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Indian Textiles:
Growth Amidst Global Shifts and Opportunities

It is an exciting year for the Textile Association (India) as it successfully completed 86 years and Journal of the Textile Association (JTA) has successfully completed 85 years. TAI is a pioneering association brought the textile fraternity in India together for and carried out many activities which benefitted the textile professionals. TAI disseminates the knowledge update through their regularly held conferences, exhibitions, and publications.

The Indian textile industry is expected to see higher growth in coming years in sectors, like apparel, technical textiles, knitting, etc. According to a new report by the Confederation of Indian Textile Industry, India's apparel exports are registering double-digit growth in the financial year ending March 31, 2025, while overall textile exports showed modest gains.

The technical textile segment is on the high growth trajectory of 10-12 % CAGR, some segments have shown even higher growth. Extension of minimum import price (MIP) on four popular varieties of knitted synthetic fabrics covered under Chapter-60 till 31st March 2026, is a very encouraging move by the GOI which will support knitting sector to grow.

The current turmoil caused due to trade tariff imposed by the America will significantly affect the textile businesses, particularly exports to America. It is expected that India will negotiate tariffs sooner rather than later and improve its business environment which will help growth of our industry and attract foreign investment as well.

There is a potential opportunity for India, amid US-China trade tensions, that would benefit from the companies seeking alternatives to China. America has followed the China-plus-one policy for a decade, and India has failed to take advantage of it, however, this the right time India will be on a mission mode to show its strength.

Dr. ANUP RAKSHIT
Guest Editor
Member of JTA EB
Executive Director - ITTA

T. L. PATEL, President

Empowering the Textile Industry

Dear Friends,

09th April, 2025 – The Textile Association (India) – Centre, established on 09th April, 1939, celebrating its 86 Years Birthday Anniversary and Journal of the Textile Association (JTA), celebrating its 85th Birth Anniversary.

The Textile Association (India) and the Journal of the Textile Association are celebrating a significant milestone of promoting and contributing the textile industry more than 8 decades.

Industry Advocacy: The association advocate for the textile industry's interests, shaping policies and promoting growth.

Networking Opportunities: TAI and JTA provide platforms for industry professionals to connect, share knowledge, and explore business opportunities.

Industry Development: The associations contribute to the development of the textile industry through education, training, and research initiatives.

Empowering the Textile Industry

As we navigate the complexities of the global textile industry, it is essential that we, as stakeholders, come together to address the challenges and opportunities that lie ahead. At The Textile Association (India), we are committed to empowering our members and the broader industry to thrive in a rapidly changing world.

Sustainability: The Need of the Hour

The textile industry is one of the largest polluters globally, with significant environmental and social impacts. As we move forward, it is crucial that we adopt sustainable practices that minimize our ecological footprint. Our association is dedicated to promoting eco-friendly technologies, reducing waste, and encouraging responsible sourcing practices.

Innovation and Technology

To remain competitive, our industry must embrace innovation and technology. We are committed to providing our members with access to the latest research, trends, and best practices. From digital printing to nanotechnology, we will explore the latest advancements and their applications in the textile industry.

Skill Development and Education

As the industry evolves, it is essential that our workforce possesses the necessary skills to adapt. We are dedicated to providing training and education programs that equip our members with the knowledge and expertise required to succeed.

Collaboration and Partnerships

No single organization can address the complexities of our industry alone. We believe in the power of collaboration and partnerships. Our association will work closely with government agencies, research institutions, and industry stakeholders to promote the interests of our members and the broader industry.

The Indian textile industry is facing significant challenges due to tariffs imposed by the US, with far-reaching implications for exports, competitiveness, and employment.

Impact on Exports

Reduced competitiveness: Higher tariffs make Indian textiles and apparel more expensive, reducing demand and eroding competitiveness in the US market.

Decreased exports: Indian textile exports to the US, valued at $10 billion, are likely to decline due to increased costs and reduced demand.

Shift to alternative markets: Indian exporters are exploring opportunities in Europe, Asia, and other regions to reduce dependence on the US market.

Challenges for Indian Manufacturers

Increased costs: Tariffs lead to higher production costs, making it difficult for Indian manufacturers to maintain profit margins.

Supply chain disruptions: Tariffs can disrupt supply chains, affecting the availability of raw materials and components.

Pressure to reduce prices: US buyers are demanding price reductions, which can further erode profit margins for Indian manufacturers.

Government Response

Diplomatic engagement: The Indian government is negotiating with the US to mitigate the impact of tariffs and find solutions.

Export promotion schemes: The government is providing support through export promotion schemes and infrastructure development initiatives.

- *Simplification of customs duty structure*: The government is considering simplifying the customs duty structure to reduce the average import tariff from 18.1% to below 10%.

Opportunities for Growth

Increased export volumes: The US tariffs on textiles have generated opportunities for Indian exporters to increase volumes and revenues.

Diversification of exports: Indian exporters can explore new markets and products to reduce dependence on the US market.

Innovation and sustainability: The industry can focus on innovation, sustainability, and product differentiation to enhance competitiveness.

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

Impact of Core-Sheath Composite Yarn Based Fabrics on Cut Resistance Properties

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Abstract:

This study investigates the influence of core-sheath composite yarns on the cut resistance properties of fabrics. Four types of yarns are developed, incorporating stainless steel wire (SW) fibres of varying diameters (0.025, 0.050, and 0.075 mm) and glass fibres (0.050 mm) in the core, with polyester filament and high-performance polyethylene (HPPE) in the sheath. Fabric samples are prepared using both weaving and knitting technologies. The cut resistance of these woven and knitted fabric samples is evaluated using standardized testing methods. The results demonstrate that the inclusion of stainless steel and glass fibres in the core significantly enhances the cut resistance of both fabric types. Among the different yarn types, the SW 75 yarn exhibits the highest cut resistance, followed by glass fibre 50, SW 50, and SW 25 yarns. A similar pattern is observed in the developed fabric samples. Additionally, woven fabrics show superior cut resistance compared to knitted fabrics. This study highlights the potential of core-sheath composite yarns in developing high-performance cut-resistant textiles for various applications.

Keywords: *Core sheath, composite yarns, Glass fibre, protective clothing, stainless steel fibre*

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1. Introduction

The development of high-performance textiles has become a central focus of research within the textile industry, driven by the increasing demand for advanced materials that offer superior protection, comfort, and functionality [1]. Among these innovations, cut-resistant textiles have garnered significant attention due to their critical applications in personal protective equipment (PPE) for both civil and military use [2]. The necessity for such textiles is underscored by the growing emphasis on safety and the stringent regulations governing occupational health and safety standards. Cut-resistant textiles are essential across various industries, including construction, manufacturing, law enforcement, and military operations, where users are exposed to sharp objects and potential cut hazards [3, 4].

Traditional cut-resistant materials, such as metal mesh and heavy-duty fabrics, often suffer from drawbacks such as rigidity, heaviness, and lack of flexibility. These limitations can impede the wearer's mobility and comfort, leading to reduced compliance and effectiveness of the protective gear. Core-sheath composite yarns have emerged as a promising solution, offering a unique combination of strength, flexibility, and cut resistance [5]. These yarns consist of a core material, typically made of high-strength fibres such as stainless steel or glass, surrounded by a sheath of softer, more flexible fibres like polyester. The core provides the necessary cut resistance, while the sheath enhances the overall flexibility and comfort of the fabric [6]. These materials have practical applications in producing durable and protective workwear, gear, and industrial textiles.

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Previous studies have demonstrated the potential of core-sheath composite yarns in enhancing the cut resistance of textiles. Researches highlighted the superior cut resistance of fabrics made from stainless steel core yarns compared to conventional materials [7-8]. Similarly, some researchers investigated the use of glass fibres in the core and reported significant improvements in cut resistance and durability [9]. These findings underscore the importance of material selection and yarn structure in achieving the desired protective properties.

However, there remains a gap in the literature regarding the comprehensive evaluation of different core materials and their impact on fabric performance. Specifically, the comparative analysis of stainless-steel fibres of varying diameters and glass fibres in the core, combined with polyester sheaths, has not been extensively studied. Several researchers investigated the forces required to cut various fabrics using a reciprocating knife and observed that plain weave fabric has the highest cut resistance [10]. Some studies highlight the variation in cut resistance with varying cutting directions and found that adjusting the core-sheath ratio in hybrid yarns made from para-aramid staple fibres enhances resistance to mechanical stress [11, 12]. Furthermore, the influence of fabric construction techniques, such as weaving and knitting, on the cut resistance properties of these composite yarns warrants further investigation.

Glass fibre cores are known for their high tensile strength and stiffness, which significantly enhance the cut resistance of composite yarns. These properties make them ideal for applications requiring exceptional protection against sharp objects. However, despite their potential for cut resistance, glass fibres are not typically used in gloves due to inherent limitations. Glass fibres are brittle and prone to breakage, especially during wear and washing, which reduces their protective effectiveness over time [13, 14 & 15]. To address this issue, glass fibres are bundled with polyester and high-density polyethylene materials, improving their flexibility and comfort properties. Similarly, Stainless steel fibres provide exceptional cut resistance due to their high tensile strength and durability. This makes them ideal for use in personal protective equipment (PPE), such as cut-resistant gloves, sleeves, and aprons, which are essential for workers in industries like construction, manufacturing, and law enforcement. Stainless steel fibres exhibit excellent thermal resistance, chemical resistance and can be integrated with electronic components for applications in wearable technology, such as health monitoring systems, and anti-static or electromagnetic interference (EMI) shielding garments. Stainless steel fibres can be combined with other high-performance fibres contribute to the overall durability and longevity of the fabric [16, 17].

The study has been conducted to systematically evaluate the impact of core-sheath composite yarns on the cut resistance properties of fabrics. The fabric samples produced from core-sheath composite yarns, comprising a central core encased within a sheath material, offer a versatile platform for enhancing the functional properties of textiles. This study investigates the influence of stainless-steel cores with varying diameters (0.025, 0.050, and 0.075 mm) on the overall performance of composite yarns. Stainless steel, known for its high tensile strength and durability, is expected to significantly impact the mechanical properties of the resulting yarns. Additionally, the study explores the potential of glass fibre cores in enhancing the cut resistance of composite yarns. Glass fibre, renowned for its exceptional tensile strength and stiffness, is anticipated to provide superior protection against sharp objects when incorporated as the core component.

2. Materials and Methods

This study involves a multi-step process with the development of core-sheath composite yarns. Stainless steel wire (SW) fibres of three different diameters (0.025, 0.050, and 0.07 mm) and glass fibres (GF-50) (0.050 mm) are used as the core materials, while polyester and HPPE filaments form the sheath. The composite yarns are produced using specialized hollow spindle spinning techniques at High Performance Textiles Pvt. Ltd. Panipat India [18]. Table 1 shows the basic characteristics of the developed yarn samplesFollowing the development of core-sheath composite yarns, fabric samples are prepared using both weaving and knitting technologies. The analysis involves four distinct fabric codes: FWS-25, FWS-50, FWS-75, and FGF. Each code is represented by both woven and knitted variants. In this context, FWS refers to fabrics with stainless steel as the core material, while FGF denotes fabrics with glass fibre as the core material. Figure 1 presents the prepared fabric samples..

Table 1: Yarn characteristics of core-sheath composite yarn

Yarn Code	Core material	Sheath material of yarn	Yarn Count (Denier)
SW-25	0.025 mm Stainless steel wire	Cover: 78 D Polyester	400
		Cover: 200 D HPPE	
SW-50	0.050 mm Stainless steel wire	Cover: 150 D Polyester	740
		Cover: 400 D HPPE	
SW-75	0.075 mm Stainless steel wire	Cover: 150 D Polyester	940
		Cover: 400 D HPPE	
GF-50	0.050 mm E-Glass fibre	Cover: 150 D Polyester	840
		Cover: 400 D HPPE	

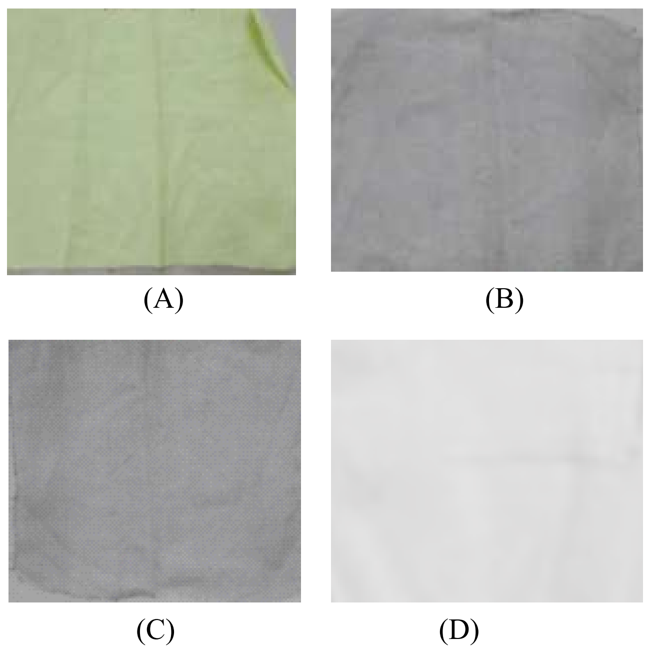


Figure 1 - (A) FWS-25 Sample, (B) FWS- 5 Sample, (C) FWS 7- sample, (D) FGF sample

The woven fabrics are produced on a shuttle loom, ensuring precise and structured interlacing of yarns. Meanwhile, the knitted fabrics are manufactured on a circular knitting machine with a gauge of 13, which provides a different structural configuration. This dual approach enables a thorough comparison of the two fabric construction methods, allowing for an in-depth analysis of their respective impacts on cut resistance. Table 2 highlights the detailed characteristics of the developed fabric samples.

Table 2 - Fabric characteristics

Fabric Characteristics	Fabric Type							
	FWS-25		FWS-50		FWS-75		FGF	
	Woven	Knitted	Woven	Knitted	Woven	Knitted	Woven	Knitted
Construction type	Plain	Weft knit	Plain	Weft knit	Plain	Weft knit	Plain	Weft knit
Fabric GSM (g/m^2)	192.4	183.2	278.8	265.4	331.2	325.3	308.4	290.3
EPI/PPI WPI/CPI	68/52	26/22	42/38	22/18	42/38	22/18	42/38	22/18
Fabric Cover Factor	8.3	3.5	10.0	5.3	12.4	6.6	11.2	6.0
Fabric Thickness (mm)	0.61	0.65	0.71	0.74	0.81	0.83	0.88	0.89

Tensile strength of the protective fabric is determined in both warp and weft directions according to ASTM D 5035 using an Instron 3365 testing machine operating under constant rate of extension (CRE) principles. Test specimens measuring 8 inches x 2 inches are subjected to a traverse speed of 20 mm/min. An average of 10 observations is recorded for each sample. Toung Tearing strength is evaluated in both the directions (warp and weft) following ASTM D 1424. Test specimens measuring 8 inches x 3 inches are prepared, with five specimens tested in each direction. The BS EN ISO 13997 standard is applied for determining the resistance of protective clothing to cutting by sharp objects. Table 3 show the test standards for cut resistance. The cut resistance is measured in wales wise direction.

Table 3 - Level of performance of material tested with EN ISO 13997

Clause/ Test Name	Level A	Level B	Level C	Level D	Level E	Level F
TDM: cut resistance (N)	2	5	10	15	22	30

Air permeability is measured using a TESTEX TF 164-A computerized air permeability tester in accordance with ASTM D 737. The results are expressed in SI units as $cm^3/s/cm^2$. Air permeability represents the volume of air (in cm^3) passing through 1 cm^2 of fabric area per second under a pressure differential of 1 cm water head. A pressure drop of 127 Pa is selected, and the fabric is tested with a 5 cm^2 adapter ring. Abrasion resistance is evaluated using a Martindale pilling and abrasion tester according to BS EN 388:2016 +A1 2018. The specimen size is specified as having a diameter of 38 ± 5 mm, while the abradant size is defined with a diameter of 14.5 ± 2 cm. The test conditions for both the woven and knitted fabric samples are maintained at 9 KPa. During testing, the specimen undergoes a cyclical rubbing motion up to 8000 cycles, which results in stress development along the fibre due to surface friction. Pilling resistance is assessed using a Box type pilling tester as per IS 10971. Pilling is characterized by the formation of small entangled fibre balls on the fabric surface. The test evaluates the fabric's resistance to pilling formation under controlled rubbing conditions. Fabric samples are rated with a rating scale of 1 (very severe pilling) to 5 (no pilling). Fabric stiffness is determined in both warp and weft directions using the cantilever bending test method as outlined in ASTM D 1388. Test specimens measure 25 cm x 2.5 cm.

3. Result and Discussion

3.1 Effect on mechanical properties

The tensile strength of the fabric samples developed using these composite yarns is crucial in determining their overall performance and effectiveness in protective applications. Table 4 presents the tensile strength properties of the different fabric samples. The stainless-steel core yarns (SW-25, SW-50, SW-75) exhibit significantly higher tensile and tear strengths compared to the glass fibre core yarn (GF-50). This is expected due to the inherent high strength and stiffness of stainless steel. Among the stainless-steel cores, SW-75 (0.075 mm diameter) consistently demonstrates the highest tensile and tear strengths, suggesting that this particular core diameter provides optimal performance. The SW-75 (0.075 mm diameter) core shows slightly higher variability in strength values compared to SW-25 and SW-50, particularly in weft tear strength. This could indicate that larger core diameters might introduce some variability in the yarn's mechanical response. Moreover, the glass fibre sample exhibits significantly moderate tensile and tear strengths compared to all the stainless-steel core yarns. This is likely due to the inherent brittleness of glass fibre, which can lead to lower load-bearing capacity and earlier failure. Additionally, the glass fibre samples show the highest variability in strength values, especially in warp tensile strength, further supporting the notion of glass fibre's brittleness and its tendency to exhibit inconsistent performance. The results indicate that stainless steel cores offer higher tensile strength compared to glass fibre cores. However, glass fibre cores provide superior flexibility, enhancing the fabric's comfort properties. The combination of polyester and high-performance polyethylene (HPPE) as the sheath material further improves the tensile strength and tear strength of the composite yarns.

Table 4 - Effect on tensile strength, tear strength and stiffness properties

Fabric code	Fabric type	Tensile Strength		Tear Strength		Stiffness	
		Warp load (kgf)	Weft load (kgf)	Warp load (kgf)	Weft load (kgf)	Warp (g/cm²)	Weft (g/cm²)
FWS - 25	Woven	308.5	249.2	63.4	71.1	0.49	0.83
	Knitted	275.4	216.3	40.3	48.2	0.34	0.80
FWS - 50	Woven	429.4	327.3	88.9	105.1	0.78	1.16
	Knitted	320.2	217.5	72.3	85.7	0.73	1.02
FWS - 75	Woven	478.9	349.3	136.9	148.9	1.22	2.03
	Knitted	349.6	229.4	93.7	108.3	1.21	1.81
FGF	Woven	377.9	294.8	118.5	99.9	0.28	0.44
	Knitted	348.2	262.3	65.8	85.3	0.27	0.41

The knitted fabric samples, on the other hand, show lower tensile strength in both wales-wise and coarse-wise directions compared to woven fabrics. This is due to the looped structure of knitted fabrics, which introduces flexibility but reduces tensile strength [19]. In case of tear strength woven fabrics with stainless steel cores (FWS) demonstrate the highest tear strength, particularly in FWS 75, making them ideal for applications requiring high resistance to tearing. Knitted fabrics, although less robust, exhibit moderate tear strength and are more suited for applications where flexibility is prioritized. Fiberglass (FGF) fabrics provide a balance of tear resistance and flexibility, offering moderate performance across both directions.

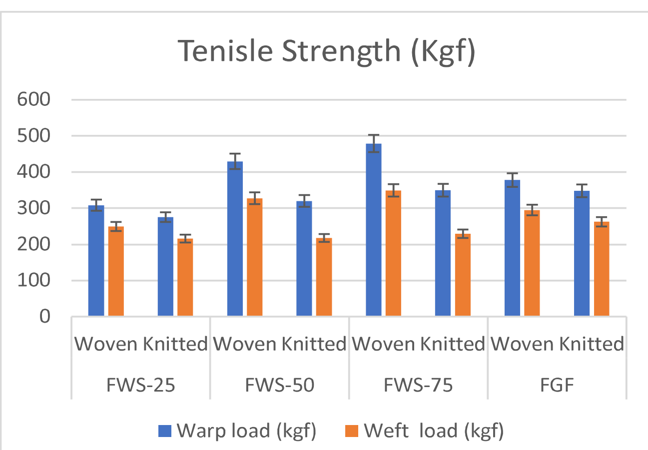
From Table 4, the stiffness values reveal that woven fabrics generally exhibit higher stiffness compared to knitted fabrics across all fabric codes. This observation is consistent with the expected behavior due to the tighter interlacing of yarns in woven fabrics, which enhances their structural rigidity. Conversely, knitted fabrics, characterized by their looped structure, offer greater flexibility but reduced stiffness. The FGF samples demonstrate better flexibility compared to the FWS samples. Specifically, the stiffness values for woven FGF samples are 0.28 g/cm² in the warp direction and 0.44 g/cm² in the weft direction. Similarly, knitted FGF samples exhibit stiffness values of 0.27 g/cm² in the Course direction and 0.41 g/cm² in the Wales direction. Meanwhile, the FWS-75 fabrics, with their stainless-steel cores, display the highest stiffness. This characteristic makes them suitable for scenarios demanding high durability and resistance to mechanical stress.

3.2 Effect on cut resistance and air permeability

This study observes the relationship between air permeability and cut resistance in a variety of woven and knitted fabrics. From table 5, woven fabrics exhibit lower air permeability compared to their knitted counterparts.

Table 5 - Effect on the air permeability and cut resistance property

Fabric Code	Fabric Type	Air permeability	Cut resistance
FWS-25	Woven	69.7	Level D
	Knitted	110.2	Level B
FWS-50	Woven	66.3	Level F
	Knitted	108.3	Level C
FWS-75	Woven	63.2	Level F
	Knitted	123.4	Level C
FGF	Woven	102.2	Level E
	Knitted	58.6	Level B



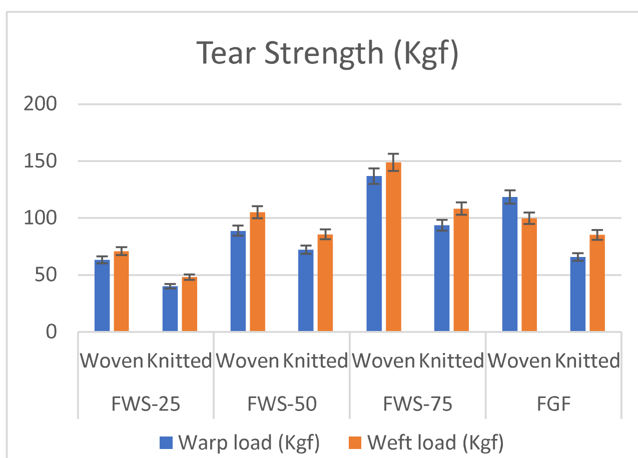


Figure 2 - Effect on Tensile and Tear strength

This is expected due to the tighter weave structure of woven fabrics, which restricts airflow more significantly than the more open structure of knitted fabrics. Among the woven fabrics, the FWS-75 woven fabric stands out with significantly higher air permeability, likely indicating a more open weave structure or the use of coarser yarns. Conversely, the FGF woven fabric demonstrates the lowest air permeability, suggesting a dense and tightly woven construction. As illustrated in Figure 3, woven fabrics consistently show higher cut resistance than knitted fabrics across all fabric codes. The tightly interlaced structure of woven fabrics enhances their mechanical integrity, making them more effective at resisting cutting forces [20, 21]. Specifically, FWS-50 and FWS-75 woven fabric samples achieve the highest cut resistance, measuring 28.8 N and 30.3 N respectively, thus reaching Level F cut resistance (Table 3).

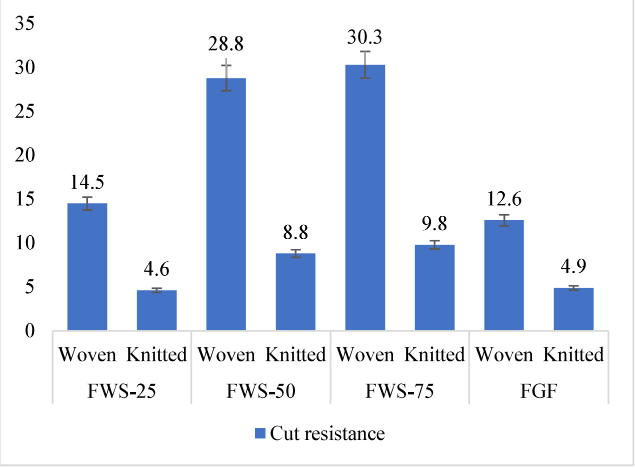


Figure 3 - Effect on cut resistance

Knitted fabrics exhibit lower cut resistance due to their looped structure, which introduces flexibility but reduces their ability to withstand sharp forces. The cut resistance of knitted fabrics ranges between 4.6 N and 9.8 N across all test categories. Woven fabrics with fiberglass (FGF) cores demonstrate moderate cut resistance at 12.6 N. While this is lower than the cut resistance of stainless steel-based woven fabrics (FWS-50 and FWS-75), it is higher than that of knitted FWS fabrics. This moderate cut resistance reflects the structural contribution of the fiberglass core, which, while less robust than stainless steel, still provides effective resistance. The tightly bound configuration of woven fabrics helps distribute cutting forces more efficiently.

3.3 Effect on abrasion and pilling properties

Table 6 presents the data on the abrasion resistance and pilling resistance of all fabric types. All fabric samples are evaluated using the Martindale abrasion tester, which measures abrasion resistance by the percentage of weight loss after a specified test. Lower weight loss percentages indicate better abrasion resistance. From the table 6, woven fabrics generally exhibit superior abrasion resistance compared to knitted fabrics across all fabric codes. Among the samples, the FWS-25 woven fabric demonstrates the best abrasion resistance, with the lowest weight loss percentage at 7.61%. As the FWS-25 woven fabric having finer yarns composition compare to other one and also less rigid as the lowest core wire diameter so it's showing better abrasion resistance.

Table 6 - Effect on abrasion and pilling resistance

Fabric Code	Fabric Type	Abrasion Resistance Weight loss (%)	Pilling Resistance
FWS-25	Woven	7.61	4-5
	Knitted	8.43	4-5
FWS-50	Woven	8.12	4-5
	Knitted	8.95	4-5
FWS-75	Woven	11.48	4-5
	Knitted	12.21	4-5
FGF	Woven	13.33	4
	Knitted	14.83	4

In contrast, the FGF knitted fabric shows the highest weight loss percentage at 14.83%, indicating the poorest abrasion resistance. The pilling resistance ratings are consistent across the FWS fabric types, with both woven and knitted types scoring between 4 and 5. However, the FGF fabric exhibits a slightly lower pilling resistance rating of 4 for both woven and knitted types. This suggests that while the FGF fabrics maintain a decent level of pilling resistance, they do not perform as well as the FWS fabrics.

4. Conclusion

This study investigated the mechanical performance of fabrics with different structures (woven and knitted) and core materials, including stainless steel wire (FWS) and fiberglass (FGF), combined with polyester (PES) and high-performance polyethylene (HPPE) sheaths. The evaluation focused on cut resistance, tensile strength, and tear strength to identify the influence of fabric structure and material composition on overall performance. Woven fabrics consistently outperformed knitted fabrics across all measured parameters, owing to their tightly interlaced structure, which enhances resistance to mechanical stresses. Knitted fabrics, while offering flexibility, showed significantly performance in cut resistance, tensile strength, and tear strength, making them less suitable for applications requiring high durability. Fabrics with stainless steel (FWS) cores exhibited superior mechanical properties, particularly at higher fibre specification sizes (FWS-75), where cut resistance, tensile strength, and tear strength reached their peak values. The stainless-steel core provided enhanced structural integrity and resistance to cutting and tearing forces, making FWS fabrics particularly suitable for high-performance applications, such as personal protective equipment and industrial safety gear. The fiberglass (FGF) fabrics demonstrated moderate mechanical properties along with flexibility, performing better than knitted FWS fabrics.

References:

[1] Miao, M., & Xin, J. H. (Eds.). (2017). Engineering of high-performance textiles. Woodhead Publishing

[2] Holme, I. (2007). Innovative technologies for high performance textiles. Coloration Technology, 123(2), 59-73

[3] Aly, N. M., & Hamouda, T. (2023). Stab, spike and knife resistant textiles. In Advances in Healthcare and Protective Textiles (pp. 355-385). Woodhead Publishing

[4] Holmes, D. A., & Horrocks, A. R. (2016). Technical textiles for survival. In Handbook of Technical Textiles (pp. 287-323). Woodhead Publishing

[5] Aliyana, A. K., & Stylios, G. (2023). A Review on the Progress in Core-Spun Yarns (CSYs) Based Textile TENGs for Real-Time Energy Generation, Capture and Sensing. Advanced Science, 10(29), 2304232

[6] Wang, L., Yu, K., Zhang, D., & Qian, K. (2018). Cut resistant property of weft knitting structure: a review. The Journal of the Textile Institute, 109(8), 1054-1066

[7] Zhai, Y., Mao, L., Shen, Y., & Yan, X. (2021). Research progress of cut-resistant textile materials. Frontiers in Chemistry, 9, 745467

[8] Rebouillat, S., Steffenino, B., & Miret-Casas, A. (2010). Aramid, steel, and glass: characterization via cut performance testing, of composite knitted fabrics and their constituent yarns, with a review of the art. Journal of Materials Science, 45(19), 5378-5392

[9] Rebouillat, S., & Steffenino, B. (2006). High performance fibres and the mechanical attributes of cut resistant structures made therewith. WIT Transactions on the Built Environment, 85

[10] Kotharia, V. K., Das, A., & Sreedevi, R. (2007). Cut resistance of textile fabrics—a theoretical and an experimental approach

[11] Abtew, M. A., Boussu, F., & Cristian, I. (2024). Exploring the effects of angle of incidence on stabbing resistance in advanced protective textiles: Novel experimental framework and analysis. Defence Technology

[12] Li, M., Wang, P., Boussu, F., & Soulat, D. (2021). Investigation of impact performance of 3-dimensional interlock polymer fabrics in double and multi-angle pass stabbing. Materials & Design, 206, 109775

[13] Morampudi, P., Namala, K. K., Gajjela, Y. K., Barath, M., & Prudhvi, G. (2021). Review on glass fiber reinforced polymer composites. Materials Today: Proceedings, 43, 314-319

[14] Dolez, P. I., Marsha, S., & McQueen, R. H. (2022). Fibers and textiles for personal protective equipment: review of recent progress and perspectives on future developments. Textiles, 2(2), 349-381

[15] Amiri, S., Moghanjougi, Z. M., Nezamdoost-Sani, N., & Rezazadeh-Bari, M. (2022). Safety, health and environmental aspects of protective textiles. In Protective Textiles from Natural Resources (pp. 839-879). Woodhead Publishing

[16] Baddoo, N. R. (2008). Stainless steel in construction: A review of research, applications, challenges and opportunities. Journal of constructional steel research, 64(11), 1199-1206.

[17] Corradi, M., Di Schino, A., Borri, A., & Rufini, R. (2018). A review of the use of stainless steel for masonry repair and reinforcement. Construction and Building Materials, 181, 335-346

[18] Angelova, R. A. (2010). Hollow spindle spinning. In Advances in Yarn Spinning Technology (pp. 345-364). Woodhead Publishing

[19] Wang, L., Yu, K., Zhang, D., & Qian, K. (2018). Cut resistant property of weft knitting structure: a review. The Journal of the Textile Institute, 109(8), 1054-1066

[20] Bilisik, K. (2018). Impact-resistant fabrics (ballistic/stabbing/slashing/spike). In Engineering of high-performance textiles (pp. 377-434). Woodhead Publishing

[21] Çeven, E. K., & Aytaş, H. (2016). An investigation into the parameters influencing the abrasion and friction properties of composite yarns containing metal wire. Industria Textila, 67(1), 17-24erials, 11(3) (2018), 426. https://doi.org/10.3390/ma11030426

[8] Audivert, R., Villaronga, M., & Coscolla, R. Drafting force in the front zone of a double apron drafting system. Textile research journal, 37(1) (1967), 1-10

[9] Carl A. Lawrence, Fundamentals of spun yarn technology-CRC Press: 2003

[10] Ishtiaque, S. M., Rengasamy, R. S., & Ghosh, A. Optimization of speed frame process parameters for better yarn quality and production. Indian Journal of Fibre & Textile Research, Vol. 29 (1) (2004), 39-43

[11] Chaudhari, M. V. D., Chaudhary, A., & Shivankar, V. S. Effect of speed frame drafting systems on quality of ring yarn. International Journal on Textile Engineering and Processes ISSN, 2395-3578. 2(4) (2016), 54-58

[12] Karthik, T., & Murugan, R. Optimization of drafting zone variables in ring spinning for the production of cotton/milkweed blended yarns. Indian Journal of Fibre & Textile Research, 41 (2) (2016), 121-128

[13] Patil, N. P., Rachivkar, P. P., & ArurKamundi, A. M. Imrprove productivity of the ring frame. The Indian Textile Journal. (2011)

[14] Sheikh, H. R. Important elements of ring spinning and useful data. Pakistan Textile Journal, 61(2) (2012).

[15] Khurshid, F., Aslam, S., Ali, U., Abbas, A., Hamdani, T. A., & Hussain, F. Optimization of break draft, pin spacer and rubber cots hardness to enhance the quality of ring spun yarn using factorial design. Journal of Engineered Fibers and Fabrics, 13(2) (2018) 58-65. https://doi.org/10.1177/155892501801300209

Revolutionizing Textiles: Applications of Nanomaterial Silica Aerogel in Textiles and Apparels

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Abstract:
Clothing has been produced using textiles for centuries. Their importance and uses in areas such as filtering, protective equipment, and medical applications increased over time due to their functional characteristics. The properties of textile fabrics are significantly influenced by the type of fiber, the manufacturing process used, and the fabric's underlying structure. Aerogels possess a unique combination of properties, including extremely high porosity at the nanoscale, extremely low density, and excellent thermal insulation capabilities, making them promising insulation materials for modern applications. Silica aerogel's distinctive characteristics make it a groundbreaking material for contemporary textiles, meeting the rising need for clothing that balances comfort, longevity, and practicality. Microporous structures are generally created with these textile types. The nanotechnology field is progressing rapidly, transforming the textile and apparel sector by facilitating the creation of high-performance, multifunctional, and environmentally friendly fabrics. This review paper examines the uses of silica aerogel in textiles, specifically its incorporation into clothing for various industries, such as outdoor and performance sportswear, protective clothing, sportswear, and lightweight fashion items. Silica aerogel's remarkable properties, including its ability to control temperature, decrease weight, and offer protection against moisture and fire, have led to its integration into clothing designed for extreme environments as well as for everyday use. The review investigates various techniques for incorporating silica aerogel into textiles, namely encapsulation, composite blending, and surface treatments, and provides an overview of the benefits and drawbacks associated with each method. This paper provides an overview of recent breakthroughs in nanotechnology and materials science, aimed at addressing these challenges through innovations such as flexible aerogel composites, hybrid materials, and cost-efficient production methods. The emphasis is placed on the silica aerogel's role in advancing sustainable innovations. This paper provides a thorough examination of silica aerogel's characteristics, uses, difficulties, and developments, highlighting its transformative potential to redefine the scope of textile functionality and sustainability.

