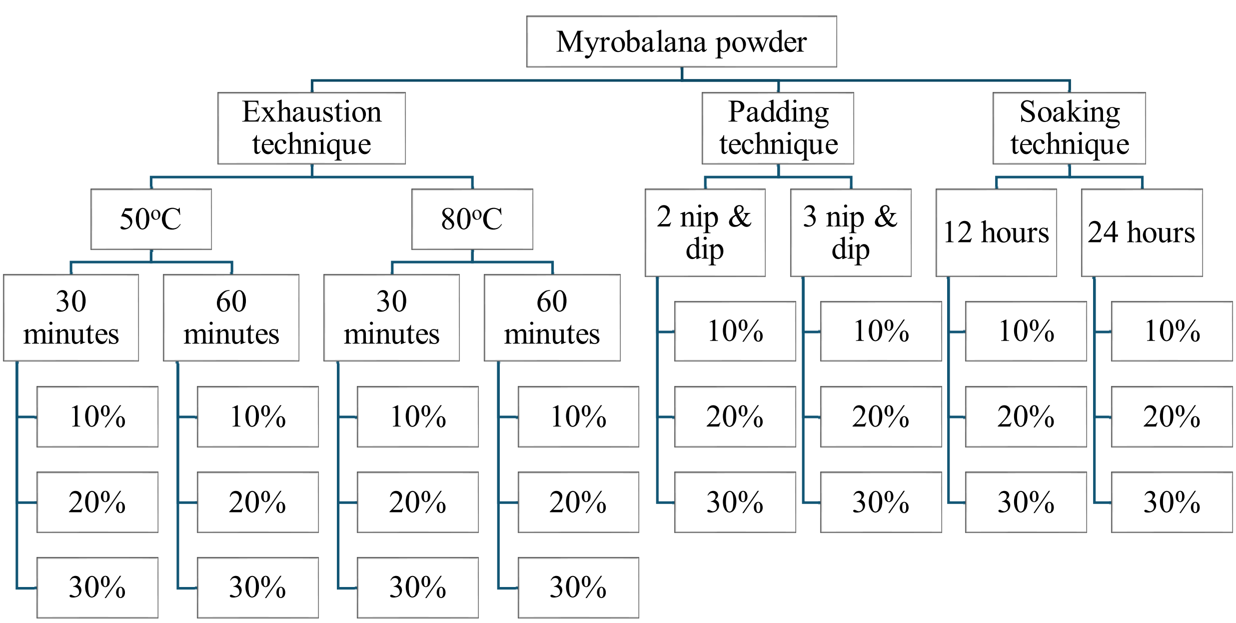
b. Padding technique

Myrobalan was applied by employing 2 and 3 nips and dips using dye liquor of 10%, 20%, and 30% owf concentration. The temperature of the dye liquor was 40-50°C (room temperature). After padding, the fabric was dried at room temperature.

c. Soaking technique

The fabric was soaked in dye liquor (10%, 20%, and 30% owf

Table 1: Independent variables for optimization of myrobalan application



concentration) at room temperature for a period of 12 hours and 24 hours each. The samples were squeezed and dried at room temperature.

Each dyeing technique was carried out in duplicate to ensure the reliability and reproducibility of results.

2.2.4 Measurement of responses for method optimisation

The efficiency of different dyeing techniques was evaluated by measuring the responses (dependent variables) to reach an optimized dyeing method.

a) Measurement of colour strength and colour coordinates

The two parameters- the K/S value and the CIE L*a*b* values were measured using the Colour-eye Macbeth 3100 Spectrophotometer. The measurement was taken at six locations on each sample to obtain the average readings.

b) Visual evaluation for uniformity

The samples were observed using the Colour Matching Cabinet under the D26 light source. The uniformity of colour on the dyed samples was evaluated by visual inspection.

c) Assessment of colour fastness

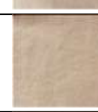
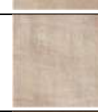
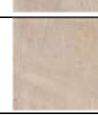
The dyed samples were assessed for their colour fastness to washing (ISO105C06:2010AIS) and rubbing (ISO105-X12:2016). The tests were conducted at the Institute of Home Economics, University of Delhi using the laboratory laundrometer and crock meter respectively. The changes in colour and staining of the adjacent fabric were assessed using the ISO105, BS1006 AO3-1978 SDC standard grey scales.

3. Results and Discussion

3.1 Measurement of colour strength and colour coordinates

The comparison of colour strength in samples dyed using myrobalan was a key parameter measured in this study to determine an optimized application process, as presented in Table 2.