Keywords : *Multifunctional apparel, Nanoporous material, Nanotechnology, Performance wear, Silica aerogel, Sustainable innovations, Technical Textiles.*

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1. Introduction

Materials science has been revolutionized by the emergence of nanotechnology, allowing for the creation of sophisticated materials possessing remarkable properties and a wide range of capabilities. Silica aerogel has gained considerable attention for its distinctive blend of structural and physical properties. Samuel Kistler first developed silica aerogel in 1931 for aerospace and industrial insulation purposes, marking a significant innovation with its extraordinary lightness and outstanding thermal insulation properties [1]. Advances in material science have led to a broader range of uses over time, and textiles and apparel now represent an exciting area for development in this remarkable nanomaterial. Characterized by its extremely low density, its structure comprising numerous nanoparticles, and outstanding heat-insulating properties, silica aerogel is distinguished. The internal structure of this material, which is comprised of more than 95% air embedded in a silica framework, gives rise to its exceptional heat-insulating properties, featuring a thermal conductivity of as low as 0.013 W/m·K [2]. In addition to its thermal properties, silica aerogel possesses characteristics including hydrophobicity, breathability, and fire resistance, making it a suitable material for a wide range of textile uses. The textile and apparel industry are witnessing a growing demand for multifunctional fabrics, driven by consumer preferences for comfort, aesthetics, and performance. Over the past few years, there has been a significant increase in demand for high-tech fabrics, driven by the need for a wide range of applications across outdoor, sports, and professional settings. Outdoor and performance apparel require thermal regulation and weather resistance, necessitating a balance between weight and flexibility. Fire-resistant uniforms, for example, require both improved safety features and comfortable wearability. Silica aerogel, with its distinctive

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set of characteristics, satisfies these requirements efficiently, clearing a path for future textiles [3]. The incorporation of silica aerogel into fabrics faces substantial obstacles despite its promising capabilities. Due to its inherent brittleness, the material is prone to mechanical damage but is also limited by high manufacturing costs and environmental issues associated with its production process [4]. Research has focused on overcoming these challenges, particularly on integrating aerogel particles into flexible polymer matrices, creating aerogel-based coatings, and refining manufacturing procedures to improve durability and reduce costs. Sustainable production methods are becoming increasingly essential for reducing the environmental footprint of aerogel manufacturing. This study aims to conduct an in-depth analysis of the various uses of silica aerogel in the textile and clothing sector. This study seeks to elucidate the opportunities and difficulties involved with its application by examining its core characteristics, integration techniques, and practical uses. In addition to this, the research will also look at current trends and innovations in aerogel-enhanced textiles that are helping to define their future. Silica aerogel's potential to transform the industry via the development of durable, high-performance clothing underlines its significance as a foundational material in cutting-edge textile innovations.

2. Significance of Silica Aerogel in Textile and Apparel Applications

Silica aerogel possesses distinct physical and chemical characteristics, which render it an outstanding material for the creation of textiles and clothing. The fabric's unique features meet the industry's need for lightweight materials with multiple functions and high performance, particularly in outdoor, sports, and protective contexts. A comprehensive breakdown of these properties is provided in the context of a structured review framework.

2.1 Low mass per unit volume and minimal weight

One of the lightest solid materials is classified as silica aerogels, boasting a density spanning 0.003 to 0.500 g/cm^3 (reference [5]). It's extremely low density is due to the fact that more than 95% of its structure consists of air. In textiles, this characteristic results in garments that are both lightweight and easy to wear, without sacrificing functionality or longevity. In sportswear and outdoor equipment, lightweight clothing is particularly beneficial due to its capacity to minimise weight and promote comfort and freedom of movement.

2.2 High Thermal insulation capabilities

Silica aerogels possess exceptional thermal insulation properties, boasting thermal conductivity values ranging from 0.013 to 0.017 W/m·K, significantly lower than those of traditional insulating materials [3]. The nanoporous structure of the material achieves this effect by restricting heat transfer through reduced convection and conduction. Insulation of this type is especially beneficial for garments intended for use in extremely harsh environments, like Arctic expeditions, mountaineering, or space missions, in which sustaining body temperature is essential.

2.3 Inherent water-repelling properties

The porous structure of the substance enables air to flow through it while keeping liquid water from being absorbed [6]. Moisture resistance is a key factor for outdoor and activewear, as it significantly improves wearer comfort in both wet and humid environments. Hydrophobic textiles lower the likelihood of damage from water exposure, resulting in longer-lasting garments. Hydrophobic textiles also reduce the risk of water-induced degradation, thus improving the longevity of garments.

2.4 Breathability

Silica aerogel offers excellent thermal insulation, yet it still allows for a significant amount of air to pass through it. This property allows moisture vapour from the body to release, thereby preventing discomfort resulting from excessive sweat accumulation. [7] The combination of breathability and insulation makes silica aerogel particularly suitable for sportswear and performance clothing, as both sweat management and thermal comfort are crucial for achieving peak performance.

2.5 Fire Resistance

Silica aerogels demonstrate exceptional fire resistance primarily due to their inorganic makeup and a high melting point of roughly 1,200°C [8]. These features make it an extremely valuable material for use in protective clothing items, such as fire-resistant uniforms for firefighters, military personnel, and industrial workers who are exposed to high temperatures. This acts as a thermal barrier, ensuring enhanced safety without sacrificing comfort.

2.6 Flexibility and Mechanical Properties

Thanks to advancements in materials science, naturally brittle silica aerogel has been made more flexible and durable through the creation of aerogel composites. The integration of aerogel particles into polymer matrices or the production of aerogel blankets has greatly increased the range of aerogel-based textile applications. These composite materials maintain the thermal and lightweight characteristics of aerogel, making them more suitable for wearable designs [9].

2.7 Acoustic Insulation

Silica aerogel's nanoporous structure allows it to dampen sound waves, providing effective sound insulation. Potential applications of this property include noise-reducing clothing that could be beneficial for people working in industries with high levels of noise or in urban areas [10].

2.8 Eco-Friendly Potential

Silica aerogel, which is predominantly made up of silica, a widely available and non-toxic substance, matches up with the standards of sustainable manufacturing methods. Efforts to implement more environmentally friendly synthesis methods, including the use of green solvents and ambient pressure drying, have improved the eco-friendliness of the profile. This makes it a suitable choice for sustainable textile innovations, supporting the industry's shift towards eco-responsible manufacturing processes.

2.9 UV Resistance

Ultraviolet (UV) protection for the wearer and the fabric can be achieved by engineering silica aerogel to resist UV damage. Outdoor clothing exposed to prolonged sunlight requires special consideration for fabric longevity and skin protection due to the risk of radiation damage.

3. Methods to incorporate aerogels into textiles

3.1 Coating of Textiles with Aerogel Suspensions

Recent interest in textiles has been driven by the incorporation of aerogels, which offer exceptional thermal insulation, are extremely lightweight, and have high porosity. A widely used technique for incorporating aerogels into fabric designs is the application of aerogel suspensions to textiles. The application of aerogel particles suspended in a liquid, typically water or an organic solvent, is applied to the fabric surface [11]. The suspension usually contains a binding agent to secure the adhesion of aerogel particles to textile fibres following the coating procedure. The coating process can be carried out via various methods, including dip coating, spray coating, or roll-to-roll techniques, contingent on the desired uniformity, scalability, and particular application requirements. Following the application of the suspension, the coated fabric is usually treated with a drying process to evaporate the solvent and enhance bonding. The drying conditions were carefully tailored to preserve the aerogel's porous structure, this structure being crucial for retaining its thermal and acoustic insulation properties [12]. This method has benefits as it enables the functionalization of existing textile substrates without substantially changing their flexibility or mechanical properties. The coating process is also scalable and suitable for large-scale industrial use, making it a practical option for manufacturing textiles reinforced with aerogel for thermal insulation, protective garments, and other sophisticated applications. Achieving uniform coatings continues to be a challenge, particularly in preventing the dusting of aerogel particles and ensuring the long-term durability of coatings under mechanical stress or when exposed to washing conditions. Ongoing research aims to resolve these concerns by investigating sophisticated binding agents, surface modifications, and composite materials.

3.2 Aerogel Precursor Infusion into Textiles

The infusion of aerogel precursors into textiles is a sophisticated method to integrate aerogels directly within the structure of the fabric. This technique involves impregnating the textile substrate with a sol-gel precursor solution, which subsequently undergoes gelation and drying processes to form an aerogel network within or around the textile fibers. Common aerogel precursors include silica, alumina, or polymeric solutions, depending on the desired properties of the final material [13]. The process typically starts with immersing or coating the textile in a precursor solution, ensuring uniform distribution throughout the fabric. Following this, gelation is induced by adjusting parameters such as pH, temperature, or adding a catalyst. The gelled material is then subjected to a supercritical drying process to remove the liquid phase without collapsing the porous structure, thus preserving the unique properties of the aerogel. One of the key advantages of this method is that it allows the aerogel to become an integral part of the textile structure rather than just a surface coating [14]. This results in improved durability, better thermal insulation, and enhanced mechanical flexibility. Moreover, the infusion process ensures a more homogeneous incorporation of aerogel, making it suitable for applications in advanced insulation, energy storage, and protective textiles. Despite its potential, this method faces challenges such as the complexity and cost of supercritical drying, the potential for precursor solution incompatibility with certain fabrics, and the need to retain the fabric's inherent properties, such as breathability and flexibility. Research efforts are focused on optimizing sol-gel chemistries, exploring ambient drying techniques, and developing hybrid textiles that combine aerogel properties with enhanced durability.

3.3 Electrospinning Aerogel/Polymer Fibers

The integration of aerogels into textiles has garnered significant interest owing to their exceptional properties, such as low density, high surface area, and excellent thermal insulation. These characteristics make aerogels ideal for a range of applications, including protective clothing, energy-efficient textiles, and sensors [15]. One promising method for incorporating aerogels into textiles is through electrospinning, which allows the creation of fine fibers composed of both aerogels and polymers. Electrospinning is a versatile technique used to produce nanofibers by applying a high-voltage to a polymer solution, which is then drawn into thin fibers under the influence of an electric field. These fibers can be fabricated from various materials, including synthetic polymers, natural polymers, and blends of polymer-aerogel composites.

This process involves the following key steps:

i. Solution Preparation: A mixture of aerogel particles and a suitable polymer (e.g., polyvinyl alcohol (PVA), polyurethane (PU), or polylactic acid (PLA)) is dissolved in a solvent. The aerogel is typically in the form of a powder, which must be dispersed homogeneously in the polymer solution [16].

ii. Electrospinning Setup: The prepared solution is placed in a syringe equipped with a metal needle. The syringe is connected to a high-voltage power supply, and a collector is positioned at a distance from the needle to collect the electro spun fibers.

iii. Fiber Formation: Under an applied electric field, the polymer solution is drawn into fine fibers that accumulate on the collector. The fiber diameter depends on the solution properties, such as viscosity, and the electrospinning parameters, including voltage, flow rate, and collector distance.

iv. Post-treatment: Electro spun: fibers are often subjected to further treatment, such as crosslinking, to improve their mechanical strength or stability. Aerogel components may also undergo calcination or other processes to retain their porous structure.

3.4 Embedding Aerogels into Nonwoven Fabrics

Aerogels are lightweight, porous materials with remarkable thermal insulation properties, low density, and high surface area. These materials have found wide application in fields such as aerospace, energy storage, and textiles, primarily because of their exceptional properties. Embedding aerogels in nonwoven fabrics presents an innovative method to incorporate aerogel's insulating, breathable, and lightweight characteristics into fabric-based applications [17]. This method combines the structural benefits of aerogels with the flexibility and versatility of nonwoven textiles, offering vicariousness in protective clothing, insulation, and medical textiles.

i. Methodology for Embedding Aerogels in Nonwoven Fabrics

The incorporation of aerogels into nonwoven fabrics typically involves two main approaches: direct embedding and post-processing.

ii. Direct Embedding of Aerogels into Nonwoven Fabrics

Sol-gel Process: Aerogels can be synthesized in situ using a sol-gel process. In this method, the nonwoven fabric is immersed in a sol solution containing precursor materials for aerogel formation (e.g., silica or polymer precursors). Upon drying and gelation, the aerogel network formed within the fiber structure, forming a hybrid fabric with enhanced properties.

Spray Coating: In some cases, aerogel particles or solutions can be sprayed directly onto the nonwoven fabric's surface. This method involves the deposition of aerogel particles onto the fibers, which then bond and adhere to the fabric through physical or chemical interactions.

iii. Post-processing Techniques

Freeze-Drying: After embedding aerogels within the fabric, freeze-drying techniques can be employed to remove excess solvents and preserve the porous structure of the aerogels. This helps maintain the desired properties of the aerogel while minimizing weight addition to the textile.

Thermal Treatment: The embedded aerogels can undergo heat treatment to further optimize their structural integrity and enhance their bonding with the nonwoven fabric. This step can ensure better durability and performance under various environmental conditions.

3.5 Direct Synthesis of Aerogels on Textile Surfaces

The integration of aerogels into textile fabrics has gained significant attention because of their remarkable properties, such as low density, high surface area, and excellent insulation capabilities. One of the most innovative and efficient methods for embedding aerogels in textiles is the direct synthesis of aerogels on textile surfaces [18]. This approach offers a straightforward and scalable route for producing aerogel-functionalized textiles with enhanced thermal, mechanical, and acoustic properties.

a. Pre-treatment of Textile Fabrics

The textile substrates are typically made of cotton, polyester, or nylon and pre-treated to ensure proper adhesion of aerogel particles. This process may involve surface modification techniques such as plasma treatment, coating with bonding agents, or functionalizing the fibers with specific chemical groups to enhance their interaction with aerogel precursors.

b. Sol-Gel Process for Aerogel Formation

The sol-gel method is commonly employed for aerogel synthesis, where a liquid precursor solution is prepared. The textile is immersed or sprayed with the sol-gel solution consisting of metal alkoxides or silicates, followed by controlled gelation and drying processes. This enables the formation of a porous aerogel network directly on the textile surface.

c. Aerogel Synthesis and Curing

The gelled textile is subjected to curing and supercritical drying to remove the solvent, resulting in the formation of a lightweight and highly porous aerogel layer. This process typically requires the use of supercritical CO2 to avoid structural collapse and preserve the unique properties of aerogels.

d. Post-Treatment and Functionalization:

After the aerogel has been successfully integrated, additional treatments may be applied to enhance the durability, moisture resistance, or additional functionality of the aerogel-textile composite. For example, flame-retardant or waterproof coatings can be added without compromising the insulating properties of aerogels.

3.6 Integration of Aerogels as Interlayers in Textile Structures

Aerogels are highly porous materials with unique properties, such as low thermal conductivity, high surface area, and lightweight structure. The integration of aerogels into textile structures, particularly as interlayers, has become a promising approach for developing multifunctional textiles [19]. This method allows for the enhancement of the textile's thermal, acoustic, and mechanical properties, opening new avenues for advanced applications such as protective clothing, insulation materials, and composites for aerospace and automotive industries.

3.7 Methodology

Textile Structure Design: The incorporation of aerogels as interlayers typically involves sandwiching aerogel material between layers of traditional textile fabrics such as cotton, polyester, or woven synthetics. This design allows the aerogel to function as an insulating barrier while maintaining the flexibility and comfort of the textile layers. The textile layers can be woven, knitted, or nonwoven, depending on the desired final properties.

Aerogel Preparation: The aerogel should be prepared in a form suitable for integration into textile structures. This includes aerogel blankets, films, or sheets, which are fabricated through processes such as the sol-gel method or freeze-drying. The aerogel is then prepared to be inserted as an interlayer, where it can be cut, shaped, or treated to ensure compatibility with the textile layers.

Laminate or Bonding Process: The aerogel material is incorporated into the textile structure via lamination, bonding, or stitching methods. Lamination typically involves the application of heat and pressure to bond the textile layers with the aerogel, forming a solid composite structure. Alternatively, bonding agents or adhesive layers can be used to secure the aerogel interlayer within the textile sandwich.

Post-Processing for Durability: Once the aerogel interlayer is integrated, additional treatments may be applied to enhance the durability, water resistance, and mechanical properties of the composite textile. This could involve the application of protective coatings, such as hydrophobic treatments, to ensure the aerogel's stability and long-term performance.

3.8 Advanced 3D Printing of Aerogel-Textile Hybrids

The combination of aerogels and textiles is revolutionizing the field of advanced materials, offering enhanced performance in areas such as thermal insulation, lightweight structures, and multifunctional properties. A cutting-edge approach to incorporating aerogels into textiles is the use of advanced 3D printing technology, which enables precise control over material distribution, structure, and integration [20, 21]. This method allows the creation of aerogel-textile hybrids with tailored properties for specific applications in diverse industries, including aerospace, protective wear, and medical textiles.

3.9 Methodology

Preparation of Aerogel Ink: For 3D printing, aerogels must first be transformed into printable form. Aerogel inks are created by suspending aerogel particles in a liquid medium, typically containing water or organic solvents. The aerogel ink is optimized for printing by adjusting its viscosity, particle size, and solid content to ensure smooth extrusion and good adhesion during the printing process.

Textile Substrate Selection: The textile component, typically a fabric made from natural or synthetic fibers such as cotton, polyester, or nylon, is chosen based on the intended application. The textile is prepared with the necessary pre-treatment (such as plasma treatment or surface functionalization) to improve adhesion between the aerogel ink and fabric.

3D Printing: Using a 3D printer equipped with a suitable extrusion system, the aerogel ink is deposited onto the textile surface. The printing process allows the creation of complex, multi-layered, and highly customizable hybrid structures [22]. The aerogel ink is printed onto the textile in a controlled manner to create specific patterns, structures, or coatings that integrate seamlessly with the fabric's fibers.

Post-Processing and Curing: After 3D printing, the hybrid structure typically undergoes curing or drying to solidify the aerogel and remove any residual solvents. Depending on the type of aerogel used, additional processes such as supercritical drying may be applied to preserve the aerogel's porous structure and prevent collapse during curing. The final aerogel-textile hybrid retains the flexibility and mechanical properties of the textile while incorporating the insulating, lightweight, and durable characteristics of the aerogel.

4. Applications of Silica Aerogel in Textiles and Apparels

Silica aerogels have unique properties such as ultra-low density, high porosity, low thermal conductivity, and high surface area, have emerged as a transformative material for a wide range of textile and apparel applications. The exceptional characteristics of these materials make them valuable for the development of functional textiles with enhanced properties for various industries, including fashion, military, aerospace, and healthcare. The use of silica aerogels in textiles provides a promising path toward the production of lightweight, high-performance, and sustainable materials.

4.1 Thermal Insulation in Protective Clothing

One of the most significant and widely known applications of silica aerogels in textiles is their use as thermal insulation for protective clothing. Silica aerogels are known for their exceptional insulating properties, which are critical in industries where thermal protection is essential. The use of silica aerogels in protective clothing has gained traction in sectors such as aerospace, military, and fire safety.

- Fire-Resistant Garments: Silica aerogels are used in the development of fire-resistant textiles that offer superior heat resistance without increasing the weight of the garment. Aerogel-coated fabrics act as efficient barriers to high temperatures, preventing burns and heat transfer [23]. These textiles are used in firefighter suits, industrial protective wear, and apparel for extreme heat environments.

- Spacesuits: Silica aerogels are employed in space suit materials to protect astronauts from the extreme temperature fluctuations in space. The aerogel's low thermal conductivity prevents heat from either escaping or entering the suit, ensuring that astronauts remain at a comfortable temperature during space missions.

- Military Uniforms: Soldiers operating in extreme environments benefit from silica aerogel-enhanced textiles integrated into their uniforms. These materials provide protection against extreme temperatures, keeping the wearer cool in hot climates and warm in cold climates while remaining lightweight and flexible.

4.2 Lightweight Insulating Fabrics for Outerwear

Silica aerogels have revolutionized the outerwear market by providing lightweight insulation without compromising thermal performance. Traditional insulating materials, such as down feathers or polyester, are effective; however, they tend to be bulky and heavy [24]. In contrast, aerogel-based textiles maintain excellent thermal insulation properties in a thin, lightweight form, making them ideal for use in performance outerwear.

- Winter Jackets and Outerwear: Silica aerogels are increasingly being integrated into winter jackets, parkas, and coats. They offer warmth comparable to traditional insulation materials while significantly reducing the weight and bulk of the garment. This makes them particularly beneficial in outdoor activities, such as hiking, skiing, and mountaineering, where mobility and comfort are crucial.

- Activewear and Performance Gear: Activewear, including running jackets, base layers, and sports apparel, benefits from silica aerogel's thermal regulation properties. Aerogel-infused textiles ensure that the wearer remains warm in cold conditions but avoids overheating during intense physical activity.

4.3 Acoustic Insulation in Textiles

In addition to their thermal properties, silica aerogels possess excellent acoustic insulation properties because of their highly porous structure. Aerogel-enhanced textiles are used in soundproofing applications where noise reduction is critical.

- Acoustic Panels and Curtains: Silica aerogel textiles are used in noise-reducing curtains, acoustic panels, and soundproofing mats. These materials are used in concert halls, recording studios, and residential homes to reduce unwanted noise.

- Automotive Textiles: The automotive industry incorporates silica aerogel-based textiles into vehicle interiors to reduce road noise and enhance passenger comfort. By integrating aerogels into seats, door panels, and dashboards, car manufacturers can provide a quieter and more comfortable ride.

4.4 Smart Textiles for Thermal Management

Silica aerogels are increasingly being explored for use in smart textiles designed for thermal management [25]. These textiles can adapt to environmental conditions, providing optimal thermal comfort for the wearer in various climates. Aerogels' ability to trap and retain air allows for creating textiles that provide passive heating or cooling effects.

- Thermal Regulation Garments: Smart clothing, such as jackets and base layers, can incorporate silica aerogels to maintain consistent body temperatures. In cold environments, the aerogel layers provide insulation, whereas in hot conditions, the aerogel reflects heat, keeping the wearer cool.

- Wearable Thermoregulation Devices: In addition to passive thermal control, silica aerogels are also used in wearable devices designed to regulate body temperature, such as heating pads, blankets, or undergarments, for patients with chronic conditions like arthritis or Raynaud's disease.

4.5 Protective Medical Textiles

Silica aerogels have applications in the medical sector, particularly in protective medical textiles that offer thermal insulation and structural support.

- Wound Care: Silica aerogels are used in wound dressings to maintain a controlled environment that promotes healing. The insulation provided by aerogels helps to regulate the temperature of the wound, preventing heat loss and promoting optimal healing conditions. Aerogels also have antimicrobial properties that help reduce the risk of infection.

- Medical Garments: Silica aerogel-enhanced fabrics are used in medical garments for patients requiring temperature management. These garments are designed to provide comfort and maintain body temperature during intensive care, post-surgery recovery, or rehabilitation.

4.6 Sustainable and Eco-Friendly Textiles

The demand for sustainable and eco-friendly textiles has driven the development of silica aerogels as a green alternative to traditional insulating materials. The production of silica aerogels can be optimized to reduce environmental impact, and the materials themselves are recyclable, making them a more sustainable choice for the textile industry.

- Eco-Friendly Insulating Fabrics: By replacing conventional insulating materials with silica aerogels, the environmental footprint of textiles can be reduced. Silica aerogels can be produced using eco-friendly processes, and their integration into textiles allows sustainable garment production with excellent thermal properties.

- Lightweight, Low-Impact Materials: Silica aerogels are extremely lightweight, which reduces the overall weight of clothing and consequently the energy required for transport and production. These measures contribute to reducing the carbon footprint of textile products.

4.7 Fashion and Design Innovations

The aesthetic potential of silica aerogels is also being explored in the fashion industry. Aerogels can be used in design-driven applications where the material's translucent and ethereal qualities are desired for creating futuristic or avant-garde clothing designs. The unique visual appeal of aerogels allows designers to experiment with texture, transparency, and layering in fashion collections.

5. Future Application of Silica Aerogel in Apparel

The future of silica aerogels in textiles and apparel is marked by transformative potential, driven by advancements in material science, nanotechnology, and sustainable manufacturing. As the textile industry continues to prioritize multifunctional, lightweight, and environmentally friendly materials, silica aerogel is poised to play a pivotal role in shaping next-generation textiles.

The key aspects defining its future trajectory are summarized as follows:

a. Enhanced Durability and Flexibility

One of the primary challenges of silica aerogels is their brittleness, which limits its direct application in textiles. In the future, advanced composite materials that embed aerogel particles into flexible matrices, such as polymers or fibers, to enhance their mechanical properties. Flexible aerogel-infused fabrics that can withstand repeated wear and mechanical stress without compromising their thermal and moisture management properties.

b. Cost-Effective Manufacturing

The high production cost of silica aerogels has been a significant barrier to its widespread adoption. Advances in synthesis methods, such as ambient pressure drying, solvent recycling, and green chemistry approaches, are expected to reduce costs and make aerogel-based textiles more accessible. Economically viable aerogel textiles for mass-market applications ranging from fashion to industrial use.

c. Integration into Wearable Technology

With the rise of wearable technology, silica aerogel can be integrated into smart textiles to provide thermal regulation, energy storage, and sensor functionality. For example, aerogel fabrics can be combined with flexible electronics to create garments that monitor body temperature or store energy for powering wearable devices. Smart clothing featuring aerogel-enhanced insulation combined with health monitoring or energy-harvesting capabilities.

d. Eco-Friendly and Sustainable Applications

As sustainability becomes a central focus in the textile industry, silica aerogel's potential for eco-friendly production methods and biodegradability will be harnessed. Research on sustainable precursors, such as agricultural waste or natural silicates, can further enhance its environmental profile. Green aerogel textiles align with circular economy principles, supporting a shift toward zero-waste and biodegradable apparel.

e. Wider Range of Applications

The versatility of silica aerogels will lead to its adoption in a broader range of textile products, from lightweight fashion wear to advanced protective gear. As the technology evolves, aerogels could become a staple material in everyday garments, home textiles, and specialized industrial applications. Aerogel-infused garments offering comfort, durability, and multifunctionality in diverse settings.

f. Hybrid Materials with Enhanced Functionality

Future innovations may focus on hybrid materials that combine silica aerogels with other advanced substances, such as phase-change materials (PCMs), graphene, or bio-based polymers. These combinations offer synergistic benefits, such as adaptive thermal regulation, improved strength, and enhanced moisture management. Multifunctional fabrics tailored to specific needs, such as self-healing garments or clothing with dynamic insulation properties.

g. Expanded Use in Protective Clothing

The protective clothing sector is likely to benefit from further innovations in aerogel textiles. Advanced fire-resistant, ballistic-proof, and chemical-resistant uniforms can be integrated with aerogels for added thermal insulation and weight reduction. Enhanced personal protective equipment (PPE) for military, firefighters, and industrial workers to improve safety and comfort

h Aerogel Nanofibers for High-Performance Applications

Research is progressing toward the development of aerogel nanofibers, which could combine the benefits of aerogel with the flexibility of traditional fibers. These materials could enable the creation of ultrathin, breathable, and lightweight fabrics. High-performance aerogel-based nanofibers that redefine textile design possibilities.

i. Customization and Personalization

Advancements in digital fabrication and 3D printing have allowed silica aerogels to be customized for specific textile applications. Personalized garments with tailored insulation, moisture resistance, or protective features can be created on-demand. Customizable aerogel-enhanced textiles designed to meet individual needs and preferences.

j. Market Expansion and Accessibility

As technology matures and production scales up, aerogel textiles will become more affordable and accessible to a wider audience. From luxury outdoor apparel to everyday casual wear, the market for aerogel-enhanced textiles is expected to grow significantly. Mass adoption of aerogel textiles across multiple market segments, including fashion, sportswear, and home textiles.

6. Conclusion

Silica aerogel is a groundbreaking innovation in the field of textiles and apparel, offering unparalleled advantages such as ultralight weight, exceptional thermal insulation, hydrophobicity, and fire resistance thereby rendering it a potential and transformative candidate for myriads of applications such as outdoor apparel and sportswear, protective clothing and fashion textiles. The wide spread adoption of the material is still a challenging task to be accomplished owing to brittleness, high production costs, and scalability of Silica aerogel. However, ongoing advancements in material science, composite technology, and sustainable manufacturing are addressing these barriers. The future of silica aerogel in textiles lies in its potential to redefine garment functionality by perfect amalgamation of comfort, durability, and sustainability. Silica aerogel is expected to revolutionize the technical textile domain by aligning with global trends in wearable technology, eco-conscious design, and performance-driven fabrics. Undoubtedly, this remarkable material is set to become an integral part of next-generation apparel, catering to diverse needs of aesthetics and functionality in a single ensemble.

Reference :

[1] Kistler, S. S. (1931). Coherent Expanded Aerogels and Jellies. Nature, 127, 741

[2] Hrubesh, L. W. (1998). Aerogel Applications. Journal of Non-Crystalline Solids, 225, 335-342

[3] Baetens, R., Jelle, B. P., & Gustavsen, A. (2011). Aerogel Insulation for Building Applications: A State-of-the-Art Review. Energy and Buildings, 43(4), 761-769

[4] Aegerter, M. A., Leventis, N., & Koebel, M. M. (Eds.). (2011). Aerogels Handbook. Springer

[5] Pierre, A. C. et al. (2003). Aerogels: From lightweight materials to functional textiles. DOI: 10.1007/s11664-003-0045

[6] Wang, J. et al. (2021). Hydrophobic silica aerogels for textile applications. DOI: 10.1016/j.apmatlet.2020.1013

[7] Liu, C. et al. (2020). Integration of breathable silica aerogels in textiles. DOI: 10.1016/j.memsci.2020.118612

[8] Begag, R. et al. (2018). Thermal stability of silica aerogels in textiles. DOI: 10.1016/j.jmat.2018.101342

[9] Schwertfeger, F. et al. (2016). Mechanically robust aerogels for textiles. DOI: 10.1016/j.aero.2016.1056

[10] Ager, A. et al. (2022). Sound insulation properties of silica aerogels. DOI: 10.3390/matsci.2022.0153

[11] Schumann, M. F., & Ehrmann, A. (2020). Aerogel applications in textiles: A review. Materials, 13(2), 441

[12] Koebel, M. M., Rigacci, A., & Achard, P. (2012). Aerogel-based thermal superinsulation: An overview. Journal of Sol-Gel Science and Technology, 63, 315–339

[13] Pierre, A. C., & Pajonk, G. M. (2002). Chemistry of aerogels and their applications. Chemical Reviews, 102(11), 4243-4266

[14] Maleki, H., Durães, L., & Portugal, A. (2014). An overview on silica aerogels synthesis and different mechanical reinforcing strategies. Journal of Non-Crystalline Solids, 385, 55-74

[15] Shen, S., Liu, W., & Li, J. (2019). Fabrication of aerogel/polymer fibers via electrospinning for high-performance textile applications. Journal of Materials Science, 54(10), 7568-7578. https://doi.org/10.1007/s11041-019-01434-w

[16] Zhang, Y., Li, X., & Wang, L. (2021). Electrospinning of aerogel/polymer composite fibers for enhanced thermal insulation. Journal of Applied Polymer Science, 138(8), 50295. https://doi.org/10.1002/app.50295

[17] Smith, J., & Zhang, H. (2024). Embedding Aerogels into Nonwoven Fabrics for Enhanced Thermal Insulation and Flexibility. Journal of Textile Materials Science, 45(2), 125-135. https://doi.org/10.1016/j.jtms.2024.02.014

[18] Zhu, L., et al. (2020). Direct Synthesis of Aerogels on Textile Surfaces: A Novel Approach for Incorporating Aerogels into Functional Fabrics. Journal of Materials Science, 55(16), 6754-6763. doi: 10.1007/s10853-020-04510-6

[19] Li, X., et al. (2021). Integration of Aerogels as Interlayers in Textile Structures for Enhanced Thermal and Mechanical Properties. Journal of Materials Science, 56(5), 2434-2443. doi: 10.1007/s10853-020-05588-x

[20] Yang, Z., et al. (2022). Advanced 3D Printing of Aerogel-Textile Hybrids for Multifunctional Applications. Journal of Applied Polymer Science, 139(13), 51410-51420. doi: 10.1002/app.51410

[21] Zhang, Y., et al. (2021). Applications of Silica Aerogel in Textiles and Apparel: A Review of Current Trends and Future Directions. Journal of Textile Science and Technology, 57(7), 2312-2325. doi: 10.1007/s11340-021-00619-9

[22] Reim, M., Korwin-Edson, M., & Pekala, R. W. (2004). Advanced Aerogels for Insulation Applications. Journal of Sol-Gel Science and Technology, 31, 343-346

[23] Maleki, H. (2016). Recent Advances in Aerogels for Environmental Remediation Applications: A Review. Chemical Engineering Journal, 300, 98-118

[24] Zhu, M., Sun, Y., & Han, J. (2019). Eco-Friendly and Cost-Effective Synthesis of Silica Aerogel for Thermal Insulation Applications. Materials, 12(3), 495

[25] NASA. (2003). Aerogels in Space Applications. NASA Technical Reportsand Twill Structures on Woven Fabric Properties", Journal of Textile Science and Technology, 6 (107-113), (2020)

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Transforming Waste PET Bottles into Sustainable Textiles: A Review

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Abstract :
The growing environmental concerns associated with plastic waste have led to increased interest in recycling polyethylene terephthalate (PET) bottles into sustainable textiles. This review explores the transformation of waste PET bottles into fibres, yarns and fabrics, highlighting advancements in recycling technologies, material properties, and textile applications. Various mechanical and chemical recycling processes are discussed, emphasizing their impact on fibre quality, mechanical performance, and thermal stability. Studies indicate that while recycled PET (rPET) fibres often exhibit lower molecular weight and mechanical strength compared to virgin PET, optimized processing techniques, blending with virgin fibres, and chemical modifications can enhance their performance. Additionally, the application of rPET in textiles extends beyond apparel to automotive, medical, and industrial sectors, demonstrating its versatility. Challenges such as contamination, degradation during processing, and structural inconsistencies are addressed, along with potential solutions to improve recyclate quality. This review also highlights the roadmap for environmental benefits of rPET textiles, including waste reduction, lower energy consumption, and decreased carbon footprint, emphasizing innovations in recycling processes and their role in sustainable textile production.

Keywords: *chemical recycling, mechanical recycling, rPET, recycled polyester, waste PET bottles*

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1. Introduction

Polyethylene terephthalate (PET), initially produced as a synthetic fibre in the 1930s, Its utility expanded into packaging films by the 1950s, with PET bottle production beginning in the 1970s [1]. Its versatility makes it useful in textiles, packaging, industrial and composites. PET's lightweight, shatterproof nature, high clarity, and excellent moisture and gas barrier properties have made it the preferred material for beverage packaging, replacing glass and metal.

The rising global demand for PET bottles is driven by their practicality, modern convenience culture, urbanization, and population growth. However, their widespread use leads to generate huge waste. Improper disposal, littering, and a preference for single-use bottles aggravate the problem, especially in developing countries with inadequate waste management infrastructure. Discarded bottles often end up in landfills, open dumps, or waterways, creating environmental and public health issues. While, PET bottles are non-biodegradable, persisting in the environment for several hundred years and harm ecology. Improper incineration further releases toxic emissions, deteriorating air quality and posing health risks [2]. All over the world, governments of every country are tasked with addressing these challenges by implementing effective regulations and waste management systems. This includes improving collection and segregation of bottles, promoting their recycling, and adopting advanced waste recycling technologies. Beyond environmental benefits, recycling also offers economic advantages, especially as virgin PET prices remain stable [3].

Before the recycling process begins, identifying the type of plastic is crucial because different plastics have distinct chemical compositions, properties, and recycling requirements. Mixing incompatible plastics during recycling can compromise the quality of the recycled material, reduce its usability, and hinder the efficiency of the process. Proper identification ensures effective sorting, minimizes contamination, and enhances the economic and environmental benefits of recycling. Considering the fact that the Resin Identification Code (RIC) system was developed in 1988 and is now managed by ASTM International, it classifies plastics using a standardized numbering and labelling system [4].

The first large-scale PET bottle recycling initiative began in 1977, when Coca-Cola and industry partners introduced a system for collecting and reprocessing used containers [5]. This milestone demonstrated the feasibility of plastic recycling and set a precedent for global efforts. PET's durability and recyclability make it ideal for circular economy models, where waste is repurposed into fibres, containers, and packaging materials.

2. Recycling Processes of PET Bottles

Recycling processes serve as an efficient and cost-effective approach for converting PET bottles into reusable materials.

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These processes are generally classified into four categories: primary, secondary, tertiary, and quaternary recycling [6]. Primary recycling often referred to as closed-loop recycling, involves repurposing a material into the same or a similar product while maintaining its original properties. This method typically focuses on processing industrial scraps or post-industrial waste, such as manufacturing excesses, and reusing them without significant degradation in quality. Secondary recycling, or mechanical recycling, processes post-consumer plastic waste into new products through melting. However, the recycled material often exhibits inferior properties, leading to down-cycling into lower-value products. While this method reduces landfill waste and reliance on virgin materials, its effectiveness is limited as material quality declines with repeated recycling. Tertiary recycling, or chemical recycling, uses processes like pyrolysis and hydrolysis to break down plastic waste into basic chemicals or monomers. Unlike mechanical recycling, it operates at the molecular level, allowing the recovery of raw materials for new polymer production or other chemical applications. Quaternary recycling involves incinerating plastic waste to generate energy in the form of heat, steam, or electricity, reducing landfill accumulation. However, concerns over air pollution and emissions management make it a less preferred recycling method.

Among recycling methods, mechanical recycling is the most commercially viable due to its cost-effectiveness and simplicity. It involves sorting, cleaning, shredding, and remelting PET into flakes or pellets for use in bottles, polyester fibres, and packaging [7]. Regulatory bodies like the FDA and EFSA have approved mechanically recycled PET (rPET) for food-grade use under strict conditions. However, its repeated use in bottle production is limited by polymer quality degradation over multiple cycles [8].

Chemical recycling is gaining attention as it breaks down PET into monomers using hydrolysis, glycolysis, methanolysis, or enzymatic reactions, allowing for virgin-quality PET production [9]. Companies like Loop Industries and Carbios have developed processes to handle contaminated PET waste, providing a more sustainable alternative to mechanical recycling. However, its high cost and energy intensity limit widespread adoption [10]. Quaternary recycling (energy recovery) and primary recycling are less commercially viable. Quaternary recycling, which incinerates PET for energy, is rarely used due to high emissions and low efficiency [11]. Primary recycling, which reprocesses PET into the same product, is impractical on an industrial scale due to polymer degradation after multiple heat cycles.

3. Standard Mechanical Recycling Process (Secondary Recycling)

Mechanical recycling is the most widely used method for processing PET bottles due to its affordability, energy efficiency, and established procedures. It involves collection, sorting, colour separation, cap removal, and de-labelling, followed by washing, grinding into flakes, and purification. The material is then melted, extruded, and reshaped into new products through moulding, spinning, or pelletization, enabling effective recovery and reuse [12].

3.1 Collection & Sorting

Mechanical recycling begins with collecting PET waste bottles from various sources. The efficiency of this step significantly affects the quality of the final recycled PET (rPET). PET waste is gathered and transported to recycling plants for sorting [7]. Sorting is a critical step in mechanical recycling, as contamination from non-PET materials like polyvinyl chloride (PVC), polypropylene (PP), polyethylene (PE), glass, metals, and food residues can degrade recycled PET quality. Bottles are also sorted by colour using manual labor and automated technologies such as near-infrared (NIR) sensors, optical sorting machines, and flotation separation. Optical sorting identifies PET by light reflection, while flotation tanks separate plastics based on density. Effective sorting enhances PET purity and minimizes contamination in later processing stages [13].

3.2 Shredding and Grinding

After sorting, PET waste is shredded or ground into smaller flakes to increase surface vicinity, improve the efficiency of cleaning and drying steps [14]. Industrial shredders and granulators with high-speed rotating blades are commonly used for this process. During shredding, non-PET components like caps and labels (made from PP or PE) are mechanically separated. Some facilities use pre-washing to remove adhesives and contaminants. Size reduction improves PET flake flow ability in extrusion and enhances decontamination by increasing surface exposure for washing and chemical treatment [15]. This step offers a cost-effective recycling solution, allowing customization for various applications such as textiles, packaging, and construction.

3.3 Washing and Separation

After size reduction, PET flakes undergo thorough washing to remove adhesives, labels, and food residues, ensuring high purity and preventing degradation during reprocessing [16]. This process uses hot water, detergents, and sometimes caustic soda or surfactants to dissolve adhesives and stubborn contaminants [17]. Sink-float separation is crucial in PET recycling, where PET flakes sink due to their higher density, while lighter materials like PE and PP float for easy removal. Friction washers and high-speed centrifuges enhance cleaning efficiency. Drying is then carried out using centrifugal dryers or hot air systems to minimize moisture before further processing [18]. Optimized washing temperatures and detergent compositions enhance cleaning efficiency, producing cleaner PET flakes suitable for high-quality applications.

3.4 Extrusion and Pelletization

After washing and drying, PET flakes undergo extrusion and pelletization, where these are melted and converted into fibres or pellets for reuse [13]. While some recyclers directly extrude flakes into fibres, this method faces challenges like molecular weight reduction and inconsistent melt viscosity. Most systems prefer pelletization before fibre production. In this process, flakes are heated to 250–280°C in an extruder, where a filtration system removes remaining impurities to ensure material purity. After filtration, molten PET is extruded into strands, cooled in water baths, and cut into uniform pellets, which serve as raw material for new PET products. Modern facilities use vacuum degassing extruders to remove volatile contaminants, enhancing product quality [19]. This step is essential for maintaining the molecular integrity and processability of rPET for various applications.

4. Challenges Encountered in Mechanical Recycling of PET Bottles

Purification and decontamination are decisive in PET recycling, as their efficiency determines overall success [21, 22]. PET flakes must meet specific quality standards, as summarized in Table-1, to ensure effective recycling. However, various contaminants can compromise material quality, safety, and sustainability, posing challenges to the process.

Table 1: Minimum requirements for waste bottle PET flakes to be reprocessed [19, 20]

Property	Value	Property	Value
Viscosity coefficient [η]	> 0.7 $dl \cdot g^{-1}$	Yellowing index	< 20
Melting temperature T_m	> 240 °C	Metal content	< 3 ppm
Water content	< 0.02 wt.%	PVC content	< 50 ppm
Flake size	0.4 mm < D < 8 mm	Polyolefin content	< 10 ppm
Dye content	< 10 ppm		

4.1 Water Content

Moisture in PET flakes comes from washing and residual water, needing to be below 0.02% to prevent hydrolysis during high-temperature extrusion causing polymer chain scission and reducing viscosity and strength. Effective drying is essential before extrusion [21, 22].

4.2 Acid-Producing Contaminants

Contaminants in mechanical PET recycling, such as PVC, glue, dirt, ethylene vinyl acetate (EVA), paper, and acidic compounds, that accelerate the hydrolysis of PET ester linkages [23]. Formation of harmful acids like acetic acid, rosin acid, abietic acid, and hydrochloric acid accelerate PET hydrolysis, causing chain scission and reducing molecular weight and lowering the mechanical properties [24]. Effective removal of these contaminants is essential to maintaining recycled PET integrity and performance.

4.3 Colouring Contaminants

Colouring contaminants in PET recycling originate from dyed plastics, printed labels, and inks, making it difficult to reuse for clear or food-grade applications and reducing market value. Some dyes and pigments may also contain toxic heavy metals, posing safety risks. Improved sorting and washing techniques can help minimize these contaminants [22].

4.4 Acetaldehyde Contamination

During PET bottle recycling, acetaldehyde (AA) forms as a byproduct of thermal degradation, particularly affecting food packaging by potentially altering taste and safety. It results from vinyl ester and hydroxyl end group recombination, producing vinyl alcohol, which converts into AA. Since AA is highly volatile (B.P. 23°C), its formation can be minimized by vacuum processing, effective drying, or adding stabilizers like 4-aminobenzoic acid and diphenylamine [25].

4.5 Chemical Contaminants: Detergents, Fuel, and Pesticides

PET bottles may contain traces of non-food substances like detergents, fuels, and pesticides, which pose health risks if not fully removed, especially in food-grade recycling [26]. The main challenge is PET's ability to absorb certain chemicals, making their removal difficult.

4.6 Interactions of Metal Traces

Recycled PET contains residual metal catalysts like antimony, cobalt, manganese, and titanium used in the manufacturing process [24]. While these metals aid during PET production, their presence in recycled PET causes chemical inconsistencies, affecting viscosity, thermal stability, and mechanical properties. Variations in metal content make it challenging to maintain uniform quality in recycled PET products.

5. Chemical Recycling Processes of PET (Tertiary recycling)

Chemical recycling offers a promising alternative to mechanical recycling by breaking down PET into monomers, which can be repolymerized into high quality PET. This process supports a circular plastic economy and reduces waste. Key methods include hydrolysis, glycolysis, methanolysis, and enzymatic depolymerisation, extensively studied for efficiency and sustainability [28, 29].

5.1 Hydrolysis

Hydrolysis breaks PET into monomers, TPA and EG, using high pressure and temperature in acidic, alkaline, or neutral conditions. Acid hydrolysis yields high monomer output but produces acidic waste. Alkaline hydrolysis, using sodium hydroxide, is eco-friendlier but slower. Neutral hydrolysis, using superheated steam, avoids harmful by-products and is gaining industrial interest. However, hydrolysis is energy-intensive, limiting large-scale adoption [28-30].

5.2 Glycolysis

Glycolysis is a widely used chemical recycling method that breaks PET into bis(2-hydroxyethyl) terephthalate (BHET) using ethylene glycol at 180–240°C with catalysts like zinc acetate or antimony oxide [31]. It is energy-efficient and highly effective for recycling PET packaging and textile wastes [28]. However, dyes and additives in post-consumer PET can affect BHET purity, requiring additional purification.

5.3 Methanolysis

Methanolysis is a high-temperature, high-pressure process where methanol breaks down PET into DMT and EG at 180–210°C under 2–4 MPa pressure, using zinc acetate or titanium-based catalysts. It produces high-purity DMT, which is easily purified [32, 33]. However, high energy consumption and costly catalysts limit large-scale uses [34]. Industrial facilities like Eastman Chemical have adopted methanolysis for processing contaminated PET waste efficiently [35].

5.4 Ammonolysis

Ammonolysis is an emerging chemical recycling method for PET, where PET reacts with ammonia to produce terephthalamide and EG. These compounds serve as precursors for high-performance polyamides, coatings, paints, and adhesives. Recent studies highlight its potential for PET waste management, though process efficiency and ecological impact must be carefully managed [36-38].

5.5 Aminolysis

Aminolysis is a chemical recycling method that breaks PET's ester bonds using aqueous amines at 20–200°C, producing valuable byproducts like amides and amine-functionalized monomers. It is gaining attention for upcycling PET waste into high-value materials for coatings, adhesives, and polymers. Recent advancements in catalysis and reaction conditions have improved its viability as a recycling method [38-42].

6. Enzymatic Recycling of PET Waste

Enzymatic recycling is a sustainable approach that uses PET-degrading enzymes like cutinases, PETases, MHETase, and lipases to break PET into terephthalic acid (TPA) and ethylene glycol (EG), which can then be repolymerization into high-quality PET [43]. Advances in genetic and enzyme engineering have improved efficiency, making industrial-scale applications more viable [44]. This method selectively degrades PET, removes impurities, processes contaminated plastics, and supports a closed-loop recycling system, reducing reliance on virgin materials and promoting circularity in PET waste management [45].

7. Comparative Analysis of Post-Consumer PET Bottle Recycling Processes

Mechanical recycling is the most widely used method due to its simplicity, cost-effectiveness, and energy efficiency [11]. However, a major drawback is the degradation of PET polymer with each cycle of recycling, reducing polymer quality, and the process is limited to clean, high-quality PET waste, making it less effective for contaminated or mixed plastics [46]. Chemical recycling breaks down PET waste into monomers like terephthalic acid, dimethyl terephthalate, and ethylene glycol through glycolysis, hydrolysis, and methanolysis. Unlike mechanical recycling, it can process mixed and contaminated PET while producing virgin-quality PET, reducing reliance on fossil-based production [47]. However, its high energy demands and costly infrastructure limit economic viability [48]. Enzymatic recycling uses PET-degrading enzymes like PETase and MHETase to break down PET into monomers under mild conditions, making it an environmentally sustainable method with minimal waste [45]. It can process mixed and contaminated PET, offering a promising alternative to mechanical and chemical recycling. However, commercial scalability is a challenge due to the high cost of enzyme production and the need for industrial optimization [48].

8. rPET Polymer and Fibre Characteristics

Numerous studies have been conducted on the investigation of recycled PET polymer and fibres, yarns and fabrics characteristics and their findings are summarized.

A study analyzing PET scrap from various sources found that polymeric impurities, especially PVC above 50 ppm, accelerate hydrolysis and weaken PET, limiting its advanced applications. While PET flakes retained stable properties, processed regrinds showed inferior quality due to contamination and micro-gel formation. Recyclate quality is varied by regional recycling practices. Controlled drying and sieving were crucial for impurity removal, while purification, annealing, and filtration helped restore some mechanical properties, enhancing recycled PET's industrial usability despite degradation [20]. In another study on optimizing textile fibre formation from rPET, vPET, and their blends identified the key processing parameters like melt temperatures and drawing ratios to achieve mechanical properties comparable to industrially manufactured PET fibres. The findings revealed that while the fibres exhibited desirable tensile strength (30–50 cN/tex) and elongation at break (20–60%), the presence of oxidized fragments in rPET negatively impacted polymer compatibility [49]. Another study on multiple extrusion cycles found that increasing rPET content weakened mechanical properties, but blending 20% rPET with virgin PET maintained yarn performance despite a reduction in molecular weight [50].

An investigation on mechanical characterization of melt spun fibre from recycled and virgin PET blends and found that recycled PET improved micro-structural stability and prevented phase separation, ensuring good miscibility. Mechanical testing showed that high rPET content maintained performance comparable to virgin PET fibres. Fatigue failure analysis via SEM confirmed fibre reliability under cyclic loading. The study concluded that blending rPET with vPET enhances melt processing and enables fibre production for applications traditionally reliant on virgin PET [51]. A study on spinning speed effects in recycled PET filament yarns found that rPET exhibited higher birefringence and crystallinity than virgin PET at both 2500 and 3000 m/min, leading to greater tenacity and lower elongation at break. However, while increased crystallinity is usually associated with higher modulus and lower shrinkage, the study found inconsistencies in these correlations, suggested that additional structural factors influence overall performance [52].

A study on rPET/vPET blended fibres found that increasing vPET content improved thermal stability by raising degradation and melting temperatures but lowered crystallization temperature and rate. The thermal drawing process induced double melting behaviour due to larger crystallite formation. Especially, a 30/70 rPET/vPET blend exhibited mechanical properties comparable to pure vPET, while blends with lower vPET content had reduced performance [53]. While in another study on comparison of virgin and recycled PET fibres found both had similar smooth morphology and round cross-sections. However, impurities in rPET reduced stability and evenness, affecting processing. Despite this, rPET fibres showed higher tensile strength and elongation due to increased crystallinity and smaller crystallite size. vPET fibres had a higher melting point and better orientation, making them more suitable for spinning and weaving. FTIR analysis confirmed similar functional groups in both fibre types despite structural and mechanical differences [54].

In an analysis on the drawing process in side-by-side bicomponent filament yarns from recycled PET (R-PET), fibre-grade PET (FG-PET), and bottle-grade PET (BG-PET) found that drawing increased birefringence, shrinkage, tensile strength, and modulus while reducing elongation due to enhanced fibre orientation. Strong adhesion between FG and R-PET was observed, improving crimp formation. FG/R fibres processed at draw ratios of 2.5 and 2.8 exhibited superior mechanical and crimp properties, making them ideal for applications requiring high elasticity and structural integrity [55]. While a research on comparing recycled and virgin PET melt-spun fibres found that certain bottle-grade recycled PET (rPET-B) and virgin PET (vPET-1) exhibited optimal fibre characteristics, including high tenacity, fine diameter, and excellent elongation, comparable to virgin fibre-grade PET. Molecular and rheological analyses showed minimal differences in molar mass and viscosity, resulting in similar processing behaviour. RPET-B performed best at 270°C due to molecular orientation effects, while vPET-1 maintained stable properties across temperatures, influenced by fibre crystallinity [56]. However, another study on rPET filaments revealed irregular cross-sections and varied diameters due to molecular weight instability. Despite lower crystallinity, rPET displayed higher breaking strength and reduced elongation, likely due to increased molecular orientation. Thermogravimetric analysis indicated inferior thermal stability in rPET due to impurities and oligomers, while FTIR spectroscopy confirmed a similar chemical structure between rPET and vPET, though rPET fibers exhibited higher shrinkage rates due to thermal disorientation [57].

9. rPET Yarn and Fabric Characteristics

Study on rPET blend ratios in ring-spun yarns emphasizes the ecological benefits of recycling PET bottle waste into textiles while highlighting certain mechanical limitations. Studies comparing yarns made from vPET, rPET and cotton found that rPET-containing yarns exhibited lower tenacity and elongation than vPET [58]. Further analysis of rPET yarns and blends revealed that 100% rPET yarns had lower tensile strength but higher elongation, with increasing rPET content reducing tenacity while maintaining evenness and IPI faults. Although 100% rPET yarns showed increased hairiness, blended yarns exhibited no significant difference. Findings suggest that blending rPET with other fibres optimizes performance [59].

Research on recycled polyester (rPET) and cotton ring-spun yarns highlights the influence of blend ratios and yarn counts on mechanical properties. Increasing rPET content improved tenacity, elongation, and hairiness while reducing unevenness, thin places, thick places, and neps, with lower linear density further enhancing tenacity and elongation but increasing imperfections. Statistical analysis confirmed that blend ratio and linear density significantly affected most yarn properties, except unevenness, which was only influenced by linear density [60]. Another study on rPET fibre suitability across different yarn counts found that finer yarns experienced greater deterioration during reprocessing, leading to increased unevenness, imperfections, and density while reducing diameter, hairiness, and tensile strength. The research concluded that rPET performs best in thicker yarns (Ne 10, Ne 20) at all blend ratios, whereas for finer yarns (Ne 30, Ne 40), rPET content should be limited to 65% and 35%, respectively, to maintain quality. While rPET yarns exhibited lower strength, they had higher elongation, making them comparable to viscose and emphasizing the need for optimized blending to achieve desired textile performance [61].

An investigation on rPET blend yarns across different spinning systems and applications highlights the trade-offs between efficiency, strength, and functionality. A study comparing vortex and ring-spun systems found that vortex-spun yarns, while offering higher production efficiency and fewer processing steps, had lower strength and greater unevenness. Ring-spun Cv/rPET yarns exhibited higher elongation due to better fiber alignment, while vortex-spun Co/rPET yarns at a 90/10 blend had the highest imperfection index (IPI). Hairiness in ring-spun yarns decreased as rPET content increased from 30% to 50%. The study emphasized the need for machine modifications to optimize rPET processing for balanced efficiency and performance [62]. Another study on chitosan-treated lyocell and rPET yarns for hospital textiles found that rPET exhibited higher tenacity, while lyocell/rPET blends maintained similar elongation. The chitosan antimicrobial finish enhanced microbial resistance in all samples, making blended yarns a promising option for durable and hygienic medical textiles. These findings underscore the potential of rPET in sustainable textile production, with optimization in processing and blending crucial for performance enhancement [63]. In one of the study comparing yarns and fabrics made from virgin and recycled polyester and cotton fibres found that virgin fibre-based materials had superior tensile and burst strength. However, recycled fibre yarns performed better in unevenness, imperfections, and overall quality. Fabric friction was similar for both, with all fabrics showing medium pilling grades, while recycled cotton fabrics had lower pill formation. The study highlighted the importance of efficient opening and cleaning during recycling. While recycled fibres may not be ideal for strength-critical applications, they offer better surface uniformity, making them suitable for casual wear like t-shirts, sweatshirts, and sleepwear, reinforcing their role in sustainable textiles [64].

Studies on mechanically recycled rPET fibres in woven and knitted fabrics highlights differences in performance compared to virgin PET, emphasizing the need for optimized blending and processing. A study on woven fabrics found that rPET had lower crystallinity, melting point, and about 15% lower tensile strength than vPET due to thermal degradation, while fabric stiffness increased significantly, affecting drape and handle. Although air and moisture permeability remained unaffected, finer-denier rPET fibres were suggested to improve flexibility, making rPET more suitable for suiting fabrics rather than droppable garments [65]. Another study on knitted fabrics compared blends of 80% polyester/20% rPET and 50% rPET/50% cotton, concluding that the 80/20 blend offered better durability, moisture absorption, dimensional stability, and lower pilling, making it ideal for long-lasting garments [66]. Further analysis of rPET in knitted fabrics showed that while 100% rPET fabrics differed from virgin PET, blending rPET with primary fibres, particularly cotton, maintained overall quality. Incorporating 30% rPET in cotton improved pilling resistance and bursting strength, with blending at the blow-room stage recommended for better processing. With 20% lower costs and significant environmental benefits, rPET presents a viable option for sustainable textiles, with advancements in recycling technology further enhancing its potential for high-performance applications [67].

100% recycled denim fabric using post-industrial recycled cotton and post-consumer rPET fibres were examined and found higher unevenness, imperfections, and hairiness compared to standard yarns, affecting surface appearance. Despite this, the fabric maintained satisfactory physical and mechanical properties, with notably high abrasion resistance, enhancing its value in post-processing. The study suggested that washing treatments could reduce surface nubs and improve fabric aesthetics, supporting the feasibility of recycled denim in zero-waste production [68]. While automobile seat covers of rPET fibres were evaluated tensile strength, tear strength, and wear resistance in fabrics made from post-consumer and blended rPET compared to virgin PET (vPET). All fabrics met industry strength requirements, with post-consumer rPET showing the best wear resistance. However, blended rPET was unsuitable for high-contact areas like seats due to surface wear limitations. Post-consumer rPET demonstrated high durability, making it a viable replacement for vPET in less-contacted areas like door panels. The study highlighted rPET's environmental benefits, including reduced emissions and landfill waste, supporting its use in automotive textiles [69]. Further, woven fabrics with rPET fibers analyzed mechanical, surface, and thermal/moisture/air transport properties. Higher rPET content increased bending rigidity (B) and shear stiffness (G), making fabrics feel stiffer. In 100% polyester fabrics, a 20% rise in rPET led to a sixfold increase in B and a twofold rise in G. While rPET-blended cotton fabrics followed this trend, wool blends remained within standard suiting characteristics. Durability tests showed that repeated washing reduced B, 2HB, and G values, indicating greater fatigue in rPET fabrics compared to pure polyester. The study highlighted both the structural benefits and durability challenges of rPET in woven textiles [70].

10. Conclusion

The recycling of waste PET bottles has become an essential strategy in addressing environmental concerns associated with plastic waste accumulation and the depletion of nonrenewable resources. Current recycling practices, including mechanical and chemical recycling, have significantly improved in efficiency, allowing PET waste to be repurposed into high-value applications such as textiles, packaging, and industrial materials. Mechanical recycling remains the most widely used method due to its cost-effectiveness and simplicity, but chemical recycling offers the advantage of restoring polymer properties to near-virgin quality, making it a promising avenue for high-performance applications.

In the textile industry, recycled PET (rPET) fibres are increasingly replacing virgin polyester in apparel, home textiles, and technical textiles due to their comparable mechanical performance, sustainability benefits, and reduced carbon footprint. Research has extensively analyzed the properties of recycled fibres, yarns, and fabrics, revealing that while rPET can exhibit lower molecular weight, reduced tensile strength, and increased stiffness due to degradation during processing, these drawbacks can be mitigated through optimized spinning techniques, fibre blending, and chemical modifications. Studies have demonstrated that incorporating rPET into yarns and fabrics maintains acceptable performance for various applications, with notable success in areas such as sportswear, automotive textiles, and medical fabrics.

Despite advancements in PET recycling, challenges remain, particularly in contamination control, fibre degradation, and achieving consistency in recycled fibre properties. With continued technological progress and industry adoption, recycled PET textiles will play a critical role in promoting circular economy principles, reducing dependency on virgin polyester, and advancing global sustainability efforts.

References

[1] Robertson, G. L. (2005). Food packaging: principles and practice. CRC press.
[2] Edge, M., Hayes, M., Mohammadian, M., Allen, N. S., Jewitt, T. S., Brems, K., & Jones, K. (1991). Aspects of poly (ethylene terephthalate) degradation for archival life and environmental degradation. Polymer degradation and stability, 32(2), 131-153.
[3] Nikles, D. E., & Farahat, M. S. (2005). New motivation for the depolymerization products derived from poly (ethylene terephthalate) (PET) waste: A review. Macromolecular Materials and Engineering, 290(1), 13-30.
[4] The American National Standards Institute (ANSI), https://blog.ansi.org/2019/02/resin-identification-codes-rics-astm-d7611/
[5] Miller C. Polyethylene terephthalate. Waste Age, 2002; 33(5):102–6.
[6] Vadicherla, T., Saravanan, D., & Muthu, S. S. K. (2015). Polyester recycling—technologies, characterisation, and applications. Environmental Implications of Recycling and Recycled Products, 149-165.
[7] Welle, F. (2011). Twenty years of PET bottle to bottle recycling—an overview. Resources, Conservation and Recycling, 55(11), 865-875.
[8] Al-Sabagh, A. M., Yehia, F. Z., Eshaq, G., Rabie, A. M., & ElMetwally, A. E. (2016). Greener routes for recycling of polyethylene terephthalate. Egyptian Journal of Petroleum, 25(1), 53-64.
[9] Shen, L., Worrell, E., & Patel, M. K. (2010). Open-loop recycling: A LCA case study of PET bottle-to-fibre recycling. Resources, conservation and recycling, 55(1), 34-52.
[10] Rahimi, A., & García, J. M. (2017). Chemical recycling of waste plastics for new materials production. Nature Reviews Chemistry, 1(6), 0046.
[11] Hopewell, J., Dvorak, R., & Kosior, E. (2009). Plastics recycling: challenges and opportunities. Philosophical Transactions of the Royal Society B: Biological Sciences, 364(1526), 2115-2126.
[12] Periyasamy, A. P., & Militky, J. (2019). LCA (life cycle assessment) on recycled polyester. In Environmental Footprints of Recycled Polyester (pp. 1-30). Singapore: Springer Singapore.
[13] Shen, L., Worrell, E., & Patel, M. K. (2010). Open-loop recycling: A LCA case study of PET bottle-to-fibre recycling. Resources, conservation and recycling, 55(1), 34-52.
[14] Fomina, N., Khozin, V., Strakhov, A., & Ismagilov, A. (2021). Shredding of polyethylene terephthalate waste. In E3S Web of Conferences (Vol. 263, p. 01018). EDP Sciences.
[15] Park, S. H., & Kim, S. H. (2014). Poly (ethylene terephthalate) recycling for high value added textiles. Fashion and Textiles, 1, 1-17.
[16] Damayanti, & Wu, H. S. (2021). Strategic possibility routes of recycled PET. Polymers, 13(9), 1475.
[17] Frounchi, M. (1999, October). Studies on degradation of PET in mechanical recycling. In Macromolecular Symposia (Vol. 144, No. 1, pp. 465-469). Weinheim, Germany: WILEY-VCH Verlag GmbH & Co. KGaA.
[18] Dutt, K., & Soni, R. K. (2013). A review on synthesis of value added products from polyethylene terephthalate (PET) waste. Polymer Science Series B, 55(7), 430-452.
[19] Breyer, K., Regel, K., & Michaeli, W. (1996). Reprocessing of post-consumer PET by reactive extrusion. Polymer Recycling (UK), 2(4), 251-255.
[20] Pawlak, A., Pluta, M., Morawiec, J., Galeski, A., & Pracella, M. (2000). Characterization of scrap poly (ethylene terephthalate). European polymer journal, 36(9), 1875-1884.
[21] Scheirs J (1998) Polymer recycling, science, technology and application. John Wiley and Sons Ltd
[22] Awaja, F., & Pavel, D. (2005). Recycling of PET. European polymer journal, 41(7), 1453-1477.
[23] Koo, H. J., Chang, G. S., Kim, S. H., Hahm, W. G., & Park, S. Y. (2013). Effects of recycling processes on physical, mechanical and degradation properties of PET yarns. Fibers and Polymers, 14, 2083-2087.
[24] Paci, M., & La Mantia, F. P. (1998). Competition between degradation and chain extension during processing of reclaimed poly (ethylene terephthalate). Polymer Degradation and Stability, 61(3), 417-420.
[25] Villain, F., Coudane, J., & Vert, M. (1995). Thermal degradation of polyethylene terephthalate: study of polymer stabilization. Polymer degradation and stability, 49(3), 393-397.
[26] Demertzis, P. G., Johansson, F., Lievens, C., & Franz, R. (1997). Studies on the development of a quick inertness test procedure for multi-use PET containers—sorption behaviour of bottle wall strips. Packaging Technology and Science: An International Journal, 10(1), 45-58.
[27] Bohre, A., Jadhao, P. R., Tripathi, K., Pant, K. K., Likozar, B., & Saha, B. (2023). Chemical recycling processes of waste polyethylene terephthalate using solid catalysts. ChemSusChem, 16(14), e202300142.
[28] Paszun, D., & Spychaj, T. (1997). Chemical recycling of poly (ethylene terephthalate). Industrial & engineering chemistry research, 36(4), 1373-1383.
[29] Shojaei, B., Abtahi, M., & Najafi, M. (2020). Chemical recycling of PET: A stepping-stone toward sustainability. Polymers for Advanced Technologies, 31(12), 2912-2938.
[30] Abedsoltan, H. (2023). A focused review on recycling and hydrolysis techniques of polyethylene terephthalate. Polymer Engineering & Science, 63(9), 2651-2674.
[31] Bartolome, L., Imran, M., Cho, B. G., Al-Masry, W. A., & Kim, D. H. (2012). Recent developments in the chemical recycling of PET. Material recycling-trends and perspectives, 406, 576-596.

[32] Chandra, R., & Adab, A. (1994). Rubber & Plastic Waste: Recycling, Reuse and Future Demand. CDB Publishers.
[33] Sir Padampat Research Centre, a division of J.K Synthetics Ltd, Kota, India, (1979), Process for the recovery of dimethyl terephthalate from poly (ethylene terephthalate) polymer waste, British Patent 2041916.
[34] Sinha, V., Patel, M. R., & Patel, J. V. (2010). PET waste management by chemical recycling: a review. Journal of Polymers and the Environment, 18(1), 8-25.
[35] Muhs, P., Plage, A., & Schumann, H. D. (1992). Recycling PET bottles by depolymerization. KUNSTSTOFFE-GERMAN PLASTICS, 82(4), 289-292.
[36] Blackmon, K. P.; Fox, D. W.; Shafer, S. J. (1988), Process for Converting PET Scrap to Diamide Monomers. Eur. Patent 365 842,
[37] Conroy, S., & Zhang, X. (2024). Theoretical insights into chemical recycling of polyethylene terephthalate (PET). Polymer Degradation and Stability, 110729.
[38] Gupta, P., & Bhandari, S. (2019). Chemical depolymerization of PET bottles via ammonolysis and aminolysis. In Recycling of polyethylene terephthalate bottles (pp. 109-134). William Andrew Publishing. https://doi.org/10.1016/B978-0-12- 811361-5.00006-7.
[39] Shukla, S. R., & Harad, A. M. (2006). Aminolysis of polyethylene terephthalate waste. Polymer degradation and stability, 91(8), 1850-1854.
[40] Soni, R. K., Dutt, K., Jain, A., Soam, S., & Singh, S. (2009). A novel route of synthesis, characterization of terephthalic dihydrazide from polyethylene terephthalate waste and its application in PVC compounding as plasticizer. Journal of applied polymer science, 113(2), 1090-1096.
[41] Ji, L., Meng, J., Li, C., Wang, M., & Jiang, X. (2024). From Polyester Plastics to Diverse Monomers via Low-Energy Upcycling. Advanced Science, 2403002.
[42] Maurya, A., Bhattacharya, A., & Khare, S. K. (2020). Enzymatic remediation of polyethylene terephthalate (PET)–based polymers for effective management of plastic wastes: an overview. Frontiers in Bioengineering and Biotechnology, 8, 602325.
[43] Cheng, Y., Cheng, Y., Zhou, S., Ruzha, Y., & Yang, Y. (2024). Closed-loop recycling of PET fabric and bottle waste by tandem pre-amorphization and enzymatic hydrolysis. Resources, Conservation and Recycling, 208, 107706.
[44] Carniel, A., de Abreu Waldow, V., & de Castro, A. M. (2021). A comprehensive and critical review on key elements to implement enzymatic PET depolymerization for recycling purposes. Biotechnology Advances, 52, 107811.
[45] Jiang, X., & Bateer, B. (2025). A systematic review of plastic recycling: technology, environmental impact and economic evaluation. Waste Management & Research, 0734242X241310658.
[46] Uekert, T., Singh, A., DesVeaux, J. S., Ghosh, T., Bhatt, A., Yadav, G., & Carpenter, A. C. (2023). Technical, economic, and environmental comparison of closed-loop recycling technologies for common plastics. ACS Sustainable chemistry & engineering, 11(3), 965-978.
[47] Chanda, M. (2021). Chemical aspects of polymer recycling. Advanced Industrial and Engineering Polymer Research, 4(3), 133-150.
[48] Singh, A., Rorrer, N. A., Nicholson, S. R., Erickson, E., DesVeaux, J. S., Avelino, A. F., ... & Beckham, G. T. (2021). Techno-economic, life-cycle, and socioeconomic impact analysis of enzymatic recycling of poly (ethylene terephthalate). Joule, 5(9), 2479-2503.
[49] Kostov, G., Atanassov, A., & Kiryakova, D. (2013). Preparation and characterization of fibers of waste and fresh polyethylene terephtalate and mixtures of them. Fibers and Polymers, 14, 216-222.
[50] Frounchi, M., Mehrabzadeh, M., & Ghiaee, R. (1997). Studies on recycling of poly (ethylene terephthalate) beverage bottles. Iranian Polymer Journal, 6, 269-272.
[51] Elamri, A., Lallam, A., Harzallah, O., & Bencheikh, L. (2007). Mechanical characterization of melt spun fibers from recycled and virgin PET blends. Journal of materials science, 42, 8271-8278.
[52] Abbasi, M., Mojtahedi, M. R. M., & Khosroshahi, A. (2007). Effect of spinning speed on the structure and physical properties of filament yarns produced from used PET bottles. Journal of applied polymer science, 103(6), 3972-3975.
[53] Lee, J. H., Lim, K. S., Hahm, W. G., & Kim, S. H. (2013). Properties of recycled and virgin poly (ethylene terephthalate) blend fibers. Journal of Applied Polymer Science, 128(2), 1250-1256.
[54] He, S. S., Wei, M. Y., Liu, M. H., & Xue, W. L. (2015). Characterization of virgin and recycled poly (ethylene terephthalate) (PET) fibers. The Journal of the Textile Institute, 106(8), 800-806.
[55] Abbasi, M., & Kotek, R. (2019). Effects of drawing process on crimp formation-ability of side-by-side bicomponent filament yarns produced from recycled, fiber-grade and bottle-grade PET. The Journal of the Textile Institute, 110(10), 1439-1444.
[56] Qin, Y., Qu, M., Kaschta, J., & Schubert, D. W. (2018). Comparing recycled and virgin poly (ethylene terephthalate) melt-spun fibres. Polymer Testing, 72, 364-371.
[57] Jiang, Z., Guo, Z., Zhang, Z., Qi, Y., Pu, C., Wang, Q., & Xiao, C. (2019). Preparation and properties of bottle-recycled polyethylene terephthalate (PET) filaments. Textile Research Journal, 89(7), 1207-1214.
[58] Sarioğlu, E., & Kaynak, H. K. (2017). PET bottle recycling for sustainable textiles. Polyester-production, characterization and innovative applications, 5-20.