Table 2: Colour strength (K/S) and colour coordinates (CIE L*a*b*) of samples dyed with myrobalan using different techniques

Dyeing technique	Dyeing temperature	Dyeing time/ nip & dip	Dye percentage	K/S	*L**	*a**	*b**	Sample
Exhaustion	50ºC	30 minutes	10%	**5.12**	**74.22**	-1.51	8.05	
			20%	6.57	72.80	-1.62	9.22	
			30%	7.24	72.84	-1.56	8.87	
	50ºC	60 minutes	10%	5.96	73.17	-1.53	8.47	
			20%	7.06	**72.09**	-1.67	9.71	
			30%	7.37	72.65	-1.59	9.65	
	80ºC	30 minutes	10%	5.58	73.10	-1.60	8.10	
			20%	7.18	74.01	-1.71	9.35	
			30%	7.77	73.91	-1.65	9.03	

Dyeing technique	Dyeing temperature	Dyeing time/ nip & dip	Dye percentage	K/S	*L**	*a**	*b**	Sample
	80°C	60 minutes	10%	5.25	72.34	-1.59	8.68	
			20%	7.64	73.68	-1.64	8.93	
			30%	7.92	72.47	-1.70	8.81	
Padding		2 nip & dip	10%	5.36	72.72	-1.53	8.36	
			20%	7.83	73.33	-1.56	9.09	
			30%	8.12	73.84	-1.56	9.32	
		3 nip & dip	10%	5.87	73.05	-1.54	9.53	
			20%	7.68	73.62	-1.58	9.41	
			30%	**8.56**	73.59	-1.64	9.55	
Soaking		12 hours	10%	5.28	73.05	-1.60	8.06	
			20%	7.65	73.44	-1.63	8.45	
			30%	7.89	73.92	-1.66	8.63	
		24 hours	10%	5.46	73.39	-1.58	8.17	
			20%	7.54	73.08	-1.54	8.91	
			30%	7.93	73.23	-1.61	9.02	

The colour strength (K/S values at λ_{max} = 560 nm) of the samples indicates the intensity or depth of colour developed on the fabric. The K/S values demonstrate an increase in colour uptake with an increase in dye concentration from 10% to 20% owf, suggesting enhanced dye absorption and fixation within this range. However, the increase in K/S values became less significant when the dye concentration was further increased from 20% to 30% owf. This suggests that the fabric reached a saturation point where additional dye molecules were not effectively absorbed or bonded to the fibre, possibly due to limited available binding sites. The highest K/S value (8.56) was achieved using three nips and dips in the padding technique, indicating that repeated applications facilitated better penetration and deposition of dye molecules.

The colour space coordinates ($L^*a^*b^*$) indicate the lightness and chromatic attributes of the dyed samples. The L^* values, which represent the lightness of the samples, ranged from 72.09 to 74.22, with lower values corresponding to darker shades. The a^* values, ranging from -1.71 to -1.51, indicate a slight greenish hue in the dyed samples, while the b^* values, varying from 8.05 to 9.71, suggest a dominance of yellow tones. The increase in b^* values with higher dye concentrations signifies a stronger yellow component, characteristic of myrobalan-dyed fabrics. These findings highlight the role of dye concentration and application technique in achieving optimal colour depth and consistency [9].

3.2 Uniformity of colour uptake

The observation under the Colour Matching Cabinet revealed that samples dyed using the padding technique exhibited more uniform colour development. This technique involved open-width dyeing, ensuring even absorption of dye molecules across the fabric without accumulation at creases.

Samples dyed using the exhaustion technique also demonstrated relatively uniform colour development. However, certain samples dyed for 30 minutes exhibited slight patchiness, which could be attributed to insufficient agitation during the dyeing process. The exhaustion technique necessitates the movement of either the textile material, the dye liquor, or both. However, incidental fabric folds due to laboratory conditions may have led to localized dye accumulation, contributing to uneven colouration. This effect was more pronounced at a lower dyeing temperature (50°C), as higher temperature (80°C) facilitates increased molecular vibration, which helps prevent localized dye aggregation.

In contrast, samples dyed using the soaking technique developed deeper hues around the fabric's edges and incidental creases, leading to visibly uneven colouration. The dye molecules exhibited greater adsorption and absorption in these areas, likely due to the absence of fabric and dye liquor movement. This resulted in non-uniform colour distribution. These results have been shown in Figure 5 below.

3.3 Assessment of colour fastness properties

The colour fastness of myrobalan-dyed cotton cambric fabric was evaluated for washing and rubbing under different dyeing techniques (exhaustion, padding, and soaking) with varying dyeing parameters, as given in Figure 6.