[59] Özdil, N., & Telli, A. (2013). Properties of the yarns produced from r-PET fibers and their blends. Textile and Apparel, 23(1), 3-10.
[60] Vadicherla, T., & Saravanan, D. (2017). Effect of blend ratio on the quality characteristics of recycled polyester/cotton blended ring spun yarn. Fibres & Textiles in Eastern Europe, 25(2 (122)).
[61] Uyanık, S. (2019). A study on the suitability of which yarn number to use for recycle polyester fiber. The Journal of the Textile Institute, 110(7), 1012-1031.
[62] Sarioğlu, E., Nohut, S., Vuruşkan, D., & Yayla, O. (2020). Production and characterization of recycled polyester (r-PET) blend vortex and ring spun yarns. The Journal of the Textile Institute, 111(12), 1705-1712.
[63] Rajamanickam, S., & Vasudevan, K. (2014). Study of antibacterial activity of chitosan on lyocell and recycled polyester yarns. International Journal of Innovative Research in Science, Engineering and Technology, 3(2), 9480-9486.
[64] Yuksekkaya, M. E., Celep, G., Dogan, G., Tercan, M., & Urhan, B. (2016). A comparative study of physical properties of yarns and fabrics produced from virgin and recycled fibers. Journal of Engineered Fibers and Fabrics, 11(2), 155892501601100209.
[65] Majumdar, A., Shukla, S., Singh, A. A., & Arora, S. (2020). Circular fashion: Properties of fabrics made from mechanically recycled poly-ethylene terephthalate (PET) bottles. Resources, Conservation and Recycling, 161, 104915.
[66] Sanches, R. A., Takamune, K. M., Guimarães, B. M. G., Seawright, R. A., Karam Jr, D., Marcicano, J. P. P., ... & Dedini, F. G. (2015). Comparative study of the characteristics of knitted fabrics produced from recycled fibres employing the chauvenet criterion, factorial design and statistical analysis. Fibres & Textiles in Eastern Europe, (4 (112), 19-24.
[67] Telli, A., & Özdil, N. (2015). Effect of recycled PET fibers on the performance properties of knitted fabrics. Journal of Engineered Fibers and Fabrics, 10(2), 155892501501000206.
[68] Telli, A., & Babaarslan, O. (2016). Commercialized denim fabric production with post-industrial and post-consumer wastes. Textile and Apparel, 26(2), 213-220.
[69] Albini, G., Brunella, V., Placenza, B., Martorana, B., & Guido Lambertini, V. (2019). Comparative study of mechanical characteristics of recycled PET fibres for automobile seat cover application. Journal of Industrial Textiles, 48(6), 992-1008.
[70] Inoue, M., & Yamamoto, S. (2004). Performance and durability of woven fabrics including recycled polyester fibers. Journal of Textile Engineering, 50(2), 25-30.

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Petri Nets to Ladder Diagrams Translation for Textile Chemical Mixing Application

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Abstract :

This paper presents a novel method for translating Petri Nets, a formal language for modeling concurrent systems, into Ladder Diagrams, the graphical programming language used in Programmable Logic Controllers, specifically for textile chemical mixing applications. This addresses the challenge of efficiently implementing complex control logic, particularly in industrial automation scenarios. The proposed two-phase method first converts the PN model into a State Transition Diagram, simplifying the subsequent translation to LD. The second phase maps the STD onto an LD using rules that maintain system behavior consistency. This approach is particularly relevant to the textile industry, where precise and automated control of chemical mixing processes is crucial for consistent product quality and efficient production. The effectiveness of this method is demonstrated through a case study of a textile chemical mixing application, where accurate mixing ratios and timing are critical. The results show that the generated LD accurately reflects the PN model, ensuring reliable and predictable control of the chemical mixing process. This automated approach improves the precision and efficiency of textile chemical mixing, minimizing errors and optimizing resource utilization. The proposed method offers a practical and efficient solution for implementing automated control systems in textile chemical mixing processes, contributing to enhanced quality control and improved productivity in the textile industry. This approach significantly reduces development time and potential errors, ensuring consistency between design and implementation, leading to more reliable and efficient PLC-based control systems.

Keywords: *Industrial Automation, Petri net, PLC, Textile Chemical Mixing, Translation*

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1. Introduction

Programmable Logic Controllers have become integral to modern textile manufacturing, driving significant advancements in automation, efficiency, and product quality. Their capacity to precisely control complex processes, flexibility, and data acquisition capabilities have revolutionized various stages of textile production, from fiber preparation to finishing. PLCs automate intricate sequences, managing parameters like temperature, pressure, speed, and timing, thereby minimizing human error and ensuring consistent product quality. This automation translates to faster production cycles, reduced downtime, and minimized material waste, ultimately leading to increased output and lower operating costs. The precise control offered by PLCs ensures uniformity in processes such as dyeing and finishing, resulting in consistent fabric properties and improved finished product quality. Their adaptability allows for seamless reprogramming to accommodate changing production needs, enabling manufacturers to switch between product lines swiftly, adopt new technologies, and respond to market demands. Furthermore, PLCs facilitate data acquisition from various sensors and actuators, providing valuable insights into process performance, which can be leveraged for optimization, predictive maintenance, and quality control. This data-driven approach further enhances efficiency and reduces costs. The ability of PLCs to integrate with other systems, such as SCADA and ERP, allows for centralized monitoring and control of the entire manufacturing process, from raw material procurement to finished product delivery.

In the specific context of textile processes, PLCs play a crucial role in various stages:

Spinning: PLCs control the speed, tension, and yarn properties during the spinning process, ensuring consistent yarn quality and minimizing defects. They manage the complex interactions of various spinning machines, optimizing fiber alignment and yarn strength.

- Weaving: In weaving, PLCs control loom operations, pattern selection, and fabric density. They manage the intricate movements of the loom, ensuring precise weft insertion and consistent fabric structure. This automation reduces weaving defects and improves fabric quality.

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- Dyeing: PLCs precisely control temperature, pH, and dye concentration during the dyeing process, ensuring uniform color and shade across the fabric. They manage the dye liquor mixing and application, minimizing variations and improving color reproducibility.

- Finishing: PLCs automate coating, drying, and curing processes in textile finishing, ensuring uniform application of finishes and consistent finish quality. They control the parameters of these processes, optimizing fabric properties such as water resistance and wrinkle resistance.

- Material Handling: PLCs control automated guided vehicles and conveyor systems, optimizing material flow and minimizing handling time. They manage the movement of materials throughout the textile plant, improving logistics and reducing production bottlenecks.

Petri Nets (PN) and Ladder Diagrams (LD) are widely used in industrial automation control. PN is a formal modeling language that provides a graphical representation of concurrent systems. LD is a graphical programming language used in programmable logic controllers (PLCs) to control industrial processes. PN and LD have different characteristics, and translating PN into LD is a challenging task. This paper proposes a method for translating PN into LD for industrial automation control.

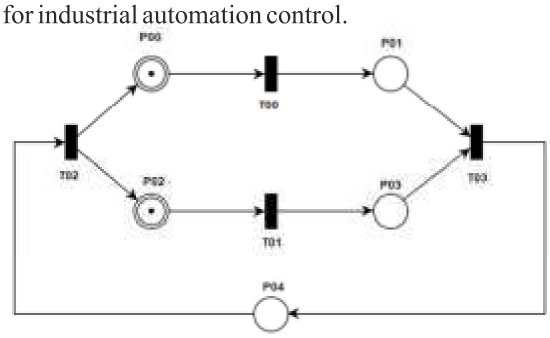


Figure 1 - Simple Petri net

Petri nets as shown in Fig 1 are a mathematical modeling language used to represent and analyse concurrent systems. They were invented by Carl Adam Petri in the 1960s and have since been widely used in various fields, including computer science, control systems, and manufacturing.

In control systems, Petri nets provide a formal and graphical way to model and analyse the behavior of complex systems, including discrete event systems and concurrent systems. They can be used to model the interaction between different components of a system and their state transitions.

Petri nets have several benefits in the context of control system design, verification, and validation. These benefits include:

i. Formalism: Petri nets provide a formal way to represent and analyse systems, which means that the system behavior can be precisely defined and verified.

ii. Visualization: Petri nets provide a graphical representation of the system, which makes it easier to understand and communicate the system's behavior.

iii. Model Checking: Petri nets can be used for model checking, which is a formal method for verifying the correctness of a system model with respect to a set of properties. Model checking can help identify errors and inconsistencies in the system design early in the development process.

iv. Validation and Verification: Petri nets can be used for system validation and verification, which involves checking that the system meets its functional and performance requirements. This can be achieved by simulating the Petri net model and testing it against various scenarios and use cases.

v. Complexity Reduction: Petri nets can be used to model complex systems simply and concisely, which can help reduce the complexity of the system design and make it more manageable.

In summary, Petri nets are an important tool in control system design, verification, and validation. They provide a formal and graphical way to model and analyse complex systems, and they can help identify errors and inconsistencies early in the development process. They are also useful for system validation and verification and can help reduce the complexity of the system design.

Ladder logic programming plays a crucial role in controlling and automating textile machinery and processes. Its graphical nature, resembling relay logic diagrams, makes it easily understandable and maintainable for technicians and engineers familiar with electrical circuits. In the textile industry, ladder logic is used to program Programmable Logic Controllers, which are industrial computers that control various aspects of textile production. These applications range from simple tasks like controlling individual motors or valves to complex operations such as managing entire production lines. For instance, in a weaving machine, ladder logic can control the movement of the warp and weft threads, the operation of the heddles and reed, and the speed of the machine. In a dyeing machine, it can control the temperature, pressure, and flow of dyes and chemicals, ensuring consistent color and quality. Similarly, in a spinning machine, ladder logic can control the speed of the rollers, the tension of the yarn, and the winding process.

The benefits of using ladder logic in textile automation are numerous. It simplifies complex control tasks, making them easier to implement and troubleshoot. The graphical representation allows for quick identification of issues and facilitates modifications to the program. Moreover, ladder logic is a robust and reliable programming language, well-suited for the harsh industrial environments found in textile mills. It can handle a wide range of input and output signals, including digital and analog sensors, actuators, and communication interfaces. This flexibility makes it adaptable to various textile machinery and processes. Furthermore, ladder logic supports various programming constructs, such as timers, counters, and mathematical functions, enabling the implementation of sophisticated control algorithms. These algorithms can optimize production efficiency, reduce waste, and improve product quality. For example, a PLC programmed with ladder logic can monitor the tension of the yarn during spinning and adjust the roller speed accordingly, preventing yarn breakage and ensuring uniform yarn thickness. In addition, ladder logic can be used to implement safety features, such as emergency stops and interlocks, protecting both personnel and equipment. Overall, ladder logic programming is an essential tool for automating textile machinery and processes, contributing to increased productivity, improved quality, and enhanced safety in the textile industry.

Several programming languages can be used to program a PLC, including:

i. Ladder Logic (LD) - This language is based on the use of symbols that resemble the rungs of a ladder, and is one of the most widely used programming languages for PLCs.

ii. Function Block Diagram (FBD) - This language uses graphical symbols to represent functions and connections between them, allowing for more complex and modular programming.

iii. Structured Text (ST) - This language is similar to traditional computer programming languages and uses textual statements to create logic and functions.

iv. Instruction List (IL) - This language uses a list of instructions to create logic and functions, and is often used for smaller, less complex programs.

Several standards govern the use of PLC programming languages, including IEC 61131-3 - This standard defines the basic programming languages used for industrial automation and control systems, including Ladder Logic, Function Block Diagram, Structured Text, and Instruction List.

Overall, the choice of programming language and adherence to programming standards depends on the specific application and requirements of the industrial automation or control system being developed.

A ladder program as shown in Fig 2 is a type of programming language commonly used in industrial automation and control systems. The program is written in a graphical format resembling a ladder, where the rungs of the ladder represent the logical operations and the inputs and outputs are connected to the sides of the ladder.

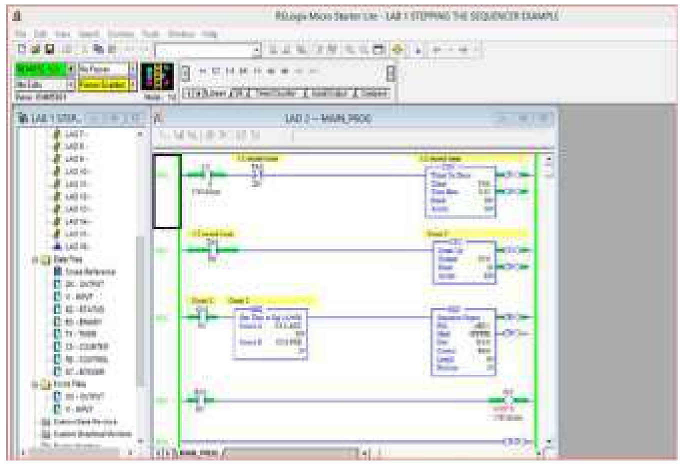


Figure 2 - PLC Ladder Program

Verification and model checking are important aspects of ladder programming to ensure the correct behavior of the control system. Verification involves analyzing the program to ensure that it meets the specified requirements and standards. This can be done manually or through the use of software tools that check the program's syntax, data types, and logical operations.

Model checking is a more advanced verification technique that uses mathematical models to check the program's behavior against a set of requirements or specifications. This involves creating a model of the system's behavior and checking whether the ladder program satisfies the desired properties. Model checking can detect potential errors and verify that the system will behave correctly under different conditions and inputs.

Overall, ladder programming is a powerful tool for controlling and automating industrial processes. Proper verification and model checking can help ensure the correctness and reliability of the control system, reducing the risk of accidents and improving overall performance. This paper is organized into sections covering the introduction, followed by a literature review, methodology of translation, implementation in TIA Portal, results of the approach, and a concluding discussion.

2. Literature Review

Petri Nets and Ladder Diagrams are two common formal languages used in industrial control systems. Petri Nets are used for modeling discrete event systems, while Ladder Diagrams are used for programming programmable logic controllers (PLCs). Several studies have been conducted on the translation of Petri Nets to Ladder Diagrams. In this literature review, we will summarize some of the key findings from these studies.

(Sener et al., 2022) details the integration of a PLC-based automation system in a textile dye dosing machine and its associated environmental system design. The study aimed to improve the dyeing process by automating the alkaline dosage, eliminating manual preparation, and enabling computer-controlled dye solution preparation. This automation ensures the dye mixture is prepared on demand, reducing preparation time and chemical waste. The system also monitors the viscose paint level and automatically replenishes it, preventing deterioration and minimizing operator workload. The primary objectives were to achieve an uninterrupted dyeing process, eliminate dye/chemical waste, and reduce unit costs while increasing production. The automated system prevents the mixing of chemicals, soda, and paint until required, storing them separately and dosing them into mixing tanks as needed. This precise dosing prevents the deterioration of the main solution and ensures consistent dyeing quality. The mechanical design was done using AutoCAD, and the prototype was assembled sequentially. The results demonstrated improved production amounts and reduced chemical waste, highlighting the environmental and economic benefits of the automated system. The study concludes that the automated system significantly improves the efficiency and sustainability of the textile dyeing process [1].

Factory automation, a rapidly evolving field, offers sustainable growth potential in today's industrial landscape. Its advantages include reduced labor dependency and enhanced process precision and accuracy. PLC-equipped automation projects aim to minimize operational costs. The dyeing industry, with its complex and multi-stage processes, stands to benefit significantly from such automation. Implementing these systems can address challenges like labor costs during periods of low order volume. In a PLC-driven automated system, all machinery is interconnected and monitored via IoT, enabling real-time control and oversight. This approach is exemplified by a prototype model developed for automating and controlling textile dyeing processes using PLC and IoT technologies. Dyeing involves rolling fabric onto a winch dyeing machine and gradually transferring dyes under controlled temperature conditions. Key machinery includes the winch dyeing machine and the boiler. The winch's rotating rod is activated by a motor, while solenoid valves control the flow of feed water and hot water based on pre-set values. This project automated the entire system using a PLC, with a level sensor monitoring the dyebath level in real time and transmitting data to the cloud. This automation enhances precision, accuracy, and real-time plant monitoring within the dyeing industry [2].

This paper presents a novel approach to applying model-checking techniques to industrial-sized PLC programs, addressing the challenge of verifying complex control systems. Traditional model-checking methods often struggle with the state explosion problem, making them impractical for large-scale industrial applications. The authors propose a method that combines static analysis with symbolic model checking to overcome this limitation. The approach involves extracting a control flow graph from the PLC program and using static analysis to identify relevant variables and their potential values. This information is then used to create a symbolic representation of the system's state space, significantly reducing the number of states that need to be explored during model checking. The authors demonstrate the effectiveness of their method by applying it to several real-world industrial PLC programs, including a control system for a chemical mixing process and a safety system for a railway crossing. The results show that their approach can successfully verify these complex systems, identifying potential errors and inconsistencies that would be difficult to detect using traditional testing methods. The proposed method offers a practical and scalable solution for verifying industrial-sized PLC programs, contributing to the development of more reliable and safe control systems. Furthermore, the paper discusses the challenges and limitations of applying model checking to industrial systems, such as dealing with incomplete or inaccurate specifications and handling the complexity of real-world environments. The authors also suggest future research directions, including exploring different symbolic representations and developing more efficient model checking algorithms. Overall, the paper provides valuable insights into the application of formal verification techniques to industrial control systems, paving the way for more robust and dependable automation solutions [3].

One of the earliest studies on Petri Net to Ladder Diagram translation was conducted by Shao et al. in 2001. The authors proposed a method for translating Petri Nets into Ladder Diagrams, which involved constructing a state table from the Petri Net and then using the state table to generate the Ladder Diagrams. The method was tested on several case studies and was found to be effective [4].

In 2006, Li et al. proposed another method for translating Petri Nets to Ladder Diagrams, which was based on a hierarchical structure of Petri Nets. The authors used a transformation algorithm to convert the Petri Net into a state graph and then used the state graph to generate the Ladder Diagrams. The method was tested on a case study and was found to be effective [5].

In 2015, Fuchs et al. proposed a method for translating colored Petri Nets into Ladder Diagrams, which was based on a formal model of Petri Nets. The authors used a transformation algorithm to convert the Petri Net into a hierarchical structure and then used the hierarchical structure to generate the Ladder Diagrams. The method was tested on several case studies and was found to be effective [6].

In 2019, Zhang et al. proposed a method for translating high-level Petri Nets into Ladder Diagrams. The authors used a transformation algorithm to convert the high-level Petri Net into a hierarchical structure and then used the hierarchical structure to generate the Ladder Diagrams. The method was tested on a case study and was found to be effective [7].

In 2021, Bhardwaj et al. proposed a method for translating timed Petri Nets to Ladder Diagrams, which was based on the concept of time abstraction. The authors used a transformation algorithm to convert the timed Petri Net into a time-abstracted Petri Net and then used the time-abstracted Petri Net to generate the Ladder Diagrams. The method was tested on a case study and was found to be effective [8].

This paper (Petri Net Markup Language: Implementation and Application) discusses the Petri Net Markup Language from two perspectives. First, it describes PNML's implementation within the PEP tool, enabling Petri net exchange with other tools. Second, it presents a translator from PNML to Scalable Vector Graphics for web-based display. The authors explore PNML's benefits and drawbacks, proposing extensions for tool-specific needs. They also detail converting PNML files, enhancing PEP's integration with other Petri net tools [9].

Overall, the studies reviewed here demonstrate that there are various methods for translating Petri Nets into Ladder Diagrams, and that these methods can be effective in generating correct and efficient Ladder Diagrams from Petri Nets. However, the choice of method depends on the specific application and the requirements of the industrial control system being developed. There is a need for a method that streamlines the implementation of control logic designed in PNs, directly impacting industrial automation development. This contributes to a more efficient and robust design process for PLC-based control systems.

3. Methodology

The authors propose a two-phase method for PN to LD translation. In the first phase, the PN is transformed into a State Transition Diagram (STD) to simplify the translation process. In the second phase, the STD is mapped onto LD using a set of rules that preserve the system behaviour.

The proposed method for translating Petri Nets (PN) into Ladder Diagrams (LD) for industrial automation control consists of two main phases: PN to State Transition Diagram (STD) and STD to LD.

- **Phase 1:** PN to STD Petri Nets (PN) can represent concurrent systems with multiple processes that interact with each other. However, PN models can be complex and difficult to translate into industrial automation control languages such as Ladder Diagrams (LD). Therefore, the first phase of the proposed method is to transform the PN into a State Transition Diagram (STD) to simplify the translation process.

To achieve this, the authors use an algorithm to transform the PN into the STD. The algorithm involves identifying the places and transitions in the PN and creating a set of states for the STD. The transitions between these states are defined based on the PN. If necessary, additional states and transitions are added to ensure that the resulting STD is a valid representation of the PN.

The resulting STD is a simplified representation of the PN that preserves its essential structure and behaviour. The use of STD as an intermediate step helps to reduce the complexity of the translation process and improve the accuracy of the translated LDs.

- **Phase 2:** STD to LD in the second phase, the STD is mapped onto LD using a set of rules that preserve the system behaviour. The authors define a set of rules for this purpose, which takes into account the structure and semantics of LD. The rules ensure that the translated LDs accurately represent the STD and preserve the essential behaviour of the system.

The mapping process involves mapping each state in the STD onto a corresponding set of LD instructions. The instructions define the behaviour of the system in that particular state. Similarly, each transition in the STD is mapped onto a corresponding set of LD instructions that define the behaviour of the system during the transition.

If necessary, additional instructions are added to ensure that the resulting LDs are a valid representation of the STD. The resulting LDs are correct and consistent with the original PN model. The use of rules and guidelines ensures that the translated LDs are accurate and efficient representations of the original PN model.

In conclusion, the proposed method provides an effective solution for translating PN into LD for industrial automation control. The use of an intermediate STD helps to simplify the translation process and improve the accuracy of the translated LDs. The use of rules and guidelines ensures that the translated LDs are accurate and efficient representations of the original PN model.

Translating industrial automation control logic from state transition diagrams to Petri nets or ladder diagrams can offer several advantages:

a) Visual Clarity and Understanding: Petri nets and ladder diagrams provide clear visual representations of control logic, which can aid in understanding complex systems. State transition diagrams can be translated into these formats to make the logic easier to comprehend for engineers and technicians.

b) Formal Analysis: Petri nets offer a formalism that enables rigorous analysis of system behavior, including deadlock detection, reachability analysis, and performance evaluation. This can help identify potential issues in the control logic before implementation.

c) Flexibility and Modifiability: Both Petri nets and ladder diagrams allow for easy modification and iteration of control logic. Changes can be made to the diagrams without extensive reworking, enabling quick adjustments to accommodate new requirements or optimize existing processes.

d) Simulation and Validation: Petri nets can be simulated to verify the correctness of control logic and ensure that it behaves as intended. Simulation can identify potential problems or unintended consequences before deploying the control logic in a real-world environment.

e) Scalability: Petri nets can model complex systems with multiple concurrent processes and interactions, making them suitable for large-scale industrial automation applications. They can handle the complexity of state transition diagrams more effectively than ladder diagrams, especially in systems with numerous states and transitions.

f) Standardization and Documentation: Ladder diagrams are widely used in industrial automation and are well-understood by engineers and technicians. Translating state transition diagrams to ladder diagrams can leverage existing standards and documentation practices, streamlining communication and maintenance processes.

g) Integration with PLC Programming: Ladder diagrams are commonly used for programming programmable logic controllers (PLCs) in industrial automation. Translating control logic from state transition diagrams to ladder diagrams facilitates direct implementation in PLC programming environments, reducing the effort required for development and deployment.

By translating control logic from state transition diagrams to Petri nets or ladder diagrams, industrial automation systems can benefit from improved clarity, formal analysis capabilities, flexibility, scalability, and integration with existing practices and technologies.

4. Textile Chemical mixing Application: A case study

The dyeing process in the textile industry is a critical operation that imparts color to fabrics, requiring precise control over chemical mixing, temperature, and timing to achieve consistent and high-quality results. The process begins with the preparation of the dye bath, where chemicals and dyes are mixed in specific proportions to create the desired color and ensure proper fixation on the fabric. Chemical mixing is a highly controlled batch process, often automated using Programmable Logic Controllers (PLCs) to ensure accuracy and repeatability. The dye bath typically consists of water, dyes, and auxiliary chemicals such as leveling agents, dispersing agents, pH regulators, and fixing agents. Each chemical plays a specific role; for instance, leveling agents ensure uniform dye distribution, while pH regulators maintain the optimal pH level for dye fixation. The mixing process involves adding these chemicals in a predefined sequence and quantity, often guided by a recipe that accounts for the type of fabric, dye, and desired color shade. Automated systems, such as PLCs, control the addition of chemicals using pumps and valves, while sensors monitor parameters like temperature, pH, and chemical concentration to ensure consistency. Once the dye bath is prepared, the fabric is immersed in the solution, and the dyeing process begins. The temperature of the dye bath is gradually increased to a specific level, often between 50°C to 130°C, depending on the type of dye and fabric. This temperature control is crucial, as it affects the rate of dye absorption and fixation. During the dyeing process, the fabric is agitated to ensure even exposure to the dye bath, and the system continuously monitors and adjusts parameters to maintain optimal conditions. After the dyeing cycle is complete, the fabric undergoes rinsing and washing to remove excess dye and chemicals, followed by drying and finishing. The chemical mixing process is integral to the success of the dyeing operation, as even minor deviations in chemical composition or mixing sequence can lead to defects such as uneven dyeing, color fading, or poor wash fastness. Automation and advanced modeling tools, such as Petri Nets, are increasingly used to optimize the chemical mixing process, ensuring precise control, reducing human error, and improving efficiency. By leveraging these technologies, textile manufacturers can achieve consistent dye quality, reduce resource wastage, and enhance overall productivity, making the dyeing process a cornerstone of high-quality textile production.

Here's a simple example of how the proposed method can be used to translate a Petri Net model of a Mixer control system as shown in Fig 3 into a Ladder Diagram program.

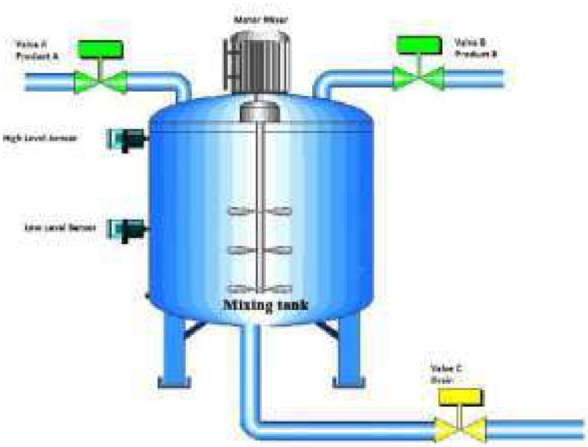


Figure 3 - Mixer Control Process

The mixer machine is made up of a mixer (Motor A), two separate product valves (A and B), and a drain valve (Valve C). Pressing a Start Push-Button will start the operation and open two product valves till the high-level sensor shows entire tank is full. The drain valve ought to be left open once the tank has been filled and the mixer turned on for 10 seconds after that, until the low-level sensor sounds an alarm.

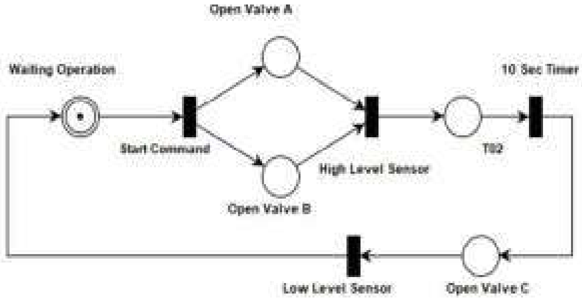


Figure 4 - Petri net for Mixer Control Process

Phase 1: PN to STD - The first phase involves transforming the Petri Net model into a State Transition Diagram (STD). The transformation algorithm involves identifying the places and transitions in the Petri Net model and creating a set of states for the STD. The resulting STD for this example is shown below fig. 5.

Formulating the steps and transitions and foreseeing any potential incoherence need building the state machine diagram. The chemical mixer state machine should encompass the starting state, tank filling, mixing, and draining of the mix. While the activities of each step should encompass the outputs and program logic instructions to interact with the system, every transition condition should be the requirements required for the machine to advance.

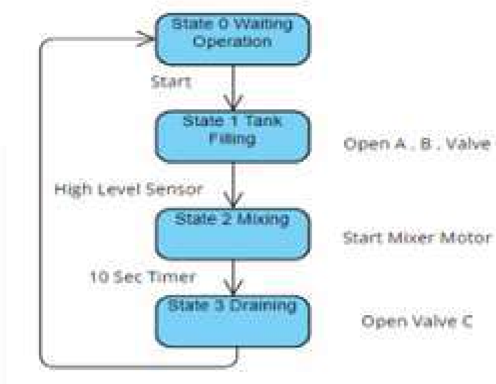


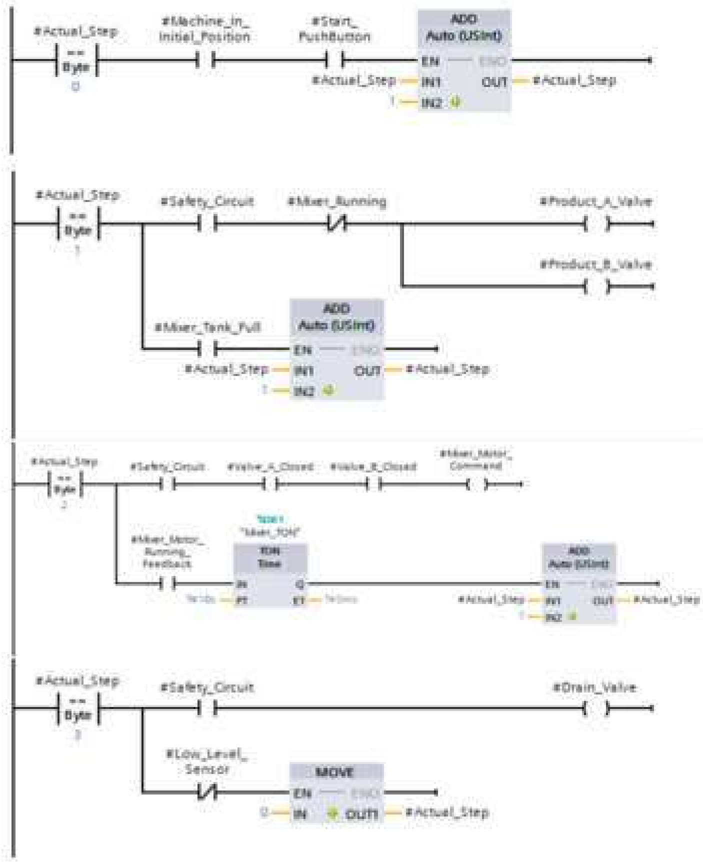
Figure 5 - State Transition diagram

Phase 2: The second phase of the process translates the State Transition Diagram into Ladder Diagram instructions. This involves mapping each state and transition in the STD to corresponding sets of LD instructions.

A generic state machine template is used to program each step, its associated actions, and transitions within the ladder logic. The initial step represents an idle state with no actions and a single condition: the start command.

Upon receiving the start command, the machine transitions to the filling phase. This step activates both product valves, opening them until a high-level sensor signal indicates completion and triggers the next step.

In the subsequent step, the valve open commands are deactivated. The mixer motor is then activated for a predetermined time. A 10-second timer serves as the transition condition, moving the machine to Step 3 after the mixing duration. The final phase opens the drain valve. This valve remains open until a low-level sensor signal indicates completion, signifying the end of the process. The machine then returns to the idle state, awaiting the next start command.



Process

This Ladder Diagram program as shown in Fig 6 accurately represents the Petri Net model of the conveyor system and preserves its essential behavior [10].

In conclusion, the proposed method provides a simple and effective solution for translating Petri Net models of industrial automation systems into Ladder Diagram programs.

The automatic generation of ladder logic programs from a state machine description via a translation tool represents a significant advancement in programming environments.

Typically, these environments facilitate the importation of textual ladder logic code, enabling the generation of project files from high-level descriptions. The input to this translation tool must include a formalized state logic description, encompassing distinct sections for states, events, and transition conditions.

The translation tool enhances productivity by automating routine tasks associated with ladder logic generation. It offers a high-level language that abstracts underlying implementation details, supports symbolic programming, automatic tag address assignment, and compatibility with standard text editing tools. Furthermore, it performs comprehensive error and consistency checks, supports custom ladder logic entries, and ensures the generation of accurate state transition code. This structured methodology, when applied to sequential control logic, provides a standardized development approach, fostering productivity and improved documentation.

4.1 Exploring the Benefits of Using a Translator for Ladder Logic Implementation

While delving into ladder logic implementation, you might find yourself facing a myriad of details and complexities. Fortunately, utilizing a translator can significantly ease this burden, offering a range of benefits that streamline the process and enhance efficiency. Let's delve into the advantages:

a. **Simplified Language**
   A translator provides a high-level, problem-oriented language that effectively conceals the intricate details of the underlying ladder logic implementation. This abstraction makes it easier for users to grasp and work with the logic without getting bogged down in technical minutiae.

b. **Symbolic Programming Environment**
   One of the key benefits is the provision of a pure symbolic programming environment. This environment allows users to focus on the logic itself, rather than getting entangled in the complexities of memory management. Moreover, the tool enables the allocation of variables to memory addresses, facilitating seamless operation.

c. **Auto Address Assignment**
   The translator simplifies the process of tag management by offering auto address assignment for tags. In cases where an address is omitted, the translator automatically assigns the next available address to the tag, reducing the need for manual intervention and streamlining workflow.

d. **Text-Based Editing**
   Since the translator operates textually, users can edit the high-level description using typical text editing and manipulation tools. This flexibility empowers users to make quick edits and revisions, enhancing overall productivity and facilitating collaboration.

e. **Error and Consistency Checks**
   One of the critical functions performed by the translator is conducting a set of error and consistency checks on the state transition specification. This ensures that the logic remains robust and error-free, minimizing the risk of system failures and enhancing reliability.

f. **Support for Special Cases**
   The translator accommodates special or unusual cases by permitting direct entry of ladder logic code in its textual format. This feature allows users to handle unique requirements and customize the logic for specific situations, increasing its overall flexibility and adaptability.

4.2 Code Generation

Perhaps one of the most significant advantages is the translator's ability to generate correct state transition code. This alleviates the burden of manual coding, ensuring accuracy and efficiency in the implementation process. Additionally, any changes to the underlying ladder logic implementation can be seamlessly accommodated by modifying the translator, preserving existing user application work.

4.3 Extensibility

The translator offers room for growth and expansion by allowing additional features to be incorporated, such as file inclusion and free-form commenting. This extensibility ensures that the tool remains relevant and adaptable to evolving needs, providing long-term value to users.
In conclusion, leveraging a translator for ladder logic implementation offers a plethora of benefits, ranging from simplified language and symbolic programming to error checking and extensibility. By harnessing the power of this tool, users can streamline their workflow, enhance efficiency, and ensure the robustness of their logic implementation.

5. Conclusion

In conclusion, this paper proposed a method for translating Petri Nets into Ladder Diagrams for industrial automation control. The proposed method includes two main phases: PN to State Transition Diagram and STD to LD. The method was tested using a case study of a conveyor system, and the results showed that the translated LDs were correct and consistent with the PN model. Petri Nets and Ladder Diagrams are important tools in industrial control systems, and the proposed method provides a way to bridge the gap between the two languages. Proper verification and model checking can help ensure the correctness and reliability of the control system, reducing the risk of accidents and improving overall performance. In the future, this translation process can be automated to reduce the time required for conversion.

6. Conflicts of interest

The authors declare no conflicts of interest.

References:

[1] A. Sener, D. D. Koc, K. Yilmaz, and T. Demirdelen, “PLC-BASED AUTOMATION SYSTEM INTEGRATION IN TEXTILE DYE DOSING MACHINE AND ENVIRONMENTAL SYSTEM DESIGN.” Jun. 2022

[2] M. Thangatamilan, S. J. Suji Prasad, C. Sagana, R. Subikshaa, D. P. Kumar and M. M. Shimak, "Automation and Control Mechanism For Textile Dyeing Process Using PLC and IoT," 2023 International Conference on Circuit Power and Computing Technologies (ICCPCT), Kollam, India, 2023, pp. 485-490, doi: 10.1109/ICCPCT58313.2023.10244880

[3] B. F. Adiego et al., “Applying Model Checking to Industrial-Sized PLC Programs,” Dec. 01, 2015, Institute of Electrical and Electronics Engineers. doi: 10.1109/tii.2015.2489184

[4] Shao, S., Zhang, Y., & Ji, Z. (2001). A method for translating petri nets to ladder diagrams. In Proceedings of the 2001 IEEE International Conference on Systems, Man, and Cybernetics (Vol. 2, pp. 1289-1294). IEEE

[5] Li, J., Hu, Y., & Li, Y. (2006). A method for translating Petri nets into ladder diagrams. In Proceedings of the 2006 IEEE International Conference on Automation and Logistics (pp. 1585-1590). IEEE

[6] Fuchs, M., Langer, T., & Wortmann, A. (2015). Translation of colored Petri nets into ladder diagrams. In Proceedings of the 2015 IEEE 13th International Conference on Industrial Informatics (pp. 1152-1157). IEEE

[7] Zhang, Y., Yang, Z., Hu, X., & Ma, Y. (2019). Translation from high-level petri nets to ladder diagrams based on transformation rules. IEEE Access, 7, 140711-140719

[8] Bhardwaj, R., Sinha, A., & Biswas, S. (2021). Translating timed petri nets to ladder diagrams using time abstraction. IEEE Transactions on Automation Science and Engineering, 18(2), 581-592

[9] C. Stehno, “Petri net markup language: implementation and application” Jan. 01, 2002. Accessed: Aug. 13, 2024. [Online]. Available: http://ceur-ws.org/Vol-65/02stehno.pdf

[10] Letácio Lins (no date) Programming a State Machine in Ladder Logic, www.solisplc.com.Available at: https://www.solisplc.com/tutorials/programming-a-state-machine-in-ladder-logic (Accessed: Jan 15, 2025).

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A Study of Impulse Buying Behavior in Fashion and Beauty Among Young Adults

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Abstract:

This paper aimed to identify the impact of promotion-driven purchases (PDP) and peer influence-driven purchases (PIDP) on impulse buying behaviour for fashion beauty products among young consumers. The study was performed among 259 consumers aged in between 18-30 across India, using a structured questionnaire developed based on existing literature. SPSS software was used to analyze the research findings. The data was analyzed using factor analysis, correlation, and regression tests. The findings of the study reveal that promotion-driven purchases have a significant impact whereas peer influence-driven purchases have an insignificant impact on young consumers' impulse buying behaviour for fashion beauty products. This study also investigates the importance of PDP and PIDP and how retailers can improve their marketing strategies using these factors in order to boost impulse buying behaviour for beauty products among young consumers.

Keywords: *Impulse Buying Behaviour, Promotions, Peer Influence, Young Consumers*

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1. Introduction

Knitted The Indian beauty and personal care industry is a rapidly growing sector that encompasses a wide range of products and services. The industry includes skincare, hair care, colour cosmetics, fragrances, personal care products, and more. Skincare is the largest segment within the Indian beauty and personal care market, accounting for 33.6% of the market in 2022. One of the key drivers of growth in the Indian beauty and personal care industry is the rise of the middle class. With increasing disposable incomes, consumers are now able to spend more on personal grooming and fashion beauty products. Additionally, the growth of e-commerce has made it easier for consumers to access a wide range of beauty products, regardless of their geographic location. The industry has been growing rapidly over the past years. According to a report by market research firm, IMARC Group, the size of the Indian beauty and personal care industry was US$ 26.3 Billion in 2022. The report also predicts that the industry will reach a value of US$ 38.0 Billion by 2028, growing at a compound annual growth rate (CAGR) at 6.45% during the forecast period 2023-28. Impulse buying is a significant contributor to sales across a variety of product categories [1- 2]. The possibility of consumers making impulsive purchases can be further boosted by the existence of certain elements, such as online and teleshopping channels, as well as 24-hour convenience stores, as these will offer consumers accessibility and convenience for making purchases at any time [3]. Numerous social and psychological variables have been examined in connection to their impact on impulsive purchasing. Low price, minimal necessity for the item, self-service, and small size or light weight are the main elements that might be cited as causes of impulsive buying [4]. The personality factors that have an impact on a consumer's propensity to make impulsive purchases are lack of self-control, degree of reactivity, and absorption of stress [5]. Due to their increasing spending power and the relatively cheap availability of credit cards, young consumer groups have earned substantial prominence from marketers. Therefore, it is worthwhile to conduct research on the purchasing habits of young consumers, a significant segment of the youthful customer group. Retailers look for factors that affect customers' inclinations and decisions to make impulsive purchases and aim to regulate these factors through strategic marketing and merchandising activities [6].

The aim of this study is to determine the relationship between young consumers' impulsive buying behaviour of fashion beauty products and the external factors that lead to this behaviour. The external factors that are studied in this research are promotion-driven purchases (PDP) and peer influence-driven purchases (PIDP). Therefore, this study has two main objectives:

- To examine the impact of promotion-driven purchases (PDP) on the impulse buying behaviour of young consumers for fashion beauty products.
- To evaluate the impact of peer influence-driven purchases (PIDP) on the impulse buying behaviour of young consumers for fashion beauty products.

Impulse Buying

"Impulse buying has been considered a pervasive and distinctive phenomenon in the American lifestyle and has

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been receiving increasing attention from consumer researchers and theorists" [5]. Despite the negative aspects of impulsive buying behaviour, which is defined as irrational behaviour due to a lack of behavioural control [6], in previous research, impulse purchases still account for significant sales in a variety of product categories [1, 2]. The five steps of the customer purchasing process created by Churchill and Peter [7] are need awareness, information search, alternative evaluation, purchase decision, and post-purchase evaluation. When a need is recognized, the process of buying begins. This desire for recognition may be triggered by an internal feeling or by external stimuli encouraging a purchase. Consumers begin seeking out information when their motivation comes from identifying needs. Consumers assess options for meeting needs based on the information. After weighing their options, customers could choose to buy. After weighing their alternatives, customers might buy something. Finally, after purchasing a product, customers assess it explicitly or informally. This stage deals with the effects of the purchase and customer satisfaction; if the customer had a good experience, she or he may develop loyalty to the retailer. As customers feel a need for certain products, the process is repeated.

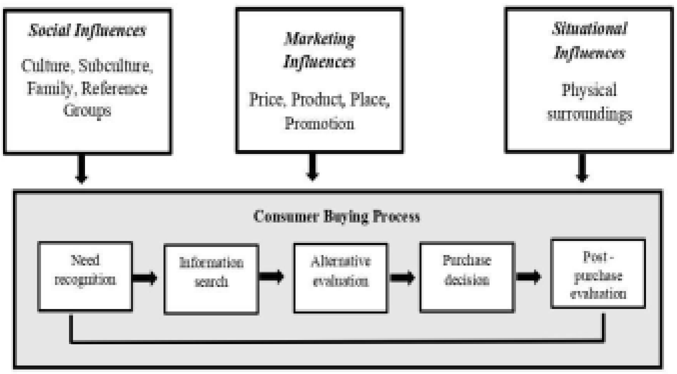

Figure 1: A model of consumer buying process Source: Adapted from Churchill & Peter (1998) [7]

Stern [8] distinguished between planned and unplanned purchasing behaviour. This classification holds that planned purchasing behaviour entails a time-consuming information search followed by logical decision-making [4, 8], a procedure close to that outlined in Churchill and Peter's [7] model. All purchases performed without such extensive planning are referred to as unplanned purchases, including impulse buying, which can be distinguished by the relatively quick decision-making that is prompted by stimuli. As fulfilment may come from the act of shopping itself, impulsive purchases are not the result of a specific search to meet a specific need. Purchases may offer some form of entertainment, but they are incidental to this quick procedure. Therefore, according to Churchill and Peter's [7] pre-purchase steps, several of Stern's [4] pre-purchase processes are completely missed in the process of impulse buying. Churchill and Peter's [7] model has been modified for the purposes of this study to describe the impulse buying process by omitting several steps, such as need recognition, information search, and alternative evaluation, and reclassifying influencing factors (Figure 2). This is because impulse purchases typically happen quickly and without prior planning.

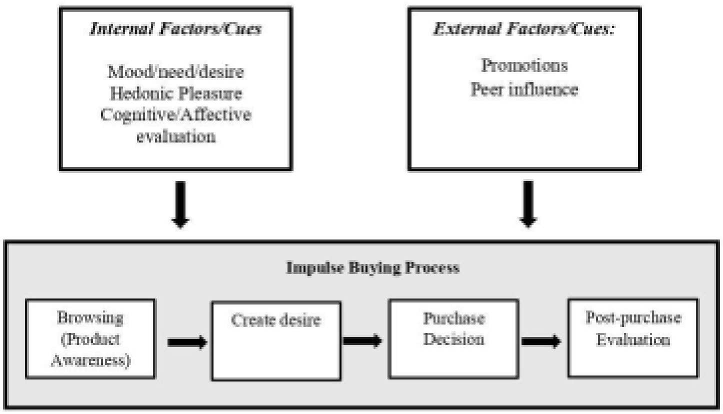

Figure 2: A model of impulse buying process Source: Adapted from Churchill & Peter (1998) [11]

Influencing factors of impulse buying

According to research, both internal and environmental/external elements might operate as cues to cause consumers to make impulsive purchases [9]. The fact that many decisions are made at the moment of purchase is a reflection of "low involvement" decision-making processes [10, 11]. To understand impulse buying behaviour, it is important to understand the internal and external factors that may contribute to the low-involvement decision-making process.

Internal Factors

Individual consumers' impulsive purchasing tendencies are associated with their requirements for enjoyment, novelty, and surprise [12]. Additionally, the social connection that is a part of shopping might help people with their emotional support requirements. For instance, research results show that customers claim to feel energised or uplifted following a shopping experience [13], confirming the contemporary theory that impulse buying is a characteristic driven by hedonic desire. Shopping without a defined goal may be more significant than buying things and can be a very enjoyable experience [14]. The items bought during these outings appear to have been picked on a whim and reflect an impulse buying event because the purpose of the shopping experience is to satisfy hedonic desires.

External Factors

External factors play a vital role in influencing the impulse buying behaviour of consumers. Customers are more likely to make impulsive purchases when there is a sense of urgency created by promotions, discounts, and limited-time offers [15]. Peer influence can also persuade customers to make impulsive purchases of beauty products, frequently fuelled by recommendations from friends, relatives, or social media influencers [16]. Desire is created and impulse purchases are influenced significantly by successful advertising and marketing efforts. Additionally, as part of visual marketing, the presentation and packaging of beauty items can draw customers in and encourage impulsive purchases [17]. Impulsive buying by young consumers for fashion beauty products is a common phenomenon that is influenced by various factors. Young consumers are often in a phase of their lives where they are trying to establish their identity and may be more susceptible to the influence of advertising and peer pressure. In addition, the desire to look good and feel attractive may also contribute to impulsive buying behaviour for beauty products. One of the primary reasons why young consumers engage in impulsive buying for fashion beauty products is the influence of social media. Social media platforms like Instagram, and YouTube are filled with fashion beauty influencers promoting various beauty products. These influencers often create a sense of urgency by promoting limited-time offers and discount codes, which can trigger impulsive buying behaviour [18]. Another reason why young consumers engage in impulsive buying for fashion beauty products is peer pressure. Young consumers often want to fit in with their peers and may feel pressured to keep up with the latest beauty trends. This can lead to impulsive buying behaviour, as they may feel the need to purchase certain products to fit in with their social circle [19]. Furthermore, the easy availability of fashion beauty products online and in stores can also contribute to impulsive buying behaviour among young consumers [20]. To fulfil the objectives of this research, impulse buying behaviour (IBB) has been considered as dependent variable and the external factors, i.e. promotion-driven purchases and peer influence-driven purchases are considered as independent variables. The following hypotheses were formulated to evaluate the relationship between dependent and independent variables.

H1: Promotion-driven purchase (PDP) significantly influences the young consumers' impulse buying behaviour for fashion beauty products.

H2: Peer influence-driven purchases (PIDP) significantly influence the young consumers' impulse buying behaviour for fashion beauty products.

2 Experimental

2.1. Methodology

With the aim of gathering a precise measurement of impulse buying behaviour (IBB), promotion-driven purchases (PDP) and peer influence-driven purchases (PIDP), this research was formulated and used a scale on which items were tested. The research method used to examine young consumers' impulsive purchases of fashion beauty products is quantitative research techniques. A survey was conducted to gather information from the target group of young consumers aged between 18-30 years using a convenience sampling technique. To evaluate the research hypothesis, a structured questionnaire, adapted from Spandita Nandi [21] with 12 questions was designed that covered various aspects of impulse buying behaviour related to fashion beauty products. The first four questions were to determine the demographic profile of respondents, i.e., gender, age, living arrangements and job status and the rest were about external factors (promotions and peer influence) affecting the impulse buying behaviour of young consumers. Each variable was measured using a five-point Likert scale that ranged from 1-strongly disagree to 5-strongly agree. Open-ended question styles were used to measure the demographic components. The questionnaire contained all instructions and consent information for the respondents. To fulfil the purpose of this study, the questionnaire was divided in three sections. The first section of the questionnaire measured the behaviour of young consumers towards impulsive purchases consisting of questions about happiness before impulsive buying and regret after impulsively buying. The second section was used to evaluate promotion-driven purchases by young consumers consisting of questions about deals, packaging, and trial options availability. The third and last section measured peer influence-driven purchases consisting of questions about brand value, celebrity endorsement and owning the same products as celebrities. The research included 259 young consumers living in different parts of India. Convenience sampling approach of non-probability sampling was used to collect responses. A mailing list, social network groups, and online discussion forums were used for distributing the survey.

2.2. Data analysis method

Statistical Package for Social Sciences' (SPSS) software (version 29) was used for the data analysis method. The analysis plan was as follows:

- First, descriptive statistics and frequency of demographics were generated.
- Second, Cronbach's alpha was used to evaluate the reliability of the data and factors analysis (PCA) was used to identify the loading values of each item in the scale.
- Third, the Pearson correlation test was used to determine the correlation between young consumers' impulse buying behaviour and external factors (promotion-driven purchases and peer influence-driven purchases)
- Finally, the hypotheses were tested using regression analysis to determine the relationship between dependent and independent variables.

This study used some statistical methods that has own assumptions and limitations. For reliability Cronbach alpha widely used to measure the internal consistency of data. For this all items in the scale measure a single construct or latent variable. If a scale measures multiple constructs (multidimensionality), Cronbach's alpha may give misleading results. Factor analysis can help assess uni-dimensionality. Correlation analysis measures the strength and direction of a linear relationship between two variables. The relationship between variables is linear. Correlation only indicates an association between variables but does not establish cause and effect. A third variable may influence both. Regression analysis predicts one variable (dependent) based on another (independent). The relationship between the dependent and independent variables is linear. Violations of assumptions (such as nonlinearity or heteroscedasticity) can lead to misleading results.

Table 1 and table 2 summarize the descriptive statistics of demographics and variables respectively. Table 3 represents the principal component analysis with a reliability test (Cronbach's alpha). The findings showed that factor loading of each item is above 0.6 which indicates that each item belonged to one group. The Cronbach's score for all variables was above 0.7 (minimal criterion) [22], showing that the data was statistically suitable and reliable for further study.

Table 1 - Descriptive statistics for demographics

Question		Frequency	Percent
Gender	Female	162	62.5
	Male	97	37.5
Age	18-22	127	49.0
	23-26	125	48.3
	27-30	7	2.7
Living Arrangements	Alone	53	20.5
	Family	138	53.3
	Roommate	68	26.3
Job Status	Full-time	14	5.4
	Part-time	83	32.0
	Unemployed	162	62.5

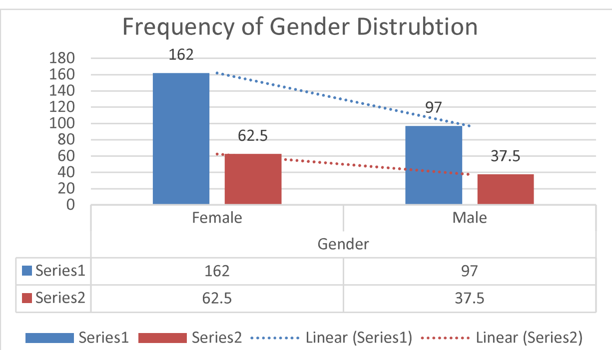

Figure 3 - Frequency of Gender Distribution

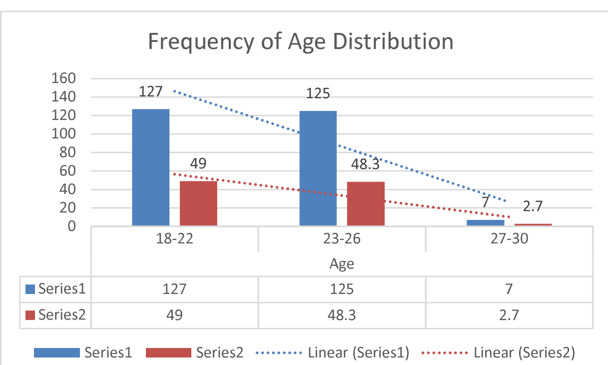

Figure 4 - Frequency of Age Distribution

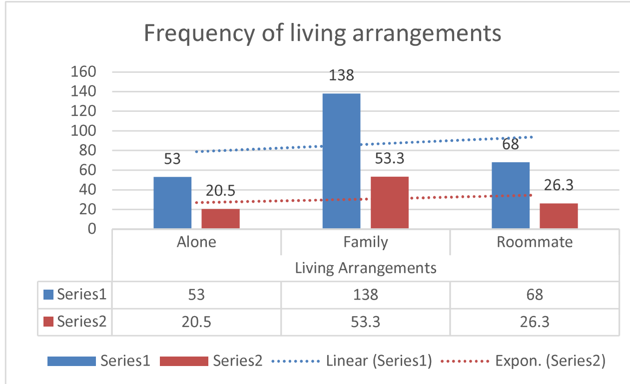

Figure 5 - Frequency of living Arrangements

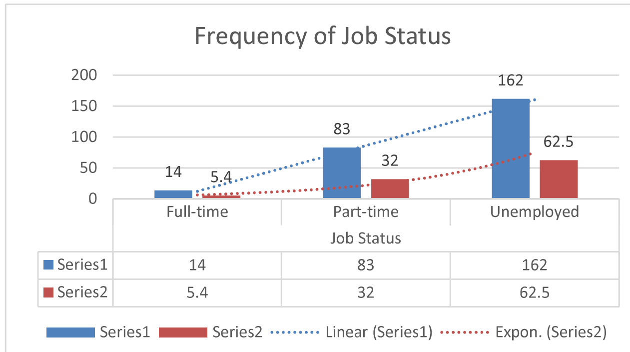

Figure 6 - Frequency of Job Status

Table 2 - Descriptive statistics for variables

Latent Variables	N	Mean	Std. Deviation
Impulse Buying Behaviour	259	3.3726	.57329
Promotion Driven Purchases	259	3.8391	.61305
Peer influence Driven Purchases	259	3.4363	.61607

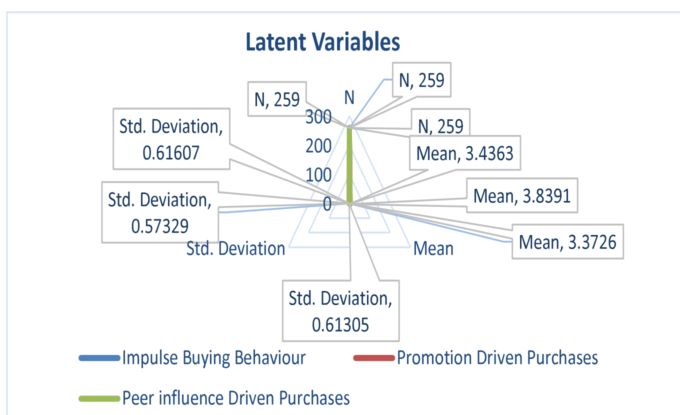

Figure 7 - Descriptive Statistics for Latent Variable

Table 3 - Results of principal component analysis with reliability test

Factor	Item	Factor Loading	Eigen Value	Variance (%)	Cronbach Alpha
Impulse buying behaviour (IBB)	IBB1	0.754	1.785	54.255	0.737
	IBB2	0.698			
Promotion Driven Purchases (PDP)	PDP1	0.7	1.551	51.703	0.724
	PDP2	0.668			
	PDP3	0.784			
Peer Influence Driven Purchases (PIDP)	PIDP1	0.838	1.879	49.304	0.708
	PIDP2	0.634			
	PIDP3	0.854			

3. Results and discussion

3.1. Descriptive statistics for demographics

Demographic statistics show that out of 259 respondents, 62.5% are females and 37.5% are males. The percentage of respondents from the age group of 18-22 and 23-26 are 49 and 48.3 respectively and 2.7% are from the age group of 27-30. The majority of respondents live with their family (53.3%), while 20.5% live alone and 26.3% live with a roommate. 62.5% of respondents are unemployed, 32% work in a part-time job and 5.4% have a full-time job.

3.2. Descriptive statistics for variables

Responses were evaluated on a Likert scale of 1 to 5, with 5 being the strongest agreement that's why responses in each section that scored higher than 3 (neutral) were considered to support the variables i.e., impulse buying behaviour, promotion-driven purchases, and peer influence-driven purchases.

3.3. Pearson Correlation and Regression Analysis

Pearson correlation tests were performed to evaluate the relationship between the independent variable i.e., promotion-driven purchases and peer influence-driven purchases and the dependent variable i.e., impulse buying behaviour. In addition to that, a multiple regression analysis was conducted for the hypotheses testing using impulse buying behaviour as a dependent variable and promotion-driven purchases and peer influence-driven purchases as predictors to see if there is relationship to determine the relative importance of these influences on the impulse buying behaviour of young consumers.

H1: Promotion-driven purchases significantly influence young consumers' impulse buying decisions for beauty products.

Table 4 represents a Pearson Correlation test with r-value 0.373 and a significance level of 0.000 which is less than 0.05 indicating that there is a moderate positive correlation between promotion-driven purchases and impulse buying behaviour for fashion beauty products. Furthermore, the regression analysis (Table 5) reveals that promotion-driven purchases have a substantial effect on impulse buying behaviour for fashion beauty products among young consumers. These findings are consistent with the study of Xiao et.al and Zhou Dong [23, 24]. The hypothesis is accepted as the p-value (0.000) is lower than the alpha level (0.05) and the value of t-statistics (5.589) is greater than expected value of t-statistics (1.96).

H2: Peer influence-driven purchases significantly influence young consumers' impulse buying decisions for beauty products.

A Pearson correlation test resulted in an r-value 0.207 and a significance level of 0.000 which is less than 0.05 indicating a weak positive correlation between peer influence-driven purchases and impulse buying behaviour for fashion beauty products among young consumers (Table 4). However, the regression analysis reveals that peer influence-driven purchases insignificantly influence young consumers' impulse buying behaviour (Table 5). This study's findings are consistent with Tanveer T, Kazmi SQ, Rahman MU study [25] but not consistent with the study of Trivedi. V, Joshi P [26]. As the p-value (0.131) is greater than the alpha level (0.05) and the value of t-statistics (1.515) is less than the expected value of t-statistics (1.96), the hypothesis is rejected.

Table 4 - Correlation with impulse buying

Variables	Coefficient (r)	Significance (p)
Promotion Driven Purchases	0.373	<0.001
Peer Influence Driven Purchases	0.207	<0.001

Table 5 - Regression analysis

Hypothesis	β (Unstandar-dized Coefficients)	Sig.	β (Standar-dized Coefficients)	t-statistics	Comments
H1: Promotion influences the impulse buying decision of fashion beauty products	0.320	<0.001	0.342	5.589	Significant
H2: Peer influences the impulse buying decision of fashion beauty products	0.086	0.131	0.093	1.515	Insignificant

Test Results
R (Coefficient of regression): 0.383
R2 (Coefficient of determination): 0.147
Adjusted R2: 0.140

Table 6 - ANOVA results

Model	Sum of squares	Degree of Freedom (df)	Mean square	F	Significance (F)
Regression	12.471	2	6.235	22.070	0.000
Residual	72.325	256	0.283		
Total	84.795	258			

Table 6 represents ANOVA results indicating a moderate relationship between impulse buying behaviour and external variables (promotion-driven purchases and peer influence-driven purchases) of fashion beauty products among young consumers because of an R-value of 0.383 which is greater than zero, an F-value of 22.070 and a significance level of 0.000 which is lower than the alpha level of 0.05.

4. Conclusions

This study used a structural model to analyze the relationships between external variables (promotions-driven purchases and peer influence-driven purchases) and young consumers' impulse buying behaviour for fashion beauty products. As a result of our thorough investigation of young consumers' impulsive purchases of beauty products, the findings of this study have significant implications for both retailers and consumer behaviour studies.

- This study conclusively shows that promotion-driven purchases have a significant impact whereas peer influence-driven purchases have an insignificant impact on young consumers' impulse buying behavior for fashion beauty products. This finding emphasizes how crucial a role social networks and marketing tactics play in influencing the purchasing behaviors of young consumers.

- Promotion, in the form of discounts, exclusive deals, attractive packaging, and trial option availability, emerges as the main factor influencing impulsive purchasing. Retailers can take advantage of young consumers' obvious attraction to marketing by creating and conducting tailored promotional strategies. Retailers can successfully grab the interest and purchasing power of young consumers in the beauty product market by comprehending the psychological triggers driving these promotions.

- This study also highlights the significant impact of peer influence on the impulsive buying of beauty products. For young consumers, the desire to fit in with peer preferences and societal norms is a powerful drive. Therefore, companies should consider the influence of peer recommendations and endorsements in their marketing plans. Enhancing brand loyalty and trust can lead to higher sales through forming alliances with powerful peers, using customer feedback, and encouraging a feeling of community among consumers.

- From the perspective of retailers, these findings highlight the necessity of personalized marketing plans. The study shows that promotions have a significant impact on young consumers' impulsive purchasing choices. As a result, retailers in the beauty product industry should spend money developing focused and alluring promotional strategies that strategically appeal to the interests and habits of this demographic. Retailers can also look into creative ways to leverage peer influence. Encouragement of word-of-mouth advertising, the use of customer feedback, and the promotion of social media endorsements may generate a feeling of social validation that motivates impulsive purchasing. Collaborations with well-known influencers or brand ambassadors also stand out as potentially successful tactics for establishing credibility and trust.

- Despite these findings, this study has few limitations. Promotion-driven purchases and peer influence-driven purchases were the main topics of this study as factors affecting impulse buying. Although these are unquestionably important aspects, it's possible that other elements, like one's own financial condition, exposure to advertisements, and emotional states, which were not thoroughly investigated but may also affect impulsivity, exist. Another important limitation was the sample size of this study. A larger, more representative sample would enable a better understanding of impulsive purchasing for young consumers.

- Since Indian consumers have diverse cultural origins, lifestyles, and purchasing habits, further research on the subject can be expanded in the following ways: i) exploring regional variations to understand how cultural and economic factors influence the choices ii) evaluating the impact of digital and social media on impulse buying iii) making comparisons across other nations iv) gathering data from a broader variety of demographic attributes v) including other variables like store environment, salesperson influence, availability of time and money.

References

[1] IYER, G.R., BLUT, M., XIAO, S.H. Impulse buying: a meta-analytic review. Journal of the Academy of Marketing Science, 48(3), 384–404, (2020)

[2] Rook, D.W. Fisher, R.J. Trait and normative aspects of impulsive buying behavior. Journal of Consumer Research, 22(3), 305-13, (1995)

[3] Kacen, J.J., LEE, J. A. The Influence of culture on consumer impulsive buying behavior. Journal of Consumer Psychology, 2(2):163-176, (2002)
[4] Stern, H. The significance of impulse buying today. Journal of Marketing, 26(2), 59-62, (1962)
[5] Youn, S Faber, R J. Impulse buying: Its relation to personality traits and cues. Advances in Consumer Research, 27(1), 179-186, (2000)
[6] Mandolfo M, LambertI L. Past, present, and future of impulse buying research methods: a systematic literature review. Frontiers in Psychology, 12(7), 1–11, (2021)
[7] Churchill, G.A. & Peter, J.P. Marketing: Creating value for customers, (1998)
[8] Piron, F. Defining impulse purchasing. ACR North American Advances, 18, 509-514, (1991)
[9] Seounmi Youn, Ronald J. Faber. Impulse buying: its relation to personality traits and cues. Advances in Consumer Research, 27(1), 179-185, (2000)
[10] Hoyer W.D. An examination of consumer decision making for a common repeat purchase product. Journal of Consumer Research, 11(3), 822- 829, (1984)
[11] Kumar Sushil, G R. Study on Motives underlying the Buying of Fast Fashion in India despite associated Sustainability issues. Tekstilec Journal, 67(01), 44-55, (2024)
[12] Dorothea B, Andrea Groeppel K. Joy and Surprise as Guides to a Better Understanding of Impulse Buying Behaviour. European Advances in Consumer Research, 6(1), 290-299, (2003)
[13] Rook, D. W. The buying impulse. Journal of Consumer Research, 14(2), 189-199, (1987)
[14] Manlow, V, Nobbs, K. Form and function of luxury flagships: An international exploratory study of the meaning of the flagship store for managers and customers. Journal of Fashion Marketing and Management, 17(1), 49-64, (2013)
[15] Verhagen T, V Dolen W. The influence of online store beliefs on consumer online impulse buying: A model and empirical application. Information and Management, 48(8), 320–327, (2011)
[16] Cheung, C.M.K, Xiao, B.S, LIU, I.L.B. Do actions speak louder than voices? The signalling role of social information cues in influencing consumer purchase decisions. Decision Support System, 65(C), 50-58, (2014)
[17] YIM CHI KIN, TSE David K. W Chan K. strengthening customer loyalty through intimacy and passion: roles of customer-firm affection and customer staff relationships in services, Journal of Marketing Research, 45(6), 741-756, (2008)
[18] Stubb C, Nystrom, A, C J. Influencer marketing. Journal of Communication Management, 23(2), 1-8, (2019)
[19] Shruti Gulati. Impact of peer pressure on buying behaviour. International Journal of Research Granthaalayah, 5(6), 280-291, (2017)
[20] Ulfraz M. B, Sufyan M, Mustak M, Salminen J, Srivastava D. K. Understanding the impact of online customers' shopping experience on online impulsive buying: a study on two leading E-commerce platforms. Journal of Retailing and Consumer Services, 68(2), 1-9, (2022)
[21] Spandita Nandi. Factors affecting impulse buying behaviour of beauty products, AIMS International Journal of Management, 15(1), 59-71, (2021)
[22] Nunnally, J.C. Psychometric theory 3E. Tata McGraw-Hill Education, (1994)
[23] Xiao, Y., Wu, B., Deng, Z. et al. Can social appearance anxiety promote the online impulse buying of beauty products among young females? A moderated mediation model of sense of control and perceived coronavirus stress. Curr Psychol 43, 18119–18132 (2024)
[24] Zhou Dong, Khunanan Sukpasjaroen. The impact of anchor attributes and product content on impulse buying behaviour of beauty consumers. Environment and Social Psychology, 9, 10, (2024)
[25] Tanveer T, Kazmi SQ, Rahman MU. Determinants of impulsive buying behavior: An empirical analysis of consumers' purchase intentions for offline beauty products. Nurture. 16, 2:75-89, (2022)
[26] Trivedi V, Joshi P. Exploring the Role of Situational Cues in Apparel Consumers' Impulsive Buying Behaviour. Tekstilec. 67, 4: 357-69. (2024)

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Application of the TOPSIS Method in Yarn Procurement for the Handloom Sector

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Abstract:

In the handloom industry, the supply of raw materials for each product varies depending on their type. The availability, affordability, and sourcing play a crucial role in the supply chain. The present work discusses the importance of the weightage of the various factors for the raw material supply chain. Technique for Order Preference by Similarity to the Ideal Solution Method (TOPSIS) is a mathematical tool that systematically identifies handloom weavers' preferred sourcing points for the raw material supply chain. It is observed that direct procurement from the local market is the preferred sourcing location. TOPSIS's proximity index has been updated in sensitivity analysis, and certain elements' weightage (global weight) has been raised. The weightage of the evenness parameter does not affect the sourcing points. In contrast, the increase in global weight of count variation and cost parameters changes the sourcing points. In those cases, Mahajan is the weavers' preferred solution for yarn purchasing.