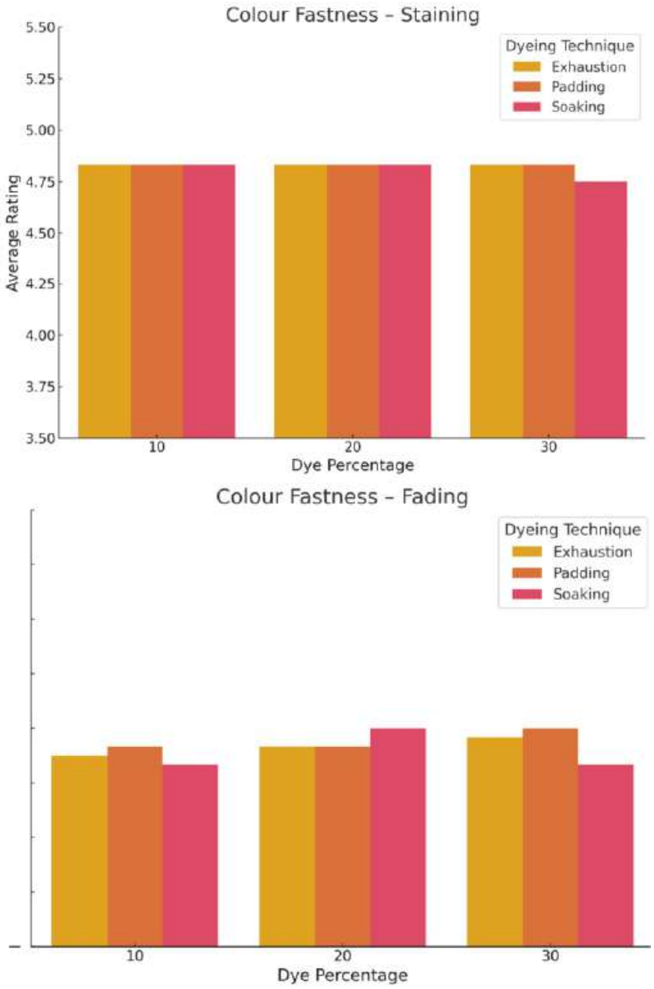


Figure 6: Colour fastness of dyed samples to different parameters

The colour fastness tests showed consistently minimal staining of the adjacent fabric, as indicated by excellent (5) and very good (4-5) ratings on grey scale (for washing and

(a) (b) c)

Figure 5: Samples dyeing using a) Exhaustion, b) Padding, and c) Soaking techniques

dry rubbing, and wet rubbing respectively). The samples, however, faded slightly on both washing and rubbing, as indicated by lower (4 to 4-5) ratings.

In exhaustion dyeing technique, temperature variations (50°C and 80°C) did not significantly impact washing fastness. However, increased dyeing duration (60 minutes) allowed better fixation of the dye molecules, as indicated by the very good ratings of fading during washing. A similar improvement was observed when dyeing the samples using padding technique with three nips and dips, as compared to two nips and dips. The samples dyed using soaking technique showed less fading on washing when the dye concentration was 10-20% owf. This indicates that the excess dye molecules (in 30% owf dye concentration) could not be adequately fixed on the fibre through soaking technique. This was also observed in the comparatively poor rubbing fastness (wet) of samples dyed with 30% dye concentration by soaking technique. The same was not observed for other dyeing technique.

The assessment of colour fastness properties clearly indicates that since myrobalan has little to no affinity towards fibre, the dye molecules need to be pushed into the fibre structure through an external force to bring about effective dyeing. This external force was present in the form heat (in exhaustion) and pressure (in padding). Therefore, the colour fastness of the dyed samples in both these cases was very good to excellent [26, 27].

In padding technique, the pressure of the rollers not only physically pushes the dye molecules to the fibre, but it also squeezes out the excess dye solution up to a pre-determined percent pickup pressure. This prevents aggregation of dye on fabric, which may lead to patchy dyeing. The fabric thus developed uniform fast colour [19].

4. Conclusion

Myrobalan is an important natural dye as well as a tannin-based mordant. This research optimized its application on cotton fabric using three dyeing techniques exhaustion, padding, and soaking through response surface methodology (RSM). The responses measured directly indicated the dyeing efficiency of myrobalan, particularly in the context of potential commercial use.

The soaking technique showed major limitations in both colour uniformity and fastness. Although this technique produces satisfying results traditionally, when used with extensive pre-treatment steps, these cannot be replicated feasibly in commercial settings. Therefore, the soaking technique was rejected for possible commercial application.

While the exhaustion and padding techniques yielded comparable results in colour strength and fastness, padding showed more consistent uniformity in colour development. Although industrial jigger machines may address uneven dyeing in exhaustion, the padding technique still offers key advantages. Notably, it reduces dyeing time, requires lower dyeing temperatures (thereby conserving energy), and operates with lower liquor ratios, thereby conserving water and reducing effluent load. These aspects make it more environmentally sustainable. Additionally, reduced process duration and resource input offer economic benefits, lowering overall operational costs. Hence, the padding method emerged as the most suitable and sustainable technique among the three for the application of myrobalan dye in commercial textile processing.

5. Limitations of the Study

This study focused exclusively on 100% cotton fabric, a cellulosic fibre with natural affinity for tannin-based dyes like myrobalan. Therefore, the findings may not be directly applicable to other natural or synthetic fibres, which may require different mordanting or processing approaches. Additionally, while the padding technique demonstrated promising results in terms of dye uniformity and resource efficiency under controlled laboratory conditions, its scalability to industrial settings may depend on factors such as availability and compatibility of padding machinery in small- to medium-scale dyeing units, and the need for precise control of process parameters during scale-up.