Keywords: *Handloom, MCDM, Supply chain, TOPSIS, Yarn*

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1. Introduction

The textile business comprises a complicated supply chain that includes stages such as raw material procurement, processing, and distribution. On the other hand, handloom weaving is an age-old tradition. The Indian handloom sector is a manifestation of our excellent craftsmanship and plays a crucial role in the restructuring and development of the economy. The handloom sector accounts for almost 15% of total domestic cloth production and according to the 4th All India Handloom Census (2019-2020), India produces 95% of the world's handwoven fabric. However, in the current context of globalisation and rapid technological change, this sector faces numerous challenges, primarily as a result of obsolete technologies, a weak supply chain, low productivity, insufficient working capital, a conventional product range, a weak marketing link, overall production and sales stagnation, capitalist control, low wages, increased yarn price, and so on [1]. To solve these challenges, businesses must invest in current technologies, enhance supply chain management, and use sustainable practices that benefit the environment while increasing productivity and profitability [2]. West Bengal's handloom sector contributes significantly to the state's economy and has a long history and tradition, but faces numerous challenges in recent years. One of the most significant issues is the lack of an efficient supply chain model that ensures the timely delivery of raw materials and completed goods.

Multi-criteria decision-making (MCDM) is a prevalent discipline of Operations Research. It refers to making decisions in the presence of multiple, usually conflicting criteria [3]. It has become a significant and valuable tool for tackling business decision-making challenges. The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) emerged in the 1980s as a multi-criteria decision-making method. TOPSIS has been used extensively for practical Multiple Attribute Decision Making (MADM) problems due to its sound mathematical foundation, simplicity, robustness, and ease of applicability. The basic philosophy behind TOPSIS is that the selected alternative should have the shortest distance from the ideal solution and the longest distance from the worst solution in a geometrical sense [4, 5]. TOPSIS was used as a tool to account for the preferences of the decision-maker and to arrange priorities according to the final goal [6]. The ranking and selection of a fabric for a specified end use is not a simple task, and in such cases, the Multi Criteria Decision Making (MCDM) technique can be used. Researchers ranked handloom cotton fabric to select the best alternatives in terms of quality parameters [7]. The determination of the quality value of cotton is a Multi-criteria Decision Making (MCDM) problem. The Fibre Quality Index (FQI), used in the textile industry to determine the overall quality, is a multiplicative expression. Researchers tried to grade and select cotton fibres using AHP-TOPSIS and GA-TOPSIS approaches [8]. It is essential to make a trade-off between tangible and intangible factors to choose the best suppliers, some of which may conflict. Researchers developed a methodology to evaluate suppliers in the supply chain cycle based on TOPSIS [9]. TOPSIS and the design of the experiment are considered to identify the most suitable cotton fabric for providing optimal comfort for the TOPSIS score [10]. Significant changes in thermo-physiological characteristics like thermal

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resistance, air permeability, water vapour permeability, etc., can be achieved by dissolving one component from a multi-component yarn. Technique for Order Preference by Similarity to the Ideal Solution Method (TOPSIS) and Grey Relational Analysis Method (GRA) has been used for ranking those fabrics produced from different percentages of wool, polyester and polyvinyl alcohol (PVA) as weft [11].

The supply of yarn and marketing was the major constraint for the handloom industry. Different researchers, government organisations, and academicians have conducted several studies on the socio-economic issues and supply chain [12-14]. According to the researcher, effective supply chain management can help handloom sectors build strong relationships with suppliers and ensure timely delivery of raw materials. The most critical area identified in the supply chain of handloom industries is raw material i.e., yarn. With a reliable and consistent supply of high-quality yarn, the handloom sector can meet the market's demands and produce quality products. In the raw material (yarn) supply chain, determining elements are – quality, price, and service (ease of availability and less waiting time).

The TOPSIS may help determine the best option for the handloom weavers to source yarn. This technique considers various factors such as cost, quality, and reliability to evaluate the available options comprehensively. Using this approach, handloom weavers can make informed decisions and select the most suitable source for their yarn, ultimately enhancing their productivity and profitability. The TOPSIS method ranks alternatives based on their proximity to an ideal solution. With the help of TOPSIS, organisations can ensure that they are using the most efficient and effective channel to connect with their customers and achieve their business goals.

The present research aims to investigate and assess the supply chain business model utilised by the handloom sector in West Bengal, India, which includes weavers, wholesalers, retailers, and end customers. Lack of access to contemporary technology and infrastructure is one of the most critical obstacles the handloom sector in West Bengal faces. The researcher found it most appropriate in this given situation of the raw material supply chain of the handloom Industry of West Bengal to compare the relative advantages and disadvantages among the options available for raw material sourcing and to assess and pinpoint the most beneficial option through the TOPSIS technique. Furthermore, to get a more precise conclusion regarding the preferred way of raw material procurement for various handloom products, sensitivity analysis is also performed by raising the relevance of particular deciding variables among evenness of the yarn (quality) - a lower number is preferable, the yarn's strength (quality) - a high value is desirable, count variations in yarn quality - a lower value is preferable, overtwisting/twist liveliness in the yarn (quality) - a lower value is desired, cost - less value is preferable, credit facility availability (cost) - a higher value is desired, waiting time (service) - a lower value is desired and purchasing difficulties (service) - less value is preferred.

2. Methodology

2.1 Questionnaire and Survey Scale

It is essential to identify yarn suppliers to improve the availability and quality of raw materials for handloom weavers. The different sources of yarns provide a diverse range of options for handloom weavers to procure raw materials based on their specific needs and preferences. Table 1 shows the questionnaire and survey scale analysed using the TOPSIS technique.

Table 1: Structured questionnaire and survey scale

Sl. No.	Questions	Scale
1	Yarn count (mostly used)	N/A
2	Purchase point/place	5-2 >> easy to difficult access
3	Mode of getting yarn	5-2 >> cost effective to expensive
4	A lead time of getting yarn	5-2 >> earliest to latest
5	Cost of yarn	5-2 >> cheapest to expensive
6	Yarn quality - Evenness	5-2>> even to uneven
7	Yarn quality - Strength	5-2 >> strongest to weakest
8	Yarn quality – Count variation	5-2 >> low to high
9	Yarn quality – Over twist	5-2 >> low to high

2.2 The Technique for order of preference by similarity to the ideal solution (TOPSIS)

The TOPSIS model is based on the concept of identifying the best alternative among a set of alternatives by comparing them with an ideal solution. The TOPSIS model involves three main steps: (i) normalisation of the decision matrix, (ii) determination of the weighted normalised decision matrix, and (iii) calculation of the closeness coefficient for each alternative. The normalisation step involves converting all criteria into a common scale to eliminate any bias towards any particular criterion. The weighted normalised decision matrix is calculated by multiplying each criterion's normalised value by its corresponding weight. Finally, the closeness coefficient for each alternative is calculated by comparing its distance from the ideal solution with its distance from the worst solution. The alternative with the highest closeness coefficient is considered to be the best alternative.

TOPSIS considers three types of attributes or criteria, i.e., qualitative benefit attributes/criteria, quantitative benefit attributes and cost attributes or criteria. In this method, two artificial alternatives are hypothesised: i) ideal alternative i.e., the one which has the best level for all attributes considered and ii) negative ideal alternative i.e., the one which has the worst attribute values. TOPSIS select the alternative which is closest to the ideal solution and furthest from the negative ideal solution.

TOPSIS assume that we have 'm' alternatives (options) and 'n' attributes/criteria and we have the score of each option to each criterion.

Let the score of option i to criterion j be a matrix X = (x_{ij}) *mxn* matrix.

Let J be the set of benefit attributes or criteria (more is better)

Let $J¢$be the set of negative attributes or criteria (less is better)

Step 1: Construct a normalised decision matrix.

- This step transforms various attribute dimensions into non-dimensional attributes, which allows comparisons across criteria.
- Normalize scores or data as follows:

$$r_{ij} = x_{ij} / \left(\sum x^2_{ij}\right) \text{ for } i = 1,\ldots m \;\&\; j = 1,\ 2,\ldots n$$

Step 2: Construct the weighted normalised decision matrix.

- Assume we have a set of weights for each criterion w_j for j=1,.....n
- Multiply each column of the normalised decision matrix by its associated weight
- An element of the new matrix is: $v_{ij}=w_j r_{ij}$

Step 3: Determine the ideal and negative ideal solutions

- Ideal solution

$$A^* = \{v_1^*, \ldots, v_n^*\}, \text{ where,}$$
$$v_j^* = \{\max_i(v_{ij}) \text{ if } j \in J;\ \min_i(v_{ij}) \text{ if } j \in J'\}$$

- Negative ideal solution

$$A' = \{v_1', \ldots, v_n'\}, \text{ where,}$$
$$v' = \{\min(v_{ij}) \text{ if } j \in J;\ \max(v_{ij}) \text{ if } j \in J'\}$$

Step 4: Calculate the separation measures for each alternative

- The separation from the ideal alternative is:

$$S_i^* = \left[\sum_j (v_j^* - v_{ij})^2\right]^{1/2} \quad i = 1,2,\ldots,m$$

- Similarly, the separation from the negative ideal alternative is:

$$S_i' = \left[\sum (v_j' - v_{ij})^2\right]^{1/2} \quad i = 1,\ldots,m$$

Step 5: Calculate the relative closeness to the ideal solution C_i^*

$$C_i^* = S_i' / (S_i^* + S_i'),\ 0 < c_i^* < 1$$

Select the option with close to 1.

MCDM methods like TOPSIS provide a comprehensive approach to decision-making that considers multiple factors and their relative importance.

2.3 Sensitivity analysis

The level of crosstalk between criterion weight and ranking was assessed in one of the sensitivity analysis approaches, which covers the essential underpinnings of this methodology. This methodology aims to determine the effect of changes in any criteria weights under consideration on the overall ranking of alternatives. Furthermore, this research identifies which criteria influence the final ranking more, allowing for better-informed decision-making. The purpose of this technique is to independently determine the effect of each element on the MCDM outputs. Each criterion's weight was changed by ± 10% (minor change), ± 20% (medium change) or ± 30% (significant change) by raising it or lowering it. This adjustment enabled decision-makers to analyse the overall ranking's sensitivity to changes in specific criteria. When the criterion weights are altered by 10%, 20% or 30%, the relative sensitivity coefficients illustrate how the rankings of the alternatives vary.

3. Results and Discussions

The main challenges in the handloom industry are attributed to one common factor, which is the raw material supply chain. Several accessible yarn-sourcing points were identified during the study after discussions with various handloom weavers and stakeholders. During the survey, it was noticed that the handloom weavers used various sources, viz., NHDC (National Handloom Development Corporation), direct purchase from Burrabazar. Kolkata, through local arrangement, through Mahajan (agent) and through Khadi society to procure yarns. The quality, price, timeliness, dependability, and availability of credit are all important parts of the yarn supply chain.

Since most respondents need more resources to pursue higher levels of education, it was unrealistic to anticipate a detailed response (either technically or monetarily). Therefore, the study specified subjective responses on a scale. This subjective structure promotes a wider variety of opinions, ensuring that the wants and needs of a more significant number of people are met. Decision-makers gain valuable insights into respondents' general attitudes and preferences through a scaling method, which collects quantitative data that can be analysed and compared. Decisions made using this method are ultimately more well-informed and thorough. Table 2 depicts responses in terms of modal value from different sources of procurement and Figure 1 describes the hierarchical structure of the value of the marketing chain.

Table 2: Response in terms of modal value through the survey

Sl. No.	Questions/Criteria	Source/Alternatives				
		NHDC	Burrabazar	Local market	Mahajan	Khadi society
1	Yarn count (mostly used)	N/A	N/A	N/A	N/A	N/A
2	Purchase point/place	5	5	5	5	5
3	Mode of getting yarn	5	5	5	5	5
4	A lead time of getting yarn	4	3	5	5	5
5	Cost of yarn	5	2	2	5	2
6	Yarn quality - Evenness	3	3	5	2	2
7	Yarn quality - Strength	4	4	5	3	3
8	Yarn quality – Count variation	3	3	5	2	3
9	Yarn quality – Over twist	5	5	5	5	5

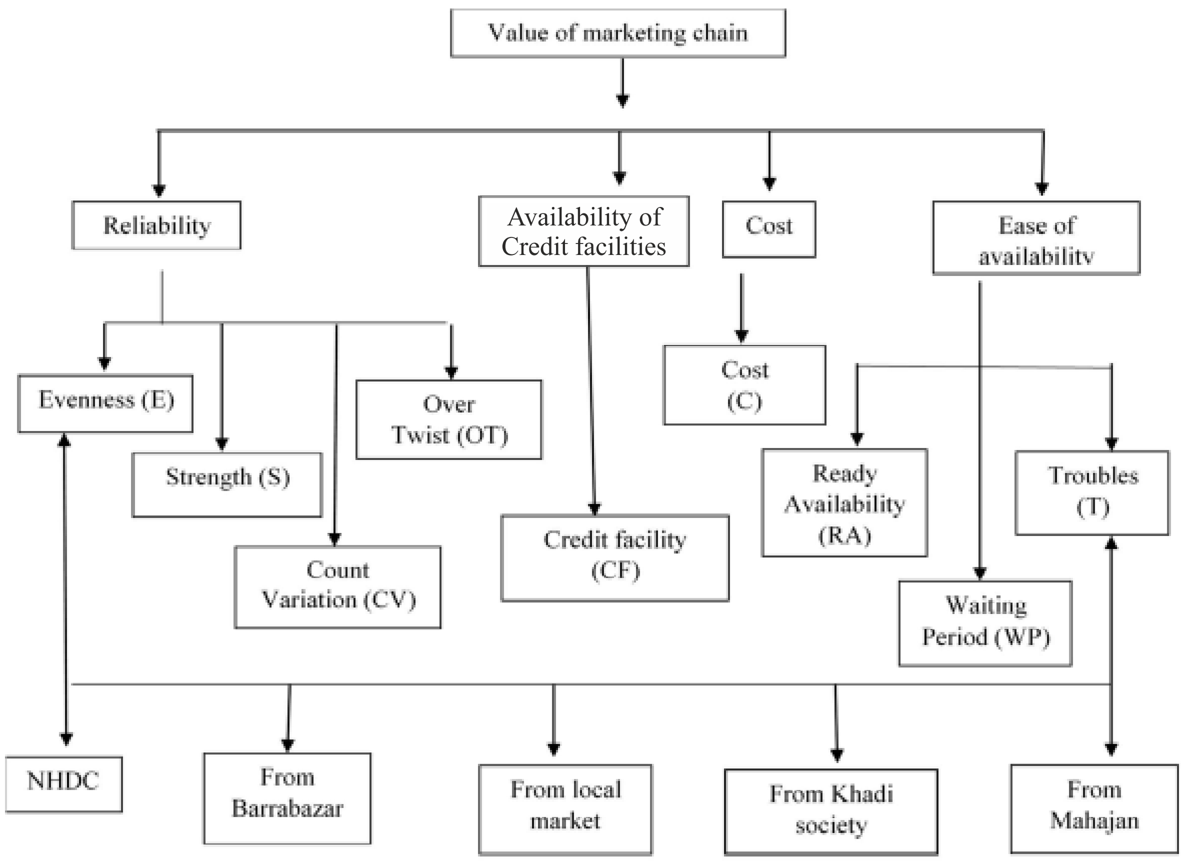

Figure 1: Hierarchical structure of value of marketing chain

3.1 Application of TOPSIS for finding the best yarn sourcing point

According to the TOPSIS model, as shown in Table 3, the most appropriate yarn-sourcing point was purchasing from the local market while considering the most critical and determining but conflicting parameters. This choice was influenced by cost, quality, lead time, and ease of procurement. Reducing transportation costs and ensuring a faster turnaround time for production can be possible by purchasing yarn from the local market, which also allows us to closely monitor the quality of the yarn and make any necessary adjustments or replacements as soon as possible. By relying on actual values and reasoning, TOPSIS provides a more transparent and systematic way of evaluating alternatives, enhancing the credibility of the research findings.

Table 3: TOPSIS model

TOPSIS										
Sourcing point		**Evenness**	**Strength**	**Count variation**	**Over twist**	**Availability credit facility**	**Cost**	**Ready availability**	**Waiting period**	**Troubles**
	Global weight	0.31	0.14	0.06	0.03	0.05	0.26	0.08	0.02	0.01
NHDC	Modal value	3	4	3	5	5	5	1	4	5
Direct purchase from Barrabazar	Modal value	3	4	3	5	5	2	1	3	5
Purchase through the local market	Modal value	5	5	5	5	5	2	1	5	5
From Mahajan/Agent	Modal value	2	3	2	5	5	5	1	5	5
Khadi society	Modal value	2	3	3	5	5	2	1	5	5

Step 1 (A) Square of modal value									
Sourcing point / Criteria	**Evenness**	**Strength**	**Count variation**	**Over twist**	**Availability credit facility**	**Cost**	**Ready availability**	**Waiting period**	**Troubles**
NHDC	9	16	9	25	25	25	1	16	25
Direct purchase from Barrabazar	9	16	9	25	25	4	1	9	25
Purchase through the local market	25	25	25	25	25	4	1	25	25
From Mahajan/Agent	4	9	4	25	25	25	1	25	25
From Khadi society	4	9	9	25	25	4	1	25	25
Sum	51	75	56	125	125	62	5	100	125
Root	7.14	8.66	7.48	11.18	11.18	7.87	2.24	10.00	11.18

Step 1 (B)	Data normalisation								
NHDC	0.42	0.46	0.40	0.45	0.45	0.64	0.45	0.40	0.50
Direct purchase from Barrabazar	0.42	0.46	0.40	0.45	0.45	0.25	0.45	0.30	0.50
Purchase through the local market	0.70	0.58	0.67	0.45	0.45	0.25	0.45	0.50	0.50
From Mahajan/Agent	0.28	0.35	0.27	0.45	0.45	0.64	0.45	0.50	0.50
From Khadi society	0.28	0.35	0.40	0.45	0.45	0.25	0.45	0.50	0.50

Step 2	Multiplication of each column by weight								
NHDC	0.13	0.06	0.02	0.01	0.02	0.16	0.03	0.01	0.005
Direct purchase from Barrabazar	0.13	0.06	0.02	0.01	0.02	0.06	0.03	0.01	0.005
Purchase through the local market	0.22	0.08	0.04	0.01	0.02	0.06	0.03	0.01	0.005
From Mahajan/Agent	0.08	0.05	0.01	0.01	0.02	0.16	0.03	0.01	0.005
From Khadi society	0.08	0.05	0.02	0.01	0.02	0.06	0.03	0.01	0.005

Step 3A: Determination of ideal solution
A*: Taken all the higher values of beneficial criteria and lower values of cost criteria
[0.223, 0.086, 0.018, 0.014, 0.025, 0.067, 0.038, 0.007, 0.005]
Step 3 (B): Determination of negative ideal solution
A': Taken all the lower values of beneficial criteria and higher values of cost criteria
[0.89, 0.051, 0.044, 0.014.025, 0.167, 0.038, 0.011, 0.005]

Table 4: Sensitivity analysis of ranking to evenness weightage

Step 4 (A)	Separation from the ideal solution for each alternative								SUM	Root
Si*										
NHDC	0.008	0.0003	0.000	0.00	0.000	0.01	0.000	0.000004	0.000	0.02	0.13
Barrabazar	0.008	0.0003	0.000	0.00	0.000	0.000	0.000	0.000000	0.000	0.01	0.09
Local market	0.000	0.000	0.0006	0.00	0.000	0.000	0.000	0.000017	0.000	0.001	0.02
Mahajan/Agent	0.018	0.0012	0.000	0.00	0.000	0.010	0.000	0.000017	0.000	0.03	0.17
Khadi society	0.019	0.0012	0.00007	0.00	0.000	0.000	0.000	0.000017	0.000	0.02	0.13

Step 4 (B)	Separation from negative ideal solution for each alternative								SUM	Root
Si'										
NHDC	0.002	0.0003	0.0003	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.05
Barrabazar	0.002	0.0003	0.0003	0.000	0.000	0.010	0.000	0.000	0.000	0.012	0.11
Local market	0.017	0.001	0.000	0.000	0.000	0.010	0.000	0.000	0.000	0.029	0.17
Mahajan/Agent	0.000	0.000	0.0007	0.000	0.000	0.000	0.000	0.000	0.000	0.0007	0.02
Khadi society	0.000	0.000	0.0003	0.000	0.000	0.010	0.000	0.000	0.000	0.01	0.10

Step 5: Calculation of relative closeness to the ideal solution

Ci*		Rank
NHDC	0.27	4
Direct purchase from Barrabazar	0.55	2
Purchase through the local market	0.86	**1**
From Mahajan/Agent	0.13	5
From Khadi society	0.42	3

So, the direct purchase from the local market is the most preferred solution for yarn procurement.

3.2 Sensitivity analysis

As sensitivity analysis aimed to determine each factor's effect on the MCDM outputs independently, each criterion's weight was modified individually by 10% (minor change), 20% (medium change) or 30% (significant change) by raising it. The remaining criterion weights remained constant. Specific values of relative sensitivity coefficients obtained indicate several changes in alternative ranking owing to criterion weight modification (10 to 30% increase). Three criteria have been selected for the present research work, i.e., evenness, count variation, and cost. The change (increase) of importance (weightage) in each criterion is considered 10%, 20% and 30%. The revised ranking in the TOPSIS method is discussed hereunder.

The relative closeness index through the TOPSIS method against evenness, count variation and cost are determined and given in Table 4 to Table 6 and Figure 2 to Figure 4 respectively. Based on the relative closeness value (CI) the ranking of the yarn procurement source is also shown in parenthesis.

Sourcing point	Level of weightage			
	Nominal	+10%	+20%	+30%
	Relative closeness index (Ci*)			
NHDC	0.27 (4)	0.28 (4)	0.28 (4)	0.34 (3)
Direct purchase from Barrabazar	0.55 (2)	0.52 (2)	0.50 (2)	0.42 (2)
Purchase through the local market	0.86 (1)	0.85 (1)	0.88 (1)	0.69 (1)
From Mahajan/Agent	0.13 (5)	0.12 (5)	0.12 (5)	0.12 (5)
From Khadi society	0.42 (3)	0.38 (3)	0.36 (3)	0.31 (4)

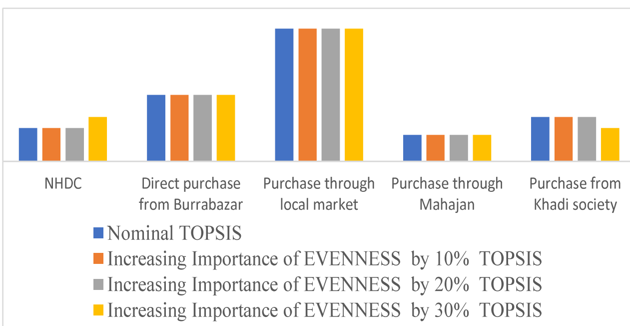

Figure 2: Closeness index with increasing importance of evenness of the yarn

It is observed from Table 4 and Figure 2 that the weightage of the evenness parameter does not affect the purchasing pattern or source. In all cases, direct purchase from the local market is the most preferred solution for yarn procurement.

Table 5: Sensitivity analysis of ranking to count variation weightage

Sourcing point	Level of weightage			
	Nominal	+10%	+20%	+30%
	Relative closeness index (Ci*)			
NHDC	0.27 (4)	0.42 (4)	0.40 (4)	0.42 (4)
Direct purchase from Barrabazar	0.55 (2)	0.43 (3)	0.42 (3)	0.43 (3)
Purchase through the local market	0.86 (1)	0.60 (2)	0.56 (2)	0.60 (2)
From Mahajan/Agent	0.13 (5)	0.76 (1)	0.74 (1)	0.74 (1)
From Khadi society	0.42 (3)	0.32 (5)	0.31 (5)	0.33 (5)

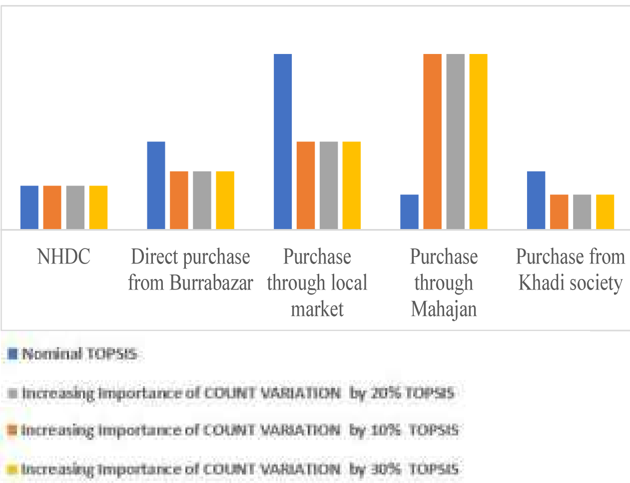

Figure 3: Closeness index with increasing importance of count variation of the yarn

Table 5 and Figure 3 show that the count variation parameter's weightage changes the procurement pattern of yarn. If we increase the global weight of count variation by 10%, 20% and 30%, then purchasing from Mahajan is the most preferred solution for yarn procurement.

Table 6: Sensitivity analysis of ranking to cost weightag

Sourcing point	Level of weightage			
	Nominal	+10%	+20%	+30%
	Relative closeness index (Ci*)			
NHDC	0.27 (4)	0.44 (3)	0.42 (3)	0.50 (3)
Direct purchase from Barrabazar	0.55 (2)	0.41 (4)	0.37 (4)	0.37 (4)
Purchase through the local market	0.86 (1)	0.61 (2)	0.54 (2)	0.58 (2)
From Mahajan/Agent	0.13 (5)	0.76 (1)	0.72 (1)	0.72 (1)
From Khadi society	0.42 (3)	0.31 (5)	0.28 (5)	0.29 (5)

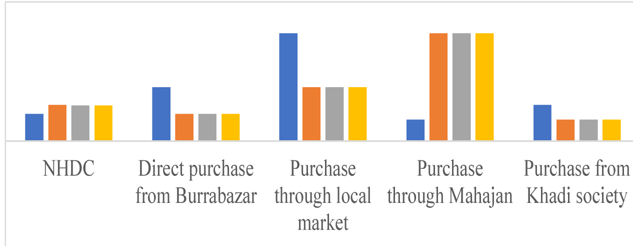

Figure 4: Closeness index with increasing importance of cost of the yarn

Table 6 and Figure 4 show that the cost parameter's weightage changes the procurement pattern of yarn. If we increase the global weight of cost variation by 10%, 20% and 30%, then purchasing from Mahajan is the most preferred solution for yarn procurement.

The ranking of sourcing points for procurement of yarn using the TOPSIS methods without sensitising parameters is calculated and observed that considering the standard relative value of all the factors, buying yarn from the local market is the best choice for the weavers. This suggests that the weavers' demands and preferences, identified by TOPSIS methodologies, are well-met when the yarn is sourced from the local market. It also implies that alternate ways of acquiring raw materials might be less beneficial for satisfying the assessed criteria. The sensitivity study shows that the TOPSIS techniques continue to rank local raw material purchasing as the best alternative, even when the importance of evenness is increased by 10%, 20%, and 30%. The local market seems to be the most obvious choice among the current yarn supply chains because of the market's proximity, adaptability, and ease of management. Suppliers in the area may also be able to meet the organisation's unique demands and preferences more precisely. Nevertheless, the TOPSIS technique indicates that the Mahajan or master weaver supply chain would be the most effective once the proportional impact of count variation or cost increases. The master weaver's knowledge and skill in the supply chain allowed them to outweigh other benefits of sourcing yarn from the local market. Thus, finding the best sourcing choice requires a thorough assessment of these aspects and the formation of a yarn bank by the Government agencies might help weavers to source better quality yarn from the local market.

4. Conclusion

Supply chain management in the handloom industry involves managing the raw material supply chain of various products, viz., gamcha, lungi, sari, dhoti, high-value Baluchari sari, etc. Weavers producing handloom materials like gamcha and lungi prioritise competitive yarn sourcing with decent quality, while Baluchari sari prioritises quality and flexible credit policies due to high raw material costs. Procurement involves a trade-off between quality, service, and price. The present study reveals that purchasing yarn from the local market is the best option, despite higher raw material prices. TOPSIS's proximity index has been updated in sensitivity analysis when certain elements' weightage is altered, resulting in Mahajan (Master Weaver) from the local market becoming the top preferred buy point.

References

[1] S. Roy Maulik, "Handloom – The Challenges and Opportunities", Handloom sustainability and culture, (Editor: Miguel Ángel Gardetti and Subramanian Senthilkannan Muthu), Part of the Sustainable Textiles: Production, Processing, Manufacturing & Chemistry Book Series, Publisher: Springer, Singapore: 2021: pp (97-117), https://doi.org/10.1007/978-981-16-5665-1_5

[2] M.L. Narsaiah, "Economics of Handloom Industry", Publisher: Sonali Publications: 2004

[3] B.K. Satapathy, A. Majumdar, & B.S. Tomar, "Optimal Fly Ash-Filled Composite Friction Materials Design Using Combined Analytical Hierarchy Process and Technique for Order Preference by Similarity to Ideal Solutions Approach", Materials and Design, 31/4, (2010), (1937-1944)

[4] C. Hwang, & K. Yoon, "Multiple Attribute Decision Making: Methods and Applications", Springer-Verlag, New York, NY: 1981

[5] S. Chakraborty, "TOPSIS and Modified TOPSIS: A Comparative Analysis", Decision Analytics Journal, 2, (2022), 100021

[6] S.C Duru, C. Candan, & B.U. Nergis, "A Multi-Criteria Decision Approach on the Physical Properties of Socks Made from Different Fibre Types", Journal of Fashion Technology & Textile Engineering, S1-009, (2015), http://dx.doi.org/10.4172/2329-9568

[7] A. Mitra, "Multi-Criteria Decision-Making Approach using Hybrid AHP-TOPSIS Methodology for Ranking and Selection of Handloom Fabrics for Summer Clothing", International Journal of Management, IT and Engineering, 8(5), (2018), (194-205)

[8] D. K. Banwet, & A. Majumdar, "Comparative Analysis of AHP-TOPSIS and GA-TOPSIS Methods for Selection of Raw Materials in Textile Industries", Proceedings of the International Conference on Industrial Engineering and Operations Management Bali, Indonesia, January 7 – 9, (2014), (2071-2080)

[9] J.C. Sasi, & A. Digalwar, "Application of AHP and TOPSIS Method for Supplier Selection between India & China in Textile Industry", International Research Journal of Engineering and Technology, 2(4), (2015), (1730-1738)

[10] S. Chakraborty, & P. Chatterjee, "A Developed Meta-model for Selection of Cotton Fabrics Using Design of Experiments and TOPSIS Method", J. Inst. Eng. India Series E, 98, (2017), (79–90) https://doi.org/10.1007/s40034-017-0108-x

[11] D. Bhatia, & S.K. Sinha, "Selection of Handloom Fabrics Based on Thermo-Physiological Characteristics Using Multi - Attributes Decision-Making Algorithm", Journal of Natural Fibers, 19(13), (2021), (6015–6030) https://doi.org/10.1080/15440478.2021.1904475

[12] R. Goswami, & R. Jain, "Strategy for Sustainable Development of Handloom Industry", Global Journal of Finance and Management, 6(2), (2014), (93-98)

[13] A. Bortamuly, & K. Goswami, "Factors Influencing Wage Structure of Handloom Workers in Assam", Journal of Rural Development, 31(2), (2012), (139–150)

[14] P. Bhadouria, "Handloom Industry on the Way of Distress: An Empirical Study over the Major Problems", Asian Journal of Research in Social Sciences and Humanities, 2(6), (2012), (71-83)

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Advancements in Computer Vision and Deep Learning for Enhanced Textile Inspection and Manufacturing

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Abstract:

There have been tremendous developments on the Technology front in recent times. New technologies, such as Artificial Intelligence (AI), the Internet of Things (IoT), Big Data Analytics, and Virtual Reality, have transformed many industries. The textile industry is also changing the way it operates. Technologies such as computer vision and deep learning have influenced how the textile industry functions. This study delves into integrating computer vision and deep learning in textile inspection, driving transformative shifts in defect detection, fabric pattern recognition, and real-time texture tracking. Notable contributions, such as Residual Networks for fabric pattern recognition and linear neural networks for fast web inspection, showcase the paradigm shift from manual to automated processes. Incorporating methodologies like CNN, GLCN, Gabor wavelet analysis, PCA, and innovative defect detection algorithms, the research explores diverse textures and regularity, emphasizing local and global assessments in woven fabric analysis. Results from topic modeling highlight key themes like textile defect detection and real-time fabric identification. The study concludes with managerial implications stressing the strategic adoption of automated systems and envisions future advancements in neural networks and real-time technologies, offering a comprehensive perspective on the current state, challenges, and prospects in automated textile inspection and manufacturing.

Keywords: *Computer, Deep Learning, Fabric, Inspection, pattern, Textile*

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1. Introduction

Computer vision and image classification-based models have been adopted in various domains of the textile industry [1, 2 & 3]. Clothing, considered one of human beings' most fundamental existential requirements, has existed for ages. The history of the textile industry responsible for human clothing is as old as human civilization [4]. Textile manufacturers in today's era have to monitor the quality of their products. Textile manufacturers must maintain the high-quality standards established by the clothing industry [5]. In recent years, significant studies have been conducted on integrating computer vision and deep learning techniques, revolutionizing textile inspection and manufacturing. Different applications, such as computer vision and digital image processing, transform industries' operations [4]. This paradigm shift, marked by defect detection, fabric pattern recognition, and real-time texture tracking innovations, transforms traditional manual processes. This introduction sets the stage for a comprehensive exploration of seminal works, illuminating the trajectory of advancements driving the evolution of automated textile inspection and manufacturing processes.