References:

[1] Julkunen-Tiitto, R., & Häggman, H., Focus on Tannins, in: Bechtold, T., Manian, A. P., & Pham, T., (eds), 'Handbook of Natural Colorants', 2nd ed., United Kingdom; Wiley-VCH: 2023: pp. 333–350. DOI:10.1002/9781119811749.ch15

[2] Rajkhowa, S., Sarma, J., Dutta, R., Ahmed, S., & Singh, R. P., "Application of Natural Dyes in Textile Industry (A Sustainable Approach)", in Dye Pollution from Textile Industry, Springer, Singapore, (2024), (221–238), doi: 10.1007/978-981-97-5341-3_11

[3] Patel, B. H., "Natural dyes", in Handbook of Textile and Industrial Dyeing: Principles, Processes and Types of Dyes, 1, Elsevier Inc., (2011), (395–424), doi: 10.1533/9780857093974.2.395

[4] Hassan, M. R. B., Chowdhury, M. N. U., Naima, T. A., Sami, S. A., Imtiaj, M. S., Huda, N., & Uddin, M. G., "A comprehensive review on the diverse pharmacological perspectives of Terminalia chebula Retz", Heliyon, 8/8, (Aug, 2022), doi: https://doi.org/10.1016/j.heliyon.2022.e10220

[5] Agrawal, A., Gupta, C., & Aggarwal, S. A., "Novel Applications of Kasim: Heritage Meets Haute Couture", ShodhKosh: Journal of Visual and Performing Arts, 5/5, (May 2024), doi: 10.29121/shodhkosh.v5.i5.2024.1685

[6] Jahangiri, A., Ghoreishian, S., Akbari, A., Norouzi, M., Ghasemi, M., Ghoreishian, M., & Shafiabadi, E., "Natural Dyeing of Wool by Madder (Rubia tinctorum L.) Root Extract Using Tannin-based Biomordants: Colorimetric, Fastness and Tensile Assay", Fibers and Polymers, 19/10, (Oct, 2018), (2139–2148), doi: 10.1007/s12221-018-8069-3

[7] Sharan, P. & Madan, V., "Therapeutic & Phytochemical Profiling of Terminalia chebula Retz. (Harad): A Review", Journal of Medicinal Plants Studies, 6/2, (Feb, 2018), (25–31)

[8] Kumar, N. & Khurana, P., "Phytochemistry and Medicinal Value of Harad (Terminalia chebula Retz.) the 'King of Medicinal Plants'", Der Pharma Chemica, 10/4, (2018), (186–195), [Online]. Available: www.derpharmachemica.com

[9] Hosseinnezhad, M., Gharanjig, K., Imani, H., & Razani, N., "Green Dyeing of Wool Yarns with Yellow and Black Myrobalan Extract as Bio-mordant with Natural Dyes", Journal of Natural Fibers, 19/10, (2022), (3893–3915), doi: 10.1080/15440478.2020.1848735

[10] Agrawal, A., Aggarwal, S., & Gupta, C., "Fermenting Kasim with Diverse Sugars – A Novel Approach to an Ancient Natural Dye", Tekstil ve Muhendis, 32/137, (2025), (35–43), doi: 10.7216/teksmuh.1557325

[11] Pargai, D., Jahan, S., & Gahlot, M., "Functional Properties of Natural Dyed Textiles", Chemistry and Technology of Natural and Synthetic Dyes and Pigments, (Jan, 2020), doi: 10.5772/INTECHOPEN.88933

[12] Jajpura, L. & Rangi, A., "Functionalization of antibacterial and UV protection properties in cotton fabric dyed with terminalia arjuna bark extract", Journal of the Textile Association, 80/4, (Dec, 2019), (261–267), [Online]. Available: https://www.scopus.com/pages/publications/85078849219

[13] 'Bagh Prints of Madhya Pradesh (Logo)- GI Application No.505', Geographical Indications Journal, 75; Government of India: Nov, 2015: pp. 7-18.

[14] Kumar, A. & Konar, A., "Dyeing of Textiles with Natural Dyes", in Natural Dyes, InTech, (2011), doi: 10.5772/21341

[15] Baaka, N., Mahfoudhi, A., & Mhenni, M. F., "Tannin-rich natural dye extracted from kermes oak (Quercus coccifera L.): Process optimization using response surface methodology (RSM)", Journal of Natural Fibers, 16/8, (Nov, 2019), (1209–1220), doi: 10.1080/15440478.2018.1458685

[16] Boominathan, S., M, S., V, K., & Magesh, G., "Application of response surface methodology (RSM) on comparative analysis of senegalia catechu dye in different mordanting conditions on cotton fabric", Journal of Natural Fibers, 19/15, (2022), (12039–12050), doi: 10.1080/15440478.2022.2050335

[17] Vankar, P. S., Natural Dyes for Textiles Sources, Chemistry and Application, 1st ed., Woodhead Publishing: 2017

[18] Lim, J., Jeong, S., Lim, S., Cho, H., Shim, J., Hong, S., Kwon, S., Lee, H., Moon, I., & Kim, J., "Development of Dye Exhaustion Behavior Prediction Model using Deep Neural Network", Computer Aided Chemical Engineering, 49, (Jan, 2022), (1825–1830), doi: 10.1016/B978-0-323-85159-6.50304-3

[19] Indi, Y. M., Patil, D., & Jujare, T., "Padding technique for natural dyeing", Indian Journal of Fibre & Textile Research, 44, (Mar, 2019), (18-121)

[20] Ratnapandian, S., "Application of Natural Dyes by Padding Technique on Textiles", PhD Thesis, School of Fashion and Textiles, India, (Mar, 2013), Available: https://core.ac.uk/download/pdf/16745807.pdf

[21] Chakraborty, J. N., "Dye–Fibre interaction", Fundamentals and Practices in Colouration of Textiles, (2010), (20–26), doi: 10.1533/9780857092823.20

[22] Umbreen, S., Ali, S., Hussain, T., & Nawaz, R., "Dyeing Properties of Natural Dyes Extracted from Turmeric and their Comparison with Reactive Dyeing", Research Journal of Textile and Apparel, 12/4, (Nov, 2008), (1–11), doi: 10.1108/RJTA-12-04-2008-B001

[23] Wagner, J. R., Mount, E. M., & Giles, H. F., "Design of Experiments", Extrusion, (Jan, 2014), (291–308), doi: 10.1016/B978-1-4377-3481-2.00025-9

[24] Barani, H. & Rahimpour, S., "The dyeing procedures evaluation of wool fibers with Prangos ferulacea and fastness characteristics", Advances in Materials Science and Engineering, 9/6, (Feb, 2014), doi: 10.1155/2014/497278

[25] Patil, H., Surve, K., & Athalye, A., "Green Process for Degumming of Tussar Silk by Sapindus Extract", Journal of the Textile Association, 84/3, (Oct, 2023), (189–194), Available: https://www.scopus.com/pages/publications/85181677163

[26] Song, J. E., Kim, S. M., & Kim, H. R., "Improvement of dye affinity in natural dyeing using Terminalia chebula retzius (T. chebula) applied to leather", International Journal of Clothing Science and Technology, 29/5, (2017), (610–626), doi: 10.1108/IJCST-03-2017-0029/FULL/XML

[27] Clark, M., 'Handbook of Textile and Industrial Dyeing. Volume 1: Principles, Processes and Types of Dyes', Woodhead Publishing: Jan, 2011.

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KARL MAYER

Interview with Mr. Karl J. Mayer

OUR CLEAR FOCUS IS ON OUR CUSTOMERS!

Karl J. Mayer on the strategy, focus and future of KARL MAYER and its exhibition at ITMA ASIA + CITME 2025.

Mr. Karl J. Mayer

KARL MAYER is working flat out to prepare for ITMA ASIA + CITME 2025 in Singapore. The leading textile machinery manufacturer launched a transformation process in January this year in response to the upheavals of our time. The first results of the reorganization will be on display at the KARL MAYER stand A 301 in Hall 5 of the Singapore EXPO.

Ulrike Schlenker from Corporate Communications at KARL MAYER spoke to Karl J. Mayer, who is supporting the transformation process as a representative of the Advisory Board and the Mayer family, about the new direction of the company and the highlights of its exhibition in Singapore.

US: Mr. Mayer, the textile machinery industry is facing enormous challenges. How is KARL MAYER positioning itself in this environment?

KJM: By putting the customer at the center of all our decisions. We can only be successful in the future if we know, understand and serve the needs of our customers.
This requires very intensive customer care and a very close customer relationship. The customer is then also the driver of all our innovation projects, in which we have to involve our customers at a very early stage in the innovation process.

We have to listen very carefully, take a close look and understand how we can help our customers.

If we develop and offer convincing customer solutions, then we are in business!
Our experience is that all companies that are active in warp knitting basically want KARL MAYER machines. It is up to us to offer new solutions cost-effectively so that our customers can earn money. Then we can be successful as well!

US: What is your personal message to customers? How do they specifically benefit from the reorganization?

KJM: KARL MAYER is back!

We have understood that corporate posturing and arrogance are detrimental to business. The free market has punished us - and rightly so. We are realistic, pragmatic and customer-oriented again. Over the next few months, we will come up with solutions that will convince our customers. I am very confident that we are on the right track. Our customers can look forward to our new developments - they will help our customers in their business - and that is the most important thing.

US: What role does innovation play in the company's strategy?