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1.1 Image Processing Techniques for Textile Inspection

Textile industry quality inspection predominantly depends on manual inspection. Still, the manual inspection process has many drawbacks, such as fatigue and lack of concentration, and the manual inspection is time-consuming [4]. However, the growth of the artificial intelligence domain has influenced the textile industry and has transformed the process for the better [6]. The textile inspection utilizes image processing technology. The digital cameras used to capture images of fabrics through analysis of these images using computer algorithm defects like holes, strains, color variations, misaligned patterns etc. are identified and classified. There are many studies that have addressed the manual nature of quality assurance in industrial textiles by introducing an innovative computer vision and machine learning approach for automated defect detection [7]. The primary objective of their study was to enhance the efficiency and accuracy of defect identification processes in industrial textiles, which traditionally relied on manual inspection methods. The manual techniques employed by the textile industry were ineffective. The researchers used a sophisticated methodology that combined normalization and classification techniques within a decision-tree model and sought to overcome the challenges associated with inhomogeneous and voluminous shapes characteristic of industrial textiles. The decision-tree model served as the backbone of their classification approach, allowing for systematic and automated defect detection. The results demonstrated a superior classification accuracy compared to existing methods, showcasing the potential of their computer vision and machine learning approach in revolutionizing defect detection processes in the textile manufacturing industry. The significant contributions to the field of textile pattern recognition by emphasizing the imperative need for automation in fabric pattern identification through technology in textile fabric defect detection was a great contribution [8]. Recognizing the manual effort and time constraints associated with traditional practices in the textile industry, the study proposed an advanced real-time classification technique. The methodology was centered on a ResNet pre-trained Convolutional Neural Network architecture [8]. The results of their study showcased the efficacy of the Deep Convolutional Neural Network in achieving high accuracy in the identification of woven fabrics. Incorporating real-time capabilities into their methodology provided a promising avenue for addressing the challenges of manual fabric pattern recognition processes in the textile industry [8, 9].

A groundbreaking vision-based system designed for the automatic quality control of web textile fabrics was introduced for the better-quality products [10]. The researchers addressed the need for robust and efficient quality assurance processes in textile manufacturing by utilizing binary, textural, and neural network algorithms. The methodology aimed to achieve high detection rates, good localization accuracy, and low false alarm rates. The proposed vision-based system offered advantages in terms of efficiency, demonstrating its compatibility with standard inspection tools and highlighting the potential of their approach for real-world applications, emphasizing its suitability for widespread adoption in the textile industry [10].

The development and application of an Automated Visual Inspection System (AVIS) provided a solution for the difficult task of identifying defects in woven textiles [11]. The study was grounded in recognizing the limitations of traditional defect detection methods, prompting the development of an innovative system leveraging computer vision technologies. The researchers utilized blob detection as a structural texture analysis approach, a technique inspired by human perception. By integrating psychophysical experiments to establish perceivable differences in blob attributes that indicate defects in woven textile fabrics. The reliance on psychophysical experiments demonstrated a unique interdisciplinary approach, combining computer vision with insights from human perception studies. This approach aimed to bridge the gap between machine-based defect detection and human visual discernment. It demonstrated the potential of AVIS as an effective and perceptually aligned system for flaw detection in woven textiles [11].

Computer vision Technology has slowly been adopted for textile pattern recognition [8]. It has become imperative for the industry to automate image pattern recognition that removes bottlenecks of the time factors in completing tasks. Convolutional Neural Network (CNN) models were employed to automate image pattern recognition. These neural network models, coupled with gray-level co-occurrence, Gabor wavelet, and Principal Component Analysis, produced superior texture analysis [8, 12].

Subhashree et al. [13] focused the research on fabric defect detection, acknowledging its critical role in ensuring the quality of textiles in the production phase. The authors specifically concentrated on developing an approach that utilized the Hough transform, emphasizing scenarios where horizontal and vertical threads were prominently visible in the image. The methodology involved identifying suitable parameters for defect-free fabric using the Hough-transform-based method. This technique proved promising, particularly in cases where the orientation of threads was discernible.

1.2 Deep Learning and Neural Networks in Textile Production

An advanced real-time classification technique was implemented, resulting in a significant improvement in textile pattern recognition [8]. The primary focus of the study was to address the challenges associated with the manual identification of woven fabrics in the textile industry, proposing a streamlined and efficient solution. The researchers employed a ResNet pre-trained Convolutional Neural Network (CNN) architecture tailored for fabric pattern recognition. Utilizing a pre-trained model like ResNet signifies a deep learning approach, harnessing the power of neural networks to enhance the accuracy and speed of fabric identification processes. The real-time classification technique was introduced and serves as a groundbreaking advancement, catering to the industry's demand for swift and accurate fabric identification [8, 14]. The study's findings demonstrated the high accuracy of the Deep Convolutional Neural Network in efficiently identifying woven fabrics. The noteworthy strides in expanding the application of vision systems beyond traditional domains, specifically in industrial processes, showcased the versatility of vision technologies by introducing a system capable of automatically detecting rotary kiln temperature by integrating neural networks and vision technologies [15].

Incorporating neural network technologies in temperature detection showcased the authors' commitment to leveraging advanced computational approaches for industrial automation. The interdisciplinary nature of vision technologies underscores their transformative impact on automating critical industrial processes [15, 16]. The study's significance lies in its pioneering efforts to bridge the gap between vision systems and industrial applications, setting the stage for subsequent advancements in integrating these technologies in diverse industrial contexts. Textile defect detection and web inspection proposed a novel approach encompassing two key facets: segmenting local textile defects and a cost-effective solution for fast web inspection [17]. The study showcased commitment to addressing critical challenges in textile quality assurance through innovative applications of neural network Technology. The creative application of neural network Technology aimed to address the economic considerations associated with implementing visual inspection systems in textile manufacturing. A seminal work introduced a pioneering two-level generative model designed to represent drapery and clothes images comprehensively. The study focused on advancing the understanding of shape from shading (SFS) problems, presenting a sophisticated approach incorporating 3D surfaces acquired through photometric stereo. Integrating 3D surfaces in the generative model showcased the authors' commitment to addressing the classical ill-posed problem of SFS [18]. Incorporating middle-level visual knowledge to enhance the accuracy and reliability of shape representation in drapery and clothes images contributes to the broader field of computer vision [15]. The study's multifaceted generative model presented a significant departure from traditional approaches, showcasing the authors' dedication to pushing the boundaries of computational imaging. The work represents a crucial advancement in understanding and representing visual information in the context of drapery and clothes images. The study's impact extends beyond the immediate applications in fashion and textile industries, laying the groundwork for further exploration of generative models in diverse visual contexts [15].

1.3 Feature Extraction and Analysis

In a recent contribution to the field of fabric pattern recognition, the author [8] demonstrated a sophisticated approach by incorporating advanced techniques for texture analysis. The researchers emphasized the significance of nuanced texture features in fabric patterns and employed a multifaceted strategy to enhance the accuracy and robustness of their recognition system. Central to their methodology was utilizing a gray-level co-occurrence matrix, Gabor wavelet, and Principal Component Analysis (PCA).

The integration of these techniques underscored commitment to a holistic and comprehensive texture analysis approach [8]. The work significantly advances fabric pattern recognition systems, particularly in scenarios where traditional methods may fall short [8].

In the evolving landscape of the textile industry is the critical aspect underscoring the imperative role of image processing in digital pattern analysis [19]. The study addressed the challenges associated with manual pattern analysis, advocating for adopting automated image processing methods. The argument is that digital pattern analysis reduces operational costs and significantly mitigates time wastage, aligning with the industry's pursuit of efficiency and productivity [19, 20]. The study acknowledges the current challenges and provides a roadmap for future developments in integrating computational techniques, positioning itself at the forefront of the evolving paradigm in textile pattern analysis by leveraging the principles of biological vision to improve the adaptability and performance of fabric defect detection algorithms [21]. The potential for enhanced fabric defect detection contributes to the broader discourse on the interdisciplinary intersections between biology and computer vision [22, 23]. The forefront of the intersection between biomimicry and computer vision demonstrates the transformative potential of integrating biological models into computational algorithms for better defect detection in fabric in the textile industry [22].

Addressing the visual inspection of deformable materials, explicitly focusing on lace, the author [24] introduced a pioneering mechatronic approach that utilized correlation and morphological filters. The work contributed to the specific domain of lace inspection and the broader field of mechatronic vision systems for deformable materials [12, 24].

1.4 Pattern Recognition and Classification

The seminal work of innovative approaches for detecting structural defects in regular and flow-like patterns provided a theoretical foundation for understanding and interpreting structural defects, offering valuable insights into the interplay between regularity, local orientation, and pattern anomalies [25]. The pivotal contribution to the field is not only for its innovative methodology but also for its broader implications. The approaches presented open avenues for further research in the characterization of irregular patterns, with potential applications extending beyond the textile domain to various fields where the identification of structural defects holds paramount importance [25, 26]. The comprehensive review of computer vision technology applied to textile analysis focuses on fabric density measurement, color analysis, and weave pattern recognition. Facilitated a thorough understanding of the synergies and interdependencies within textile inspection by presenting a unified perspective on fabric density, color, and weave pattern analysis [27].

1.5 Real-Time and 3D Techniques

The significant advancement in robotic handling of textiles has the potential to revolutionize automated textile manufacturing [28]. The core of their methodology involved the fusion of appearance features and spatial data, providing a comprehensive understanding of the garment's structure. By employing the Bag of Visual Words, a widespread technique in computer vision, the researchers effectively represented and classified visual features, enabling the robotic system to discern and identify optimal grasping points within the fabric. The significance of the work lies in its applicability to real-world scenarios where textiles, often highly wrinkled and deformable, pose challenges for conventional robotic handling systems [17, 28]. The innovative approach contributes to the ongoing efforts to automate and streamline processes in industries reliant on textile manipulation, presenting a promising trajectory for the future of intelligent robotic systems in garment manufacturing [28]. The noteworthy contributions made to garment manufacturing by focusing on real-time texture tracking and weave pattern recognition. Their research harnessed sophisticated modules, including motion estimation and lattice detection, to enhance the automated understanding of fabric textures and patterns [15]. The significance of work is underscored by its potential impact on the efficiency and precision of garment manufacturing processes. By enabling real-time tracking of textures and recognition of weave patterns, their framework offers a technological leap forward in automating quality control and production tasks in the textile industry [15].

2. Materials and Methods

This study focuses on research between 2002 and 2024, excluding patents and citations in the evaluation criteria. Initially, 103 papers were collected and subsequently filtered to 28 based on relevance for the study. The selection process considered criteria such as the paper's title, its position within the first 10 pages of search results, and the presence of keywords related to computer vision and textiles in the abstract. This initial screening was followed by acquiring full-text articles for further in-depth analysis.

The studies under consideration utilized a variety of computer vision and deep learning techniques for automated textile inspection and manufacturing processes. These techniques included convolutional neural networks (CNNs) for fabric pattern recognition, neural networks for defect detection and web inspection, Gabor wavelet analysis, Principal Component Analysis (PCA) for texture analysis, biomimicry-inspired feature descriptors, correlation and morphological filters for inspecting deformable materials, and real-time 3D information integration for robotic handling of textiles.

3. Result & Discussion

3.1 Topics extracted

- Textile defect detection
- Fabric pattern recognition
- Vision systems for industrial automation
- Deep learning and neural networks for textile inspection
- Real-time fabric identification

LDA

Topic 1: 0.025*"defect" + 0.022*"detection" + 0.021*"textile" + 0.020*"vision" + 0.018*"industrial" + 0.017*"system"

Topic 2: 0.030*"fabric" + 0.027*"pattern" + 0.022*"recognition" + 0.019*"textile" + 0.017*"application"

Topic 3: 0.035*"vision" + 0.028*"system" + 0.024*"automation" + 0.021*"industrial" + 0.020*"task"

Topic 4: 0.032*"learning" + 0.028*"network" + 0.025*"deep" + 0.022*"machine" + 0.020*"technique"

Topic 5: 0.031*"identification" + 0.029*"fabric" + 0.026*"real" + 0.023*"time" + 0.021*"challenge”

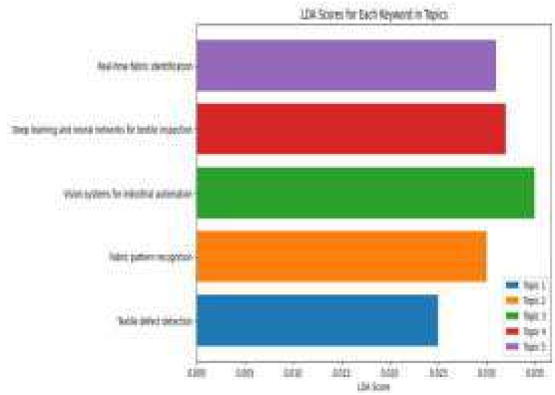


Figure 1: LDA Score for each keyword

The visual in Figure 1 effectively conveys the prevalence of keywords pertinent to textile inspection across all five topics, with terms such as "defect," "fabric," "pattern," "vision," and "system" featuring prominently. This thematic coherence aligns with the inherent connection of each topic to the overarching domain of textile inspection.

However, nuances emerge in the relative importance of specific keywords across the topics. Notably, Topic 1 (Defect Detection) distinguishes itself by assigning greater significance to "defect" and "detection," indicative of a specialized focus on the precise task of identifying defects in textiles.

Likewise, Topic 2 (Fabric Pattern Recognition) exhibits heightened relevance for "fabric" and "pattern" compared to other topics, signaling a more pronounced emphasis on the task of recognizing intricate fabric patterns. The persistent salience of "vision" and "system" across all topics underscores the indispensable role of vision systems as integral tools for tasks associated with textile inspection.

In summary, while the overarching theme of all five topics centers on textile inspection, each topic unveils a distinctive focal point: Topic 1 on defect detection, Topic 2 on fabric pattern recognition, Topic 3 on vision systems for industrial automation, Topic 4 on deep learning and neural networks for textile inspection, and Topic 5 on real-time fabric identification.

Complementary insights from the graph emphasize the uniform importance of all topics in the context of textile inspection, the nuanced significance of specific keywords, and the differentiated thematic focus of each topic.

The accompanying image serves as a comprehensive illustration of LDA scores for keywords in each topic, offering a nuanced understanding of the significance of each keyword within its respective context. The color-coded bars along the x-axis represent individual keywords, while the y-axis delineates the LDA scores.

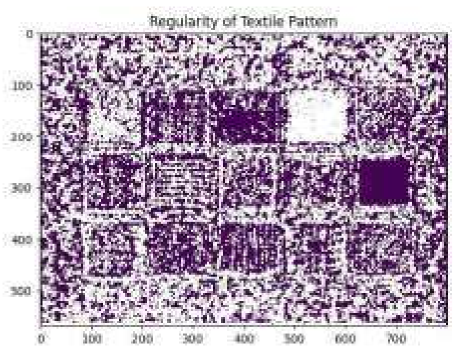
Key observations from the image underscore the critical keywords for each topic and highlight the interconnectedness of specific keywords across multiple topics, such as "textile" and "vision.". Further interpretation underscores the prioritization of "Textile defect detection" as the most crucial topic, the relatively diminished significance of "Real-time fabric identification," the comparative importance of "Fabric pattern recognition" over "Vision systems for industrial automation," and the diverse landscape within "Deep learning and neural networks."

The dataset is predominantly anchored in discussions surrounding textile defect detection, yet it unfolds into a rich tapestry encompassing various facets related to vision systems and machine learning.

3.2 Diverse textures and regularity

(Source: Raw pixel [28], pixabay [15])

Figure 2: Textile Pattern



(Source: Researchers Output)

Figure 3: Regularity of Textile Pattern

The images presented a close-up of a woven fabric exhibiting a rich and complex texture. Figure 2 showcased the fabric's intricate weave, highlighting multiple yarn thicknesses and colors contributing to visual interest and variation. As visualized in Figure 3, the analysis focused on local and global regularity within the fabric. Locally, the study examined the consistency of patterns within specific regions. Small blue and green squares likely represented extracted texture features, such as directionality, frequency, and coarseness. These features were used to quantify local regularity, differentiating between consistently spaced and straight weaves and those with more irregular or slubby characteristics.

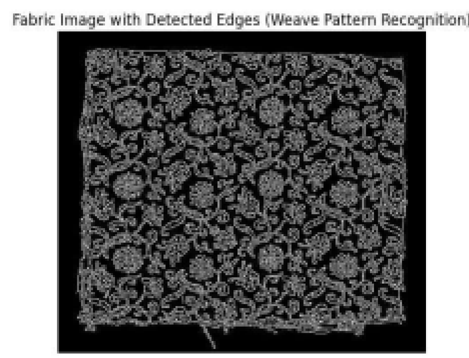
Globally, the analysis aimed to evaluate the overall uniformity of the texture across the entire fabric. While the colored bars on the right side of Figure 3 may have represented this aspect, further context regarding the analysis software was needed to confirm their function.

The blue and green squares in Figure 3 likely represented extracted texture features, providing crucial information for understanding the weave pattern's intricacies. Additionally, the colored bars likely represented color histograms, illustrating the distribution of yarn colors within the fabric. This information was vital for identifying dominant colors and assessing color consistency.

3.3 Weave Pattern Recognition

(Source: look and learn)

Figure 4: Original fabric image to be tested for detected edges



(Source: Researcher's output)

Figure 5: Fabric image with detected edges

The image provided in Figure 4 offers a detailed close-up of a woven fabric characterized by a complex geometric pattern reminiscent of a previously shared image. The weave lines exhibited a raised profile, contributing to a pronounced three-dimensional effect that enhanced depth and texture. The subsequent output of the Wave Pattern Recognition system, visualized in Figure 5, manifested as a heatmap superimposed on the original fabric image. Regions denoted by higher temperatures (in red and yellow hues) signified deviations from the expected wave pattern regularity, potentially indicating defects. Conversely, cooler temperatures (in blue and green) corresponded to areas where the weave lines adhered to anticipated patterns, reflecting consistency.

The envisioned applications for quality inspection were multifaceted. Firstly, the heatmap in Figure 5 was an effective tool for defect detection, facilitating the identification and analysis of potential flaws. Moreover, by analyzing the temperature distribution and patterns in Figure 5, algorithms could be devised to classify defects automatically based on severity and characteristics. The heatmap also found utility in pattern matching, enabling comparison with a reference template for ideal weave regularity and revealing deviations indicative of production inconsistencies or machinery issues. The overarching goal was quality control automation, achieved by setting temperature thresholds for acceptable patterns, automating quality checks, and flagging fabrics exceeding thresholds for further inspection or rejection. Moving forward, the refinement of the wave pattern recognition algorithm was paramount, necessitating training on a diverse dataset, noise reduction techniques, and exploration of varied feature extraction and classification methods for robust defect detection. Validation through extensive testing across fabric samples and production scenarios was essential, involving a comparative analysis with manual inspection by textile professionals. Lastly, consideration was given to the seamless integration of the wave pattern recognition system into existing production lines and quality control infrastructure, ensuring real-time defect detection and implementation efficacy.

3.4 Bag of Words Analysis

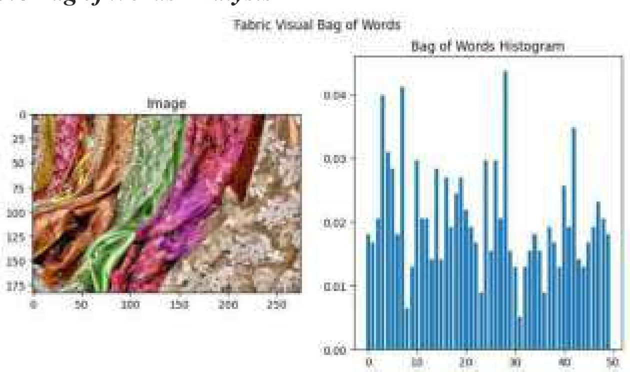


Figure 6: Fabric visual Bag of Words

The analysis of fabric visual representation employs the Bag of Visual Words (BoVW) methodology, providing a structured depiction of image features for classification and retrieval tasks. The process and its components are illustrated and explained below:

Figure 6: Left Side – Original Image

The left side of Figure 6 presents the original grayscale image of fabric, devoid of any color. This monochromatic approach accentuates the gradations of gray, enabling the detailed identification and analysis of texture and structural patterns within the fabric.

SIFT Key Points

Distinctive features within the grayscale image are identified using the Scale-Invariant Feature Transform (SIFT). These features, represented by yellow circles on the image, act as critical markers that highlight significant and invariant regions of interest across scales.

Cluster Centers Assigned to Key Points

The SIFT key points are further processed to form visual words through a clustering mechanism. Each identified key point is associated with a specific cluster, depicted as small colored squares on the image. This clustering reflects the grouping of visually similar features into cohesive clusters.

Image with Key Points and Cluster Labels

The cluster labels are overlaid on the original image, establishing a clear visual relationship between distinct regions of the fabric and their corresponding visual words. This superimposition facilitates an intuitive understanding of how the BoVW methodology abstracts and organizes image features.

Figure 6: Right Side – Histogram of Visual Words

The right side of Figure 6 features a histogram that elucidates the frequency distribution of visual words derived from the clustering process. The x-axis represents the cluster labels, while the y-axis quantifies occurrence frequencies. This histogram effectively demonstrates the BoVW methodology's ability to encapsulate an image as a collection of visual words, which serves as a foundational aspect for applications such as image classification and retrieval.

Adjustable Clusters

The number of clusters, set at 50 in this instance, is a tunable parameter. Increasing the number of clusters can yield a more detailed image representation but may also introduce noise, necessitating a balance between detail and robustness.

Feature Dependence

The nature of the visual words is inherently influenced by the features extracted from the image. In this analysis, SIFT features are employed, but alternative feature extraction methods could be utilized, potentially altering the composition and effectiveness of the visual words.

Diverse Representational Approaches

While the Bag of Visual Words is a prominent methodology for representing images in classification tasks, it is not the sole approach. Emerging paradigms and intense learning-based techniques are gaining popularity for their sophistication and ability to model complex visual patterns. These modern approaches offer a complete perspective to traditional methods like BoVW.

The segment titled "Newspaper Shirt" presents Figure-7, featuring a shirt adorned with a distinctive newspaper print pattern, wherein the textual content appears to be thematically linked to the fictional character "He-Who-Must-Not-Be-Named" from the esteemed Harry Potter

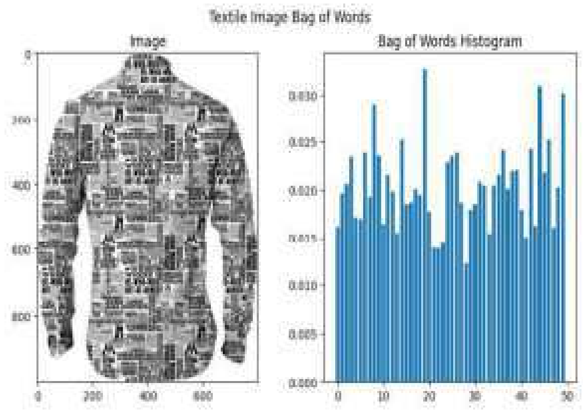


Figure 7: Textile image Bag of Words and Histogram

series. The imagery conveys an intricate interplay between fashion and literary symbolism. Concurrently, the "Bag-of-Words Histogram" section of Figure 7 supplements this visual representation with a graphical depiction, utilizing bars to delineate the frequencies of distinct words. While specific terms and their respective counts may pose challenges for direct discernment within the image, certain conspicuous words, including "DARK LORD," "NOT-BE-NAMED," and "SIGHTINGS," suggest a thematic alignment with the newspaper text, thus contributing to an interpretative layer that extends beyond the visual portrayal. This dual representation engages viewers in a nuanced exploration of semiotic connections between textual content and its graphical manifestation. The study analyzes the impact of technologies such as computer vision and deep learning in textile inspection and manufacturing. The topics extracted for the study, such as textile defection, fabric pattern recognition, etc., meet the study's objectives.

4. Conclusions

The infusion of computer vision and deep learning into textile inspection bears profound implications for textile industry managers [7, 8, 10 & 24]. Implementing automated systems can enhance defect detection precision and speed, offering a strategic shift from traditional manual processes [7, 8]. The cost-effective vision-based solutions provided a pragmatic avenue for managers to optimize quality assuran e processes, achieving higher detection rates while minimizing false alarms [10]. The mechatronic approach introduced integrated correlation and morphological filters and offered managers an innovative solution for inspecting deformable materials, potentially revolutionizing conventional visual inspection methods [24]. The textile industry's future lies in automated inspection processes, neural network architectures, deep learning techniques, and collaborations between computer vision experts and domain specialists. Real-time decision-making in garment manufacturing presents opportunities for dynamic production processes. Integrating computer vision techniques for texture tracking and pattern recognition can revolutionize quality control and production tasks, ensuring efficiency and adaptability to textile surface changes. Future research can also focus on developing real-time, robust, and cost-effective AI/ML-powered solutions for diverse textile applications, including 3D fabric inspection, predictive maintenance, and sustainable manufacturing practices.

References

[1] Latif, A., Rasheed, A., Sajid, U., Ahmed, J., Ali, N., Ratyal, N. I., & Khalil, T. (2019). "Content-Based Image Retrieval and Feature Extraction: A Comprehensive Review. "Mathematical problems in engineering, 2019(1), 9658350.

[2] Li, Y., Luo, H., Yu, M., Jiang, G., & Cong, H. (2019). Fabric defect detection algorithm using RDPSO-based optimal Gabor filter. The Journal of The Textile Institute, 110(4), 487-495

[3] Pawening, R. E., Dijaya, R., Brian, T., & Suciati, N. (2015, September). Classification of the textile image using a support vector machine with the textural feature. In 2015 International Conference on Information & Communication Technology and Systems (ICTS) (pp. 119-122). IEEE

[4] Rasheed, A., Zafar, B., Rasheed, A., Ali, N., Sajid, M., Dar, S. H., ... & Mahmood, M. T. (2020). Fabric defect detection using computer vision techniques: a comprehensive review. Mathematical Problems in Engineering, 2020(1), 8189403

[5] Anagnostopoulos, C., Vergados, D., Kayafas, E., Loumos, V., & Stassinopoulos, G. (2001). "A computer vision approach for textile quality control." The Journal of Visualization and Computer Animation, 12(1), 31-44

[6] Sikka, M. P., Sarkar, A., & Garg, S. (2024). Artificial intelligence (AI) in textile industry operational modernization. Research Journal of Textile and Apparel, 28(1), 67-83

[7] Siegmund, D., Samartzidis, T., Fu, B., Braun, A., & Kuijper, A. (2017). Fiber defect detection of inhomogeneous voluminous textiles. In Lecture Notes in Computer Science. Lecture Notes in Computer Science (pp. 278–287). doi:10.1007/978-3-319-59226-8_27

[8] Rauf, M. A., Jehanzeb, M., Ullah, U., Ali, U., Kashif, M., & Abdullah, M. (2022, May). Fabric weave pattern recognition and classification by machine learning. 2022 2nd International Conference of Smart Systems and Emerging Technologies (SMARTTECH). Presented at the 2022 2nd International Conference of Smart Systems and Emerging Technologies (SMARTTECH), Riyadh, Saudi Arabia. doi:10.1109/smarttech54121.2022.00026

[9] Poelzleitner, W. (2001, February 12). Color-based localization of patterns through distortion-tolerant graph matching. In K. G. Harding, J. W. V. Miller, & B. G. Batchelor (Eds.), Machine Vision and Three-Dimensional Imaging Systems for Inspection and Metrology. doi:10.1117/12.417212

[10] Stojanovic, R., Mitropulos, P., Koulamas, C., Karayiannis, Y., Koubias, S., & Papadopoulos, G. (2001). Real-time vision-based system for textile fabric inspection. Real-Time Imaging, 7(6), 507–518. doi:10.1006/rtim.2001.0231

[11] Bodnarova, A., Bennamoun, M., & Latham, S. (2002).” Optimal Gabor filters for textile flaw detection. Pattern Recognition”, 35(12), 2973–2991. doi:10.1016/s0031-3203(02)00017-1

[12] Murali, D., & Deepthi, M. (2023). Interwoven, A Digital Public Platform to Connect Artworks Across Museums. Ars Orientalis, 53

[13] Subhashree, V., & Padmavathi, S. (2019). Estimation of parameters to model a fabric in a way to identify defects. In Lecture Notes in Computational Vision and Biomechanics. Proceedings of the International Conference on ISMAC in Computational Vision and Bio-Engineering 2018 (ISMAC-CVB) (pp. 1251–1260). doi:10.1007/978-3-030-00665-5_118

[14] Schmitt, E., Bombardier, V., & Wendling, L. (2008). Improving fuzzy rule classifier by extracting suitable features from capacities with respect to the Choquet integral. IEEE Transactions on Systems, Man, and Cybernetics. Part B, Cybernetics: A Publication of the IEEE Systems, Man, and Cybernetics Society, 38(5), 1195–1206. doi:10.1109/TSMCB.2008.925750

[15] Hu, Y., Long, Z., & AlRegib, G. (2018). “A high-speed, real-time vision system for texture tracking and thread counting.” IEEE Signal Processing Letters, 25(6), 758–762. doi:10.1109/lsp.2018.2825309

[16] Khalifa, N. A., Darwish, S. M., & El-Iskandarani, M. A. (2012, December). “Automated textile defects recognition system using computer vision and interval type-2 fuzzy logic.” 2012 First International Conference on Innovative Engineering Systems. Presented at the 2012 First International Conference on Innovative Engineering Systems (ICIES), Alexandria, Egypt. doi:10.1109/icies.2012.6530861

[17] Ramisa, A., Alenyà, G., Moreno-Noguer, F., & Torras, C. (2014). Learning RGB-D descriptors of garment parts for informed robot grasping. Engineering Applications of Artificial Intelligence, 35, 246–258. doi: 10.1016/j.engappai.2014.06.025

[18] Wei, B., He, H., Hao, K., Gao, L., & Tang, X.-S. (2020). Visual interaction networks: A novel bio-inspired computational model for image classification. Neural Networks: The Official Journal of the International Neural Network Society, 130, 100–110. doi: 10.1016/j.neunet.2020.06.019

[19] Kumah, C., Raji, R. K., & Pan, R. (2020). “Review of printed fabric pattern segmentation analysis and application.” AUTEX Research Journal, 20(4), 530–538. doi:10.2478/aut-2019-0049

[20] Shih, C.-H. V. (1995). Real-time tracking of lace stretches using machine vision. Fifth International Conference on Image Processing and Its Applications. Presented at the Fifth International Conference on Image Processing and its Applications, Edinburgh, UK. doi:10.1049/cp:19950747

[21] Li, C., Gao, G., Liu, Z., Yu, M., & Huang, D. (2018). Fabric defect detection based on biological vision modeling. IEEE Access: Practical Innovations, Open Solutions, 6, 27659–27670. doi:10.1109/access.2018.2841055

[22] Rasheed, A., Zafar, B., Rasheed, A., Ali, N., Sajid, M., Dar, S. H., ... & Mahmood, M. T. (2020). Fabric defect detection using computer vision techniques: a comprehensive review. Mathematical Problems in Engineering, 2020(1), 8189403

[23] Sousa, C. E. B., Medeiros, C. M. S., Pereira, R. F., Neto, M. A. V., & Neto, A. A. (2020, July). Defect detection and quality level assignment in wet blue goatskin. Proceedings of the 11th International Conference on Advances in Information Technology. Presented at the IAIT2020: The 11th International Conference on Advances in Information Technology, Bangkok, Thailand. doi:10.1145/3406601.3406650

[24] Yazdi, H. R., & King, T. G. (1998). Application of 'vision in the loop' for inspection of lace fabric. Real-Time Imaging, 4(5), 317–332. doi:10.1016/s1077-2014(98)90002-x

[25] Chetverikov, D., & Hanbury, A. (2002). Finding defects in texture using regularity and local orientation. Pattern Recognition, 35(10), 2165-2180

[26] Phan, Q. H., Fu, H., & Chan, A. B. (2015). Look closely: Learning exemplar patches for recognizing textiles from product images. In Lecture Notes in Computer Science. Computer Vision – ACCV 2014 (pp. 461–476). doi:10.1007/978-3-319-16865-4_30

[27] Fan, W., Wang, Y., Liu, R., Zou, J., Yu, X., Liu, Y., ... & Meng, J. (2024). Textile production by additive manufacturing and textile waste recycling: a review. Environmental Chemistry Letters, 22(4), 1929-1987

[28] Ramisa, A., Alenyà, G., Moreno-Noguer, F., & Torras, C. (2014). Learning RGB-D descriptors of garment parts for informed robot grasping. Engineering Applications of Artificial Intelligence, 35, 246–258. doi: 10.1016/j.engappai.2014.06.025

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Investigation on Mechanical and Damping Characteristics of Silk Fiber Reinforced Polypropylene Composites

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Abstract:

This research work primarily focuses on the tensile strength and damping properties of silk fiber-reinforced polypropylene composites. Recycled silk fibers were used as a reinforcement phase and polypropylene fibers were used as a matrix phase in the composite. The composites were fabricated using a compression molding machine. Four different composite samples were developed by varying the silk fiber content in the composites (70:30, 60:40, 50:50, and 40:60). The influence of silk fiber content on the tensile strength and damping properties were investigated. It was observed from the results that the composite sample with 50% silk fiber content has shown the highest tensile, flexural, and impact strengths of 36.16 MPa, 38.12 MPa, and 29.03 kJ/m2 respectively. In the damping properties, the highest natural frequency was observed in the composite with 40% silk fiber content due to increased stiffness. It was also noticed that a reduction in the damping properties with a decrement in the silk fiber content in the composite. The composite developed can be used as an interior component in automobiles.

Keywords: *Fiber, Natural Frequency, Polypropylene, Silk, Tensile Strength, Vibration*

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1. Introduction

Natural fiber composites occupy a predominant place in all engineering fields due to global environmental concerns. The carbon footprints and greenhouse gas emissions are reduced by the utilization of natural fibers in composite manufacturing [1]. Due to the wide range of properties of natural fibers, the composite developed from them can be used in civil, marine, packing, automotive, aerospace, and electronic industries. Enormous research materials are available in natural fiber composites such as sisal [2, 3], bamboo [4, 5], coir [6, 7], and banana [8, 9].
Silk is a natural filament and queen of textile fibers. It is known for its high strength, extensibility, and compressibility [10]. These properties make silk fibers an alternative source for synthetic fibers in composite development. In silk weaving mills, silk hard waste occurs as selvedge waste. This is used for making only embroidery threads and is not utilized for any other value-added purposes.