KJM: Innovation is the key to success! Our customers are waiting for KARL MAYER to come up with something new. We are still the technology leader, market leader and industry leader. We have to live up to this responsibility. And that is only possible through genuine innovation.

US: How important is the global presence in the new strategy?

KJM: KARL MAYER has always been a global player. We produce in our main markets!

The heart of KARL MAYER is Obertshausen for warp knitting and Mezzolombardo for warp preparation.
All key strategic decisions are made here, which are then implemented in a highly efficient and customer-oriented manner at our plant in Changzhou for our main market, China.

US: ITMA ASIA + CITME will be the first major trade fair appearance for KARL MAYER since the start of the transformation. What can visitors expect?

KJM: Genuine innovations! Our aim is to attack and substitute ourselves!

In the area of 2-bar warp knitting machines for elastic fabrics, in which we are the absolute market leader, we are presenting the next generation of machines that will help our customers to improve their margins.

In the 4-bar warp knitting machine segment, we will be presenting an attractive solution for the fashion & apparel segment in line with the regional requirements and the general textile trend.

We will also be presenting textile innovations that demonstrate the market potential of our machines' textile products.

US: What would you like to convey personally at ITMA ASIA+CITME 2025?
KJM: KARL MAYER is alive!

I also want to show that I am passionate about our customers, our business and our company.

I have lived in Asia for 20 years, most of that time in Hong Kong, have traveled extensively in Asia and have met and served many KARL MAYER customers. I expect to meet many old acquaintances, but also to make many new contacts. A trade fair is the perfect place for this.

US: What does customer proximity mean to you personally?

KJM: Customer intimacy is everything and without customer intimacy there is no future for KARL MAYER.

US: How does the founding family continue to shape the culture of KARL MAYER?

KJM: Through trust! "I trust my employees and my employees trust me" - that was a central motto of my grandfather, the company founder. Our customers trust in our care for their business and that we will help them to run their business successfully. KARL MAYER was built on trust and the family continues to live this value in the company and for our customers.

Everyone who deals with us can rely on us!

US: What is the biggest challenge in the reorganization?

KJM: Nothing! It's just work. Deciding and acting. Confidence and trust. Enable and encourage. I don't see any challenges, only opportunities. And we will seize them. I'm looking forward to the realignment of our company structure and our business focus. It's going to be really good!
US: From which countries do you expect visitors? Is Singapore a suitable location for a textile trade fair?
KJM: Absolutely! It's a perfect location! Singapore has a large, international airport: "Easy in - easy out!"

There are no complicated visa requirements and it's the perfect place to combine business with pleasure. You can simply stay an extra 1-2 days and then enjoy the city. Shopping, wining & dining, a bit of sightseeing or just relaxing. It is a melting pot of different cultures, a city that never sleeps and where business is done day and night.

Singapore connects the East with the West in the Global South, especially for the Muslim world.

Our customers from South-East Asia can all come here easily and quickly, but also customers from important textile markets such as India, Pakistan and Bangladesh will come, as well as customers from North Africa and the Middle East, especially Turkey.
These are trade routes that we are hardly familiar with in the northern hemisphere and that are often greatly underestimated.

But Singapore is also easy to reach for our many customers from southern China, and we are expecting a lot of interest and visiors from this region as well.

US: Thank you very much for the interesting interview.

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KARL MAYER

Christian Botschek joins the Management Board of KARL MAYER

Christian Botschek has been Managing Director of KARL MAYER STOLL Textilmaschinenfabrik GmbH alongside Axel Wintermeyer since 1st July.

The mechanical engineer has been part of the KARL MAYER team since 2005 and has since made significant contributions to the company's success in various positions. His varied activities have focused on the areas of logistics and assembly. Christian Botschek has continuously taken on more responsibility improving the worldwide profitability situation through optimisation and increased customer benefits. He managed the overall assembly and logistics centre at the headquarters in Obertshausen for three years and then, as Chief of Technology, played a key role in the development and expansion of the company's Chinese site in Changzhou for several years.

In 2023, he became Deputy Managing Director of KARL MAYER China. At the same time, he was also Managing Director of KARL MAYER Technische Textilien GmbH.

In his new position as part of the Management Board of KARL MAYER STOLL Textilmaschinenfabrik, Christian Botschek is also responsible for assembly, production, and prototype construction, among other things. His primary goal is to achieve a sustainable increase in profitability.

"I want to help make processes more efficient, reduce waste, and sustainably strengthen our performance in production. Our ambition is to work economically successfully - with consistently high customer satisfaction," says Christian Botschek.

Customers benefit from high quality and absolute deadline reliability.

Rieter Card C 80 - Optimized Cost-Performance Ratio

The C 80 produces up to 120 kg/h, far exceeding the output of previous models

Gu Jinguo, General Manager of Chuzhou Jinshangjia, appreciates the superior sliver quality

After installing three Rieter cards C 80, Chuzhou Jinshangjia Yarn Industry Co., Ltd. saw its cost-performance ratio improve. The Chinese spinning mill, which is based in Anhui Province, values the C 80 for its high stability, remarkable production efficiency and long service life. The superior sliver quality with up to 82% fewer neps ensures excellent end spinning performance and delivers a yarn quality that their downstream customers appreciate greatly.

Jinshangjia pursues the twin goals of increasing production while keeping sliver quality high. With around 100 000 spindles the company produces 55 tons of Ne 16 to 26 carded compact yarn per day. Previously, the company used the Rieter cards C 72 with a production rate of 80 kg/h. To achieve higher capacity without using more space, Jinshangjia tested different solutions and finally chose the C 80. Today they produce up to 120 kg/h sliver per card. Neps were reduced by up to 82% during the carding process. The C 80 helps handle higher order volumes and supports the company's goal of improving both yarn quality and cost efficiency.

Features for better performance

The card C 80 has the largest active carding area, which improves fiber opening and cleaning. It has 40 active flats and precise carding gap settings, leading to high sliver quality and finally to more efficient spinning. Energy efficiency is another advantage. The improved drive system and suction technology lower energy consumption while keeping output high. The modular design reduces maintenance and machine downtime.

Long-term partnership with Rieter pays off

Jinshangjia has used Rieter's technology since 2013. Gu Jingguo, General Manager of Chuzhou Jinshangjia Yarn Industry Co., Ltd., emphasizes: “Our cooperation with Rieter dates back to 2013. For more than a decade, we have relied on Rieter's equipment, advanced technology and professional service. The card C 80 is characterized by high stability, remarkable production efficiency and a long service life. The sliver is of superior quality, with fewer neps, ensuring excellent yarn quality. This is highly appreciated by our customers.”

By investing in the C 80, Jinshangjia strengthens its position as an innovative company. With the advanced carding technology, it continues to improve production, ensuring growth and high-quality yarn for the global textile market.

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Bombay Dyeing Strengthens Crackdown on Counterfeits to Safeguard Customers and Brand Heritage

Bombay Dyeing, one of India's oldest and most respected home textile brands, is strengthening its fight against counterfeit products with raids across key cities Kolkata, Hyderabad, Kerala, and most recently at one of the prominent malls in Mumbai. With a legacy of more than 145 years the brand has always stood for trust, innovation, and uncompromising quality and it is determined to keep it that way.

As part of this crackdown, Bombay Dyeing has also uncovered the misuse of its identity. Counterfeiters are circulating products with a purple logo, whereas the original Bombay Dyeing logo is blue. The brand is urging customers to carefully check the logo when purchasing to ensure they are buying only genuine products.

These efforts are part of the company's broader commitment to safeguard its loyal customers and ensure that when someone buys "Bombay Dyeing," they are getting the authentic craftsmanship the brand is known for. Counterfeit products don't just mislead customers financially by passing off poor-quality goods as originals but also damage the trust, Bombay Dyeing has built over generations. By cracking down on such unethical practices, the company intends to reinforce its commitment that genuine quality cannot be replicated.

Battling the game of Counterfeit products, the Kiroda Jena - CFO of Bombay Dyeing shares "Our dedicated team is working tirelessly to find solutions and fight against counterfeit products. This is about more than just protecting our brand - it's about protecting the faith that millions of families have placed in us. Every household that chooses Bombay Dyeing deserves to experience the true quality and authenticity that define our brand."

Looking ahead, the brand is committed to not only pursuing counterfeiters but also working closely with local authorities, retail partners, and industry stakeholders to create a cleaner, fairer marketplace. With these steps, Bombay Dyeing continues to reaffirm the promise it made over a century ago to deliver products that combine trust, timeless design, and unmatched quality.

Uster Technologies marks 150 years of empowering quality excellence

From precision instruments to end-to-end solutions

Uster Technologies marks 150 years of excellence a milestone that reflects continuous adaptation to customer needs and industry change. Over the decades, Uster has evolved from manufacturing quality testing instruments into a trusted partner shaping the future of textile production. Moving forward, Uster can be compared to a 'family doctor' with strategic advice and end-to-end solutions optimizing mill performance. With its 'Think Quality Next Level' vision, Uster empowers customers beyond just data and devices towards intelligent decision-making. This transition sets the course for a more sustainable, efficient, and impactful textile industry.

Reaching 150 years is an achievement for any company, especially in the modern era of rapidly changing business conditions. For Uster Technologies, it has been a process of continuous development, shifting its core competence from origins manufacturing telegraphy equipment to its 21st Century role as global leader in textile quality systems and solutions.

Today, that progression sees Uster taking on a new mission customer-focused, with a business model offering end-to-end solutions for quality management and business profitability.

The family doctor

A customer once said that Uster Technologies could be compared to a family doctor. It's a powerful metaphor, and it suggests that Uster should go further than being a provider of instruments such as yarn clearers and evenness testers. Excellent as these are for measuring and controlling quality, their role typically ends at that point comparable with the medic's simple thermometer.

Taking the family doctor analogy further, Uster wants to understand in detail the context of each spinning mill its operations, goals, and market environment to advance from simply delivering data towards actively helping mills improve. In this way, Uster is evolving to make a much bigger impact, as a trusted partner – like the family doctor, who monitors health but also provides insights, guidance, and long-term care.

The trusted strategic partner

This concept opens the door to a new level of value creation. Rather than offering isolated instruments, Uster can empower mills to achieve more, by providing integrated, end-to-end solutions. This requires understanding the mill's entire production chain, identifying opportunities for improvement, and aligning quality management with the mill's broader business goals.

'Think Quality Next Level' is Uster's shift from product supplier to strategic partner. It's about helping customers move from reactive quality control to proactive quality assurance and optimization. This approach allows mills to unlock higher efficiency, better performance, and increased profitability.

The value chain manager

The ultimate goal is satisfaction for the customer's customer, in a way that is profitable for the spinning mill. Uster has the preconditions available, with what's called the 'solution stack'. That means Uster has the sensing points connecting hardware and managing parameters across the spinning mill and along the value chain. These cloud connected instruments feed data to the Uster 360Q platform. This is where the problem-solving happens, the ultimate enabler for decision-making, action and optimization with a comprehensive mill overview. Applying AI here, the result is greater automation and performance, uniquely combined with the support of top Uster textile advisors to integrate all the key data for the outcome the spinner wants. Superior sensors, intelligent analysis and unrivaled human expertise create the Uster magic that is greatly valued but rarely matched.

Uster is at the start of this transformation, but the direction remains clear and unchanged as long as it continues to meet the needs of our customers. The Uster FiberQ raw material management solution has already been proven in practice and another new solution will be introduced at ITMA Asia + CITME 2025. The full impact of 'Think Quality Next Level' might be found in a mill in the year 2035, when a mill can correlate data from the bale laydown with fabric quality parameters. Collating all this information and even connecting the data with mills across the world, can be massively influential, giving spinners early optimization potential with a clear view of the ultimate quality impact. The sheer power of this 'Next Level' is amazing.

The pioneer

A sustainable textile industry should be part of a better planet for all. Stakeholders today expect Uster to take on the kind of pioneering role it had when launching the first evenness tester in 1948. While textile recycling is still in its infancy, there is a clear call for Uster to lead the way in developing innovative quality management approaches quality management approaches that support and accelerate recycling efforts in collaboration with stakeholders. The adoption and scale-up in use of recycled fibers will see this segment evolve from a 1% niche of production to something notably bigger. In that sense, sustainability is very important, so Uster is currently developing many technologies to fit with ongoing ecological trends.

As with all Uster policies, this goal is aligned with the company's purpose statement: "We empower people to create a better future for the textile industry through quality and innovative end-to-end solutions. "A purpose is of universal importance, driving and directing the company and focusing on the basic principles especially in tough times. It's the way to build resilience for the company and for its people, and is the foundation for the optimism that Uster will continue to achieve significant milestones on into the next 150 years.

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Rieter to Install World's First Complete Air-Jet Spinning System with J 70 Technology

Guangxi Baisheng Textile Co., Ltd. signed an agreement with Rieter to implement the world's first complete spinning process using Rieter's latest air-jet spinning technology J 70. This project will elevate automation levels and reduce conversion costs at Baisheng's operations, setting a new benchmark in air-jet spinning in terms of quality and productivity.

Guangxi Baisheng Textile Co., Ltd. has decided to expand its air-jet spinning capacity with Rieter's J 70 thanks to its outstanding productivity. This move will enable the vertically integrated textile company based in Guangxi, China, to further ensure a steady yarn supply for its knitting operations. Rieter's air-jet spinning machine J 70 offers exceptional production efficiency and features 200 individually automated spinning units that independently manage quality cuts and natural ends down quickly and efficiently.

The J 70 also boasts delivery speeds of up to 600 meters per minute and supports up to four lots simultaneously. In addition, Rieter's latest generation yarn clearer identifies weak yarn during production, ensuring top quality.

The excellent performance of the existing Rieter cards, draw frames and winding machines installed at Baisheng Textile combined with the superior after-sales service have created a strong foundation for the successful collaboration with Guangxi Baisheng Textile Co., Ltd.

Yiyu Zhan, Chairman, Guangxi Baisheng Textile Co., Ltd., says: "Together with Rieter, we will set an all-new benchmark in the industry, elevating the quality and productivity of air-jet spinning to unprecedented levels."

Michael Hubensteiner, Country Managing Director Rieter China, says: "We are proud to build the world's first complete air-jet spinning system with our latest J 70 spinning technology in partnership with Baisheng Textile. This cutting-edge spinning system will enable Baisheng Textile to achieve a new level of competitiveness and expand their industry leadership."

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