Damping measures the ability to absorb and dissipate vibrational frequency further which decides the applications of composites in in automotive parts. Excellent bonding with resin/hybrid natural fibers and filter/ resin interface enhances the stiffness of the composites and improves the vibration characteristics. Factors such as frictional properties and energy dissipation at maximum strain area in the filler enhance the damping nature of the composites [11].

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Experimental investigation was carried out on free vibration characteristics of short sisal fiber (SFPC) and short banana fiber (BFPC) polyester composites. Impact of fiber length and weight percentage on mechanical properties and free vibration characteristics are analyzed. Composite specimen is fabricated with random fiber orientations using compression molding machine at 17 MPa compression. It is observed that the increase in fiber content enhances the mechanical and damping properties [12, 13]. In this research work, an attempt is made to develop a composite from the silk selvedge waste by converting it into soft waste with polypropylene fibers using a compression molding technique. The mechanical and damping properties of the silk fiber-reinforced polypropylene composites are investigated.

2. Materials and Methods

Selvedge waste of silk weaving was collected from Ethnic Fashions, Bengaluru, and converted into fibrous form by using an opening machine, Polypropylene staple fibers were procured from Zenith fibers, Vadodara. Table 1 represents the physical properties of fibers such as staple length, strength (BISFA'1998), and fineness (ASTM D-3822-07). In the composite fabrication, silk is used as a reinforcement phase and polypropylene is used as a matrix phase.

Table 1- Fiber properties

Fiber	Staple Length (mm)	Fineness (Tex)	Strength (g/d)
Silk	45	2.17	1.59
Polypropylene	51	2.5	5.5

2.1 Blending and Web Formation

Impurities from the silk fibers were removed manually. Both the silk and PP were blended with the help of a blending machine. Four types of blends such as 70:30, 60:40, 50:50, and 40:60 was prepared by varying the weight percentage of fibers in the blend. The fiber blends were converted into sheet form by carding machine [14, 15]. This sheet was used as a preform for composite development.

2.2 Composite Fabrication

Composites were developed in a compression moulding machine. The preform was kept between the top and bottom plates of the machine. Moulding was carried out at 175°C, 15 min time, and at 35 bar pressure [10]. The specimen was allowed to cool in the machine. The composite developed and structural properties are mentioned in Table 2.

Table 2 - Composite Structural Parameters

Sample ID	Composite Type (silk / polypropylene)	Thickness (mm)	Weight (g/m^2)	Density (g/cm^3)
1	70/30	1.32	1012	0.789
2	60/40	1.28	998	0.754
3	50/50	1.18	858	0.712
4	40/60	1.12	812	0.684

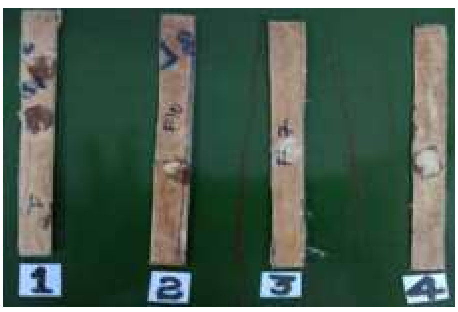

Figure - 1 Fabricated Composite Specimens

3. Testing and Analysis

3.1 Mechanical properties

Tensile strength (ASTM D 638), Flexural strength (ASTM D790-0), and impact strength (ASTM D256) were measured for the composites. A gauge length of 50 mm was used for tensile and flexural tests. The crosshead speed of 50 mm/min was maintained in the flexural testing.

3.2 Vibration Test

Vibration test was conducted with impact hammer and accelerometer setup to estimate the natural frequencies. Impact hammer having a sharp and hard aluminium tip. Piezoelectric accelerometer was glued with specimen at predefined location. Specimen size was 120*10*3 mm. Specimen was fixed identical to a cantilever beam with a suitable fixer. Impact hammer act as an external exciter and accelerometer act as a response capture element. Impact hammer was hit in four equal intervals of time on the specimen at different points. Response signal from the accelerometer was recorded using Data acquisition system (DAS). Figure 2 shows the vibration testing setup. First three mode frequencies were obtained from the results where maximum amplitude and phase difference are coincided.

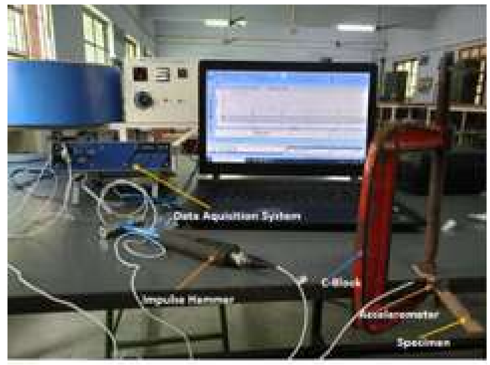

Figure - 2 Vibration testing setup

4. Results and Discussion

4.1 Mechanical properties

The mechanical properties of the silk fiber-reinforced polypropylene composites at different silk fiber content were evaluated and the values are represented in Table 3. It is observed that sample 3 has the highest tensile strength of 36.16 MPa followed by sample 4 of 32.92 MPa. This may be due to the better bonding of fibers in the polypropylene resin. The lowest tensile strength of 23.01 was noted in sample 1 which is due to the high level of fiber content led to agglomeration within the matrix causing non uniform stress transfer in the composites shown in Figure 3 [11]. Similarly, in the flexural strength of the composites sample 3 has shown maximum flexural strength of 38.12 MPa. Table 3 depicts the mechanical properties of the composites.

Table 3 - Mechanical properties of the composites

Sample ID	Tensile strength (MPa)	Flexural strength (MPa)	Impact strength (kJ/m^2)
1	23.01	24.76	21.14
2	31.84	35.18	25.56
3	36.16	38.12	29.03
4	32.92	34.16	27.56

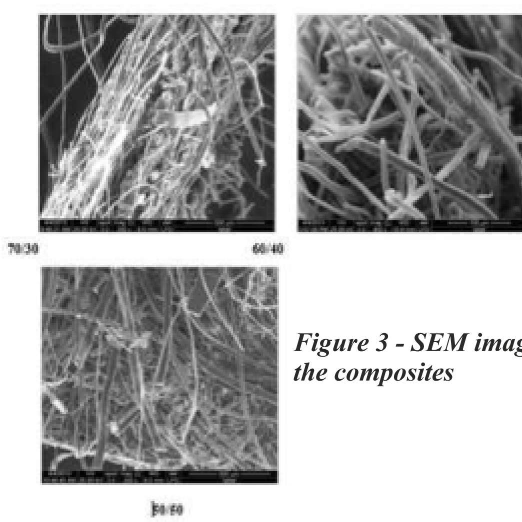

Figure 3 - SEM images of the composites

4.2 Vibration and damping properties

Natural frequencies of the composites increase with increasing polypropylene content. The first three modes are falling below 300 Hz. It exhibits more damping properties. Specimen 4 has more stiffness and hence it experiences high natural frequencies. Similarly, specimen 3 shows more damping characteristics. Vibration results are plotted in the graphs shown in Figure 4.

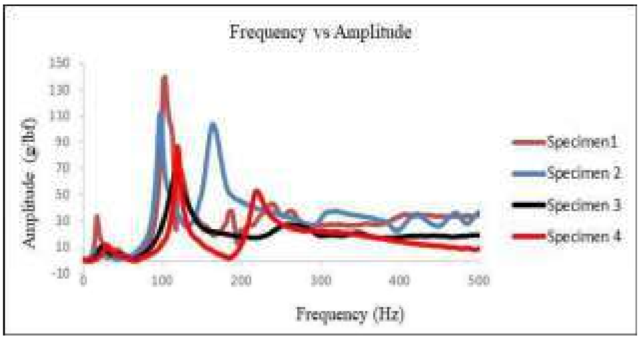

Figure 4 - Frequency vs Amplitude

Specimen 1 showed mode 1 value with maximum amplitude of 33.60 g/lbf and phase changes from -47.80 to 86.66 with the natural frequency of 17.18 Hz. Mode 2 exists at 139.79 g/lbf and phase changes from 158.48 to -117.54 with the natural frequency of 139.79 Hz. Similarly, mode 3 were found at 98.43 Hz with the maximum amplitude of 88.69 g/lbf and the phase changes occurred from 9.033 to -4.143. The natural frequencies and corresponding amplitude of the specimens 2,3 and 4 are listed in the table 4. Damping factor of the specimen 1 varies from 0.0159 to 0.1027, for specimen 2 it varies from 0.0345 to 0.648, for specimen 3 it varies from 0.199 to 0.229 and for specimen 4 it varies from 0.0039 to 0.1041.

Table 4 - Natural Frequency vs Amplitude

Specimen	Natural Frequency (Hz)			Amplitude (g/lbf)		
	Mode 1	Mode 2	Mode 3	Mode 1	Mode 2	Mode 3
1	17.18	62.50	98.43	33.60	139.79	88.69
2	18.75	96.875	164.06	9.10	111.98	104.00
3	23.43	117.18	260.93	10.88	67.95	27.36
4	31.25	138.75	278.18	15.93	32.69	82.97

5. Conclusion

Silk fiber reinforced polypropylene composites were fabricated using compression moulding technique by varying the fiber concentrations. The effect of fiber concentrations on the mechanical and damping properties were investigated. It was observed from the results that composites having 50% silk fiber content has shown highest tensile strength of 36.16 MPa, and flexural strength of 38.12 MPa. Composite has 40 % of silk and 60 % polypropylene showed highest natural frequency due to increased stiffness. As polypropylene association increases natural frequency gets increased at the same time damping characteristics are getting reduced. Composite has 60% of silk and 40% of polypropylene exhibits with improved damping characteristics among other composites. The composites developed from this work can be used as automobile interiors.

References

[1] Gholampour, A., & Ozbakkaloglu, T. (2020). A review of natural fiber composites: Properties, modification and processing techniques, characterization, applications. Journal of Materials Science, 55(3), 829-892
[2] Kalaprasad, G., Joseph, K., Thomas, S., &Pavithran, C. (1997). Theoretical modelling of tensile properties of short sisal fiber-reinforced low-density polyethylene composites. Journal of materials science, 32(16), 4261-4267
[3] Bai, S. L., Li, R. K. Y., Wu, L. C. M., Zeng, H. M., & Mai, Y. W. (1998). Tensile failure mechanisms of sisal fibers in composites. Journal of materials science letters, 17(21), 1805-1807
[4] Rajulu, A. V., Devi, L. G., Rao, G. B., & Reddy, R. L. (2003). Chemical resistance and tensile properties of epoxy/unsaturated polyester blend coated bamboo fibers. Journal of reinforced plastics and composites, 22(11), 1029-1034
[5] Cao, Y., & Wu, Y. Q. (2008). Evaluation of statistical strength of bamboo fiber and mechanical properties of fiber reinforced green composites. Journal of Central South University of Technology, 15(1), 564-567
[6] Cao, Y., & Wu, Y. Q. (2008). Evaluation of statistical strength of bamboo fiber and mechanical properties of fiber reinforced green composites. Journal of Central South University of Technology, 15(1), 564-567
[7] Jayabal, S., & Natarajan, U. (2011). Drilling analysis of coir-fiber-reinforced polyester composites. Bulletin of Materials Science, 34(7), 1563-1567
[8] Venkateshwaran, N., &Elayaperumal, A. (2010). Banana fiber reinforced polymer composites-a review. Journal of Reinforced Plastics and Composites, 29(15), 2387-2396
[9] Sapuan, S. M., Leenie, A., Harimi, M., &Beng, Y. K. (2006). Mechanical properties of woven banana fiber reinforced epoxy composites. Materials & design, 27(8), 689-693
[10] Rajkumar, G., & Srinivasan, J. (2018). Characterization of Recycled Silk Fiber PP Composites with Optimal Performance of Silk Fibers by Response Surface Methodology. Journal of Testing and Evaluation, 48(5), 3392-3409
[11] Sumesh, K. R., & Kanthavel, K. (2020). Effect of TiO2 nano-filler in mechanical and free vibration damping behavior of hybrid natural fiber composites. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 42(4), 211
[12] Rajkumar, D. R., Santhy, K., & Padmanaban, K. P. (2021). Influence of mechanical properties on modal analysis of natural fiber reinforced laminated composite trapezoidal plates. Journal of Natural Fibers, 18(12), 2139-2155
[13] Kumar, K. S., Siva, I., Jeyaraj, P., Jappes, J. W., Amico, S. C., & Rajini, N. (2014). Synergy of fiber length and content on free vibration and damping behavior of natural fiber reinforced polyester composite beams. Materials & Design (1980-2015), 56, 379-386
[14] Rajkumar, G., Srinivasan, J., & Suvitha, L. (2015). Natural protein fiber hybrid composites: Effects of fiber content and fiber orientation on mechanical, thermal conductivity and water absorption properties. Journal of Industrial Textiles, 44(5), 709-724
[15] Rajkumar, G. (2022). Silk and wool hybrid fiber-reinforced polypropylene composites. In Wool Fiber Reinforced Polymer Composites (pp. 273-299). Woodhead Publishing

Sustainable Approach towards the Extraction of Cellulose from Bamboo and Banana Natural Resources: A Review

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Abstract:

Environmental concerns and an increased demand for sustainable materials have prompted scientists to investigate alternative cellulose extraction technologies. The production of cellulose from green plant sources has gained popularity in recent years due to its vital role in resolving sustainability challenges and meeting the rising demand for ecologically friendly products. Bamboo and banana, both numerous and renewable resources, have emerged as potential alternatives because to their rapid growth rates and little environmental impact. This review study comprehensively explores the sustainable methods utilised in the extraction of cellulose from bamboo and banana, covering various extraction techniques, environmental concerns, and potential applications. The utilisation of bamboo and banana as cellulose sources has environmental and economic benefits, paving the way for a greener, more sustainable future.

Keywords: *Cellulose Extraction, Sustainable Materials, Renewable Resources, Environmental Impact*

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1. Introduction

The extraction of cellulose from renewable plant sources has received increased attention in recent years, owing to its critical role in resolving sustainability issues and satisfying the growing demand for environmentally friendly products [1, 2 & 3] . Traditionally, cellulose was derived from wood pulp (Fig.1), which typically required extensive chemical treatments and had a considerable environmental impact. However, the loss of forest supplies and worries about deforestation have prompted the investigation of alternate cellulose sources. Bamboo and banana, two abundant and fast regenerating plants [4], present intriguing options for cellulose production [5, 6]. Bamboo, known for its quick growth rate and low environmental impact, has received attention for its potential as a sustainable supply of cellulose [7]. Similarly, bananas, which are primarily grown for their fruit, generate a significant quantity of agricultural waste in the form of stalks and pseudo stems, which contain important cellulose fibres.

The use of bamboo and banana for cellulose extraction not only reduces the environmental effect of traditional sources, but also provides chances for waste valorisation and economic growth, especially in areas where these plants are plentiful. Furthermore, the sustainable extraction of cellulose from bamboo and banana is consistent with global initiatives to move towards a circular economy and lessen reliance on finite resources [8, 9]. Understanding the sustainable ways and problems of cellulose extraction from bamboo and banana is critical for furthering research in this area and realising the full potential of these renewable resources [10, 11]. The present study gives a complete overview of sustainable extraction processes, environmental concerns, prospective uses, and economic perspectives for bamboo and banana cellulose, therefore contributing to the development of greener and more sustainable materials.

The primary objective of the study is to elucidate the significance of sustainable cellulose extraction from bamboo and banana in the context of environmental conservation, resource efficiency, and circular economy principles and to provide a comprehensive overview of the sustainable extraction techniques employed for cellulose isolation from bamboo and banana, including mechanical, chemical, enzymatic, and green solvent-based methods. The present review also focused on environmental sustainability of bamboo and banana cellulose extraction processes through life cycle assessment, carbon footprint analysis, and waste minimization strategies to explore the diverse applications of cellulose derived from bamboo and banana, spanning industries such as bio-plastics, biofuels, textiles, paper, and packaging materials, to analyse the economic viability of bamboo and banana cellulose extraction, including cost analysis, market trends, and potential socioeconomic impacts, to identify the challenges and opportunities associated with sustainable cellulose extraction from bamboo and banana, and propose future research directions for advancing this field. By addressing these objectives, this review aims to contribute to the body of knowledge on sustainable materials science and technology, fostering innovation and driving the transition towards a more sustainable and circular economy.

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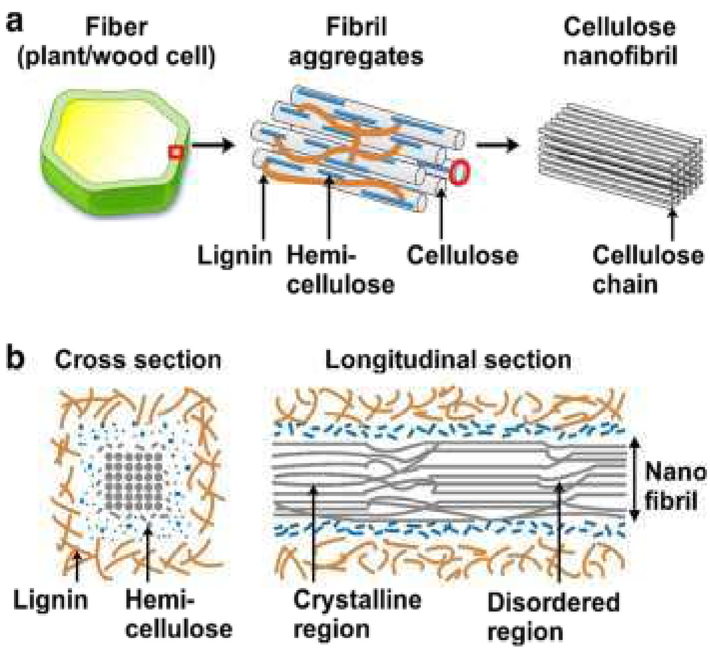

Figure 1- Illustration of cellulose a) bamboo or banana fibril aggregate and nanofibril associated with lignin and hemicellulose b) cross section and longitudinal section showing crystalline and disordered regions [12]

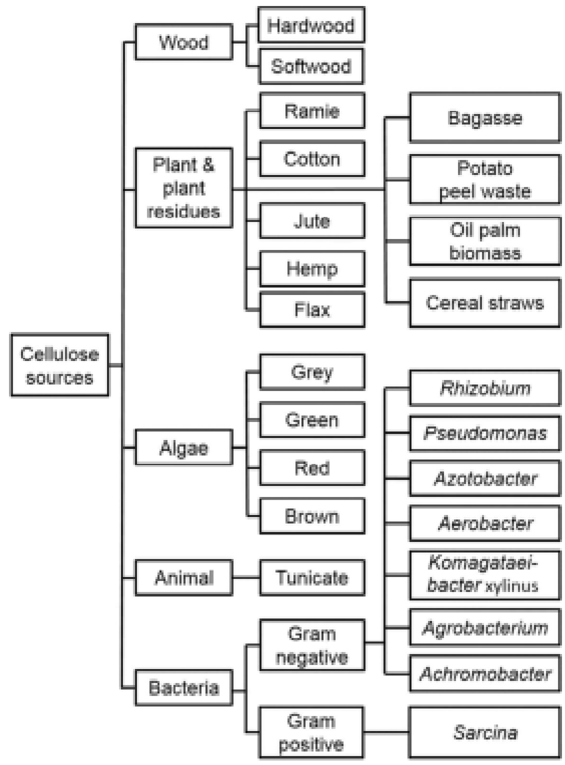

Figure 2 - Classification of cellulose according to the Source [12]

2. Importance of Cellulose

Cellulose, a polysaccharide found in plant cell walls, is one of the world's most prevalent organic molecules [1, 10, & 13]. Its unique features, including as biodegradability, renewability, and biocompatibility, make it a very desirable material for a variety of industrial applications [7, 14] . Cellulose is the principal structural component in plant tissues, giving strength, stiffness, and resilience [3]. Furthermore, its fibrous structure allows for varied processing, resulting in the manufacture of a diverse variety of cellulose-based goods such as paper, textiles, bioplastics, and biofuels [15]. As worldwide demand for sustainable materials grows, cellulose emerges as an important resource for solving environmental issues and establishing a circular economy [7].

3. Traditional Sources vs. Bamboo and Banana

There are several sources of cellulose such wood and plant residues (Fig.2) [16, 17], algae animal and bacteria (Fig.4) [12, 18]. Historically, cellulose was collected mostly from wood pulp generated from plants like pine, spruce, and eucalyptus [19]. While wood pulp remains a popular source of cellulose, worries about deforestation, habitat devastation, and biodiversity loss have led researchers to look into other sources. Bamboo and banana, two fast renewing plants with little environmental effect, represent intriguing alternatives to traditional wood-based cellulose supplies [20]. Bamboo, known for its quick growth rate and high cellulose content, has various benefits over traditional timber sources. Unlike trees, which can take decades to mature, bamboo matures in just a few years, making it a very sustainable and renewable resource. Furthermore, bamboo growing uses little water and no pesticides, further lowering its environmental impact. The use of bamboo for cellulose extraction not only conserves forest resources, but it also supports degraded land rehabilitation and climate change mitigation. Banana, which is largely grown for its fruit, generates significant volumes of agricultural waste in the form of stalks and pseudo stems [20, 21]. These fibrous wastes, which are generally considered by-products or garbage, include rich cellulose fibres that may be recovered and used in a variety of applications. By using banana trash to produce cellulose, we not only minimise waste disposal and associated environmental damage, but also provide new cash streams to farmers and encourage sustainable farming practices.

3.1 Bamboo as a Cellulose Source

Bamboo has gained popularity as a sustainable source of cellulose due to its quick growth, high cellulose content, and low environmental footprint. Bamboo cellulose has several uses, including papermaking, textiles, composites, and biofuels [4]. Bamboo-based goods are regarded for their strength, durability, and sustainability, making them viable alternatives to traditional materials sourced from fossil fuels or virgin wood pulp. Bamboo production also supports biodiversity, soil conservation, and carbon sequestration, which helps to ensure environmental sustainability and mitigate climate change [5, 22].

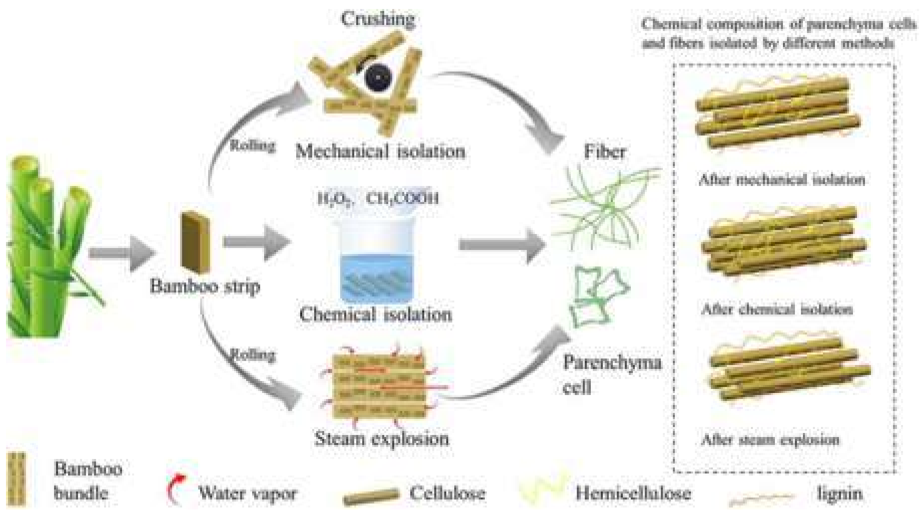

Table 8 - Changes in S/N ratio of yarn U%, CVm%, and IPI as explained by ANOVA and ranked by the Taguchi method

To summarise, bamboo is a potential and sustainable source of cellulose, with several uses and major environmental advantages. Its use in cellulose extraction emphasises the need of utilising renewable resources to address the rising demand for sustainable products in an ever-changing environment [2].

3.2 Sustainable Characteristics of Bamboo

Bamboo has various sustainable properties that make it a desirable supply of cellulose. Bamboo is notable for its quick growth, with some species reaching 91 cm (36 inches) in a single day. This high growth rate enables the speedy replenishment of bamboo resources, minimising strain on natural forests. Furthermore, bamboo growing requires little water and no pesticides or fertilisers, making it an eco-friendly alternative to traditional timber sources. Furthermore, bamboo's broad root structure prevents soil erosion and maintains soil health, so contributing to ecosystem stability and biodiversity conservation.

3.3 Bamboo Cellulose Extraction Methods

Several techniques are used to extract cellulose from bamboo (Table 1), each having its own advantages and disadvantages. Mechanical techniques entail physically breaking down bamboo fibres by grinding, milling, or mechanical pounding. Chemical procedures, such as acid or alkaline hydrolysis, use chemical treatments to dissolve lignin and hemicellulose and separate cellulose fibres (Fig.3) [24-26]. Enzymatic procedures use cellulose enzymes to catalyse the hydrolysis of cellulose, providing a more ecologically friendly alternative to standard chemical processes [27]. Furthermore, approaches for combining mechanical, chemical, and enzymatic processes have been developed to increase the efficiency and sustainability of bamboo cellulose extraction.

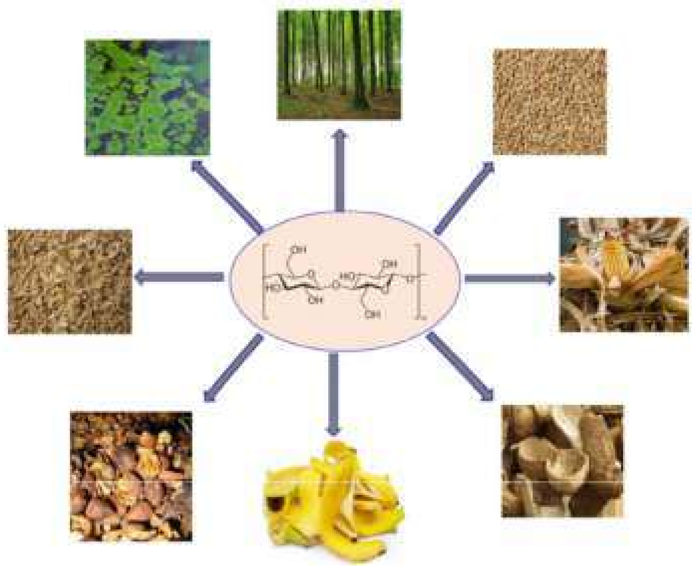

Figure 4 - Sources of cellulose [28]

Table 1 - Methods for extracting cellulose and nano-cellulose [29]

Extracted Materials	Extraction method	Evaluation method
Cellulose	Cross Bevan method	Serious environmental pollution Low product extraction rate Good effect
	Nitric acid ethanol hair	
	Alkali bleaching process	
Nano cellulose	Acid hydrolysis	Main preparation methods Environmentally friendly
	Physical mechanical method	
	Enzymolysis Solvent method	Mild process conditions Limited

3.4 Environmental Considerations

The extraction of cellulose from bamboo must be done with great attention for environmental effect. Chemical extraction procedures, if not adequately handled, can produce toxic waste and pollute water and land. As a result, using green solvents and eco-friendly chemicals is critical for reducing environmental impact. Furthermore, sustainable forestry approaches, such as bamboo growing in agroforestry systems or managed plantations, contribute to ecosystem integrity and biodiversity while providing a consistent supply of bamboo materials for cellulose extraction [29].

3.5 Potential Applications of Bamboo Cellulose

Bamboo cellulose's unique qualities and sustainability make it useful in a variety of sectors. Bamboo cellulose is spun into fibres and used in textile manufacturing to create soft, breathable textiles with inherent antibacterial characteristics. Bamboo pulp is used to make high-quality paper goods such as tissue paper, cardboard, and packaging materials. Furthermore, bamboo cellulose-based composites are used in several applications [14] like construction materials, furnishings, and automobile components due to their strength, durability, and light weight [30]. Furthermore, bamboo cellulose shows potential as a feedstock for biofuel production, providing a green alternative to fossil fuels.

3.6 Banana as a Cellulose Source

Banana, which is largely grown for its fruit, is also an excellent source of cellulose. The stalks and pseudostems of banana plants contain large amounts of cellulose fibres, which may be harvested and used in a variety of applications [31, 32]. Banana waste, which is frequently thrown or left to degrade, offers a potential for waste repurposing and resource optimisation [33]. By using banana waste for cellulose extraction, we not only minimise waste disposal and associated environmental damage, but also provide new revenue streams for farmers and encourage sustainable agricultural practices [34, 35].

3.7 Utilization of Banana Waste

Banana trash, which includes stalks, pseudostems, and other remnants from banana production and processing, represents a considerable opportunity for resource utilisation and waste reduction [36]. Traditionally considered agricultural trash, banana biomass includes rich cellulose fibres that may be recovered and used in a variety of applications [33]. By converting banana waste into cellulose, we not only reduce environmental pollution but also provide new economic possibilities for farmers and contribute to sustainable resource management. Mechanical processing is a typical method for using banana waste, in which the biomass is chopped, shredded, or crushed to break down plant tissues and liberate cellulose fibres. Chemical procedures, such as acid or alkaline hydrolysis, can also be used to dissolve lignin and hemicellulose and extract cellulose fibres from banana biomass [37, 38]. Furthermore, enzymatic techniques utilising cellulase enzymes provide ecologically favourable options for cellulose extraction from banana waste [39]. The use of banana waste for cellulose extraction adheres to the concepts of circular economy and waste-to-resource conversion, supporting sustainable farming practices and minimising dependency on raw resources. Furthermore, by reusing banana trash, we can reduce the environmental effect of garbage disposal, lower greenhouse gas emissions, and conserve natural resources.

3.8 Extraction Techniques for Banana Cellulose

Several processes are used to extract cellulose from banana waste, each of which is adapted to the biomass's structure and content. Mechanical processes, such as milling, grinding, or pulping, are used to degrade banana fibres and liberate cellulose. Chemical techniques, such as acid or alkaline hydrolysis, remove lignin and hemicellulose while isolating cellulose fibres [40]. Enzymatic techniques use cellulose enzymes to catalyse the hydrolysis of cellulose, providing a more ecologically friendly and selective way for extracting cellulose from banana waste [41, 42]. Integrating these strategies can improve the efficiency and sustainability of banana cellulose extraction while reducing energy consumption, chemical use, and environmental effect. Furthermore, optimising the extraction parameters, such as temperature, pH, and reaction time, can enhance the yield and quality of banana cellulose while decreasing process waste and environment footprint.

3.9 Environmental Sustainability

The extraction of cellulose from banana trash has several environmental benefits. First, by valorizing banana waste, we redirect organic material away from landfills or incineration, lowering greenhouse gas emissions and environmental damage. Furthermore, banana growing usually uses minimum pesticides and fertilisers, lowering the environmental effect of cellulose manufacturing from banana waste [43]. Furthermore, using banana waste for cellulose extraction helps to improve soil health and fertility by returning organic matter to agricultural areas. Furthermore, when compared to traditional cellulose sources like wood pulp, banana waste provides a more sustainable option with shorter cultivation cycles, better biomass production, and a reduced environmental footprint [39]. Adopting environmentally friendly extraction processes and waste management procedures improves the sustainability of banana cellulose manufacturing, coinciding with worldwide initiatives to promote resource efficiency and circular economy principles.

3.10 Applications of Banana Cellulose

Banana cellulose's unique qualities and sustainability make it useful in a variety of sectors. In the textile business, banana cellulose fibres may be spun into yarns and fabrics, resulting in textiles with natural antibacterial and moisture-wicking qualities [37]. Banana pulp is used to make eco-friendly paper goods such as packaging materials, stationery, and tissue paper. Furthermore, banana cellulose-based products are used in bio-composites, building materials, and biomedical applications because of their strength, flexibility, and biodegradability. Furthermore, banana cellulose shows potential as a renewable feedstock for biofuel production, providing an alternative to fossil fuels and helping to transition to a low-carbon economy. We can maximise economic and environmental benefits by investigating innovative uses and value-added products derived from banana cellulose.

4. Comparative Analysis

When comparing banana cellulose extraction to traditional cellulose sources such as wood pulp, various benefits and possibilities emerge. To begin, banana trash provides an easily available and abundant source of cellulose, decreasing the requirement for land conversion and deforestation associated with traditional forestry operations. Furthermore, banana agriculture uses less inputs such as water, pesticides, and fertilisers than timber production, resulting in less environmental impact and resource depletion [44]. Furthermore, banana cellulose extraction techniques such as enzymatic hydrolysis and mechanical processing provide ecologically favourable alternatives to standard chemical processes by reducing energy consumption, chemical usage, and waste formation. Furthermore, banana cellulose-based materials have distinct features such as natural antibacterial activity, making them ideal for use in healthcare, food packaging, and personal care good [12]. Overall, using banana waste for cellulose extraction is a sustainable and cost-effective alternative to traditional cellulose sources, with environmental, social, and economic benefits. By transforming banana trash into a valuable resource, we can promote circular economy concepts, minimise waste output, and contribute to a more sustainable future.

4.1 Comparative Assessment of Bamboo and Banana Cellulose Extraction

When comparing bamboo and banana cellulose extraction, a number of issues must be considered, including resource availability, extraction efficiency, environmental effect, and possible uses. Bamboo, with its quick growth rate and high cellulose content, provides benefits in terms of resource availability and production [26]. However, banana waste is a widely available and plentiful supply of cellulose, which helps to reduce waste and promote circular economy concepts. Extraction efficiency, environmental sustainability, and product quality are all important concerns when comparing bamboo and banana cellulose extraction processes.

4.2 Environmental Impact Comparison

The environmental effect of cellulose extraction from bamboo and banana is determined by a variety of factors, including growing methods, extraction processes, and waste management strategies. Bamboo growing often uses less water and pesticides, making it a more ecologically friendly alternative to traditional timber sources. However, if chemical extraction procedures are not adequately regulated, they might lead to pollution. Similarly, banana waste utilisation improves the environment by removing organic material from landfills and lowering greenhouse gas emissions. However, if energy-intensive extraction techniques and chemical consumption are not optimised, these advantages may be negated.

4.3 Economic Viability

The economic feasibility of bamboo and banana cellulose extraction is determined by several aspects, including resource availability, extraction efficiency, production costs, market demand, and possible income sources. Bamboo, with its quick growth and abundance, provides cost savings in terms of raw material supply. However, investing in extraction equipment and processing facilities may increase upfront expenses. Banana waste utilisation, on the other hand, offers potential for waste valorisation and income production, which offsets extraction expenses. Furthermore, market demand for sustainable and environmentally friendly materials may influence the economic sustainability of bamboo and banana cellulose products.

4.4 Sustainable Extraction Techniques

Several methods of extraction have been employed to obtain cellulose from bamboo and banana, each with advantages and limits in terms of environmental sustainability and efficiency.

1.4.1 Mechanical Methods

Mechanical techniques include physically breaking down plant fibres to get cellulose. While mechanical methods need a lot of energy, they are ecologically benign and generate little trash.

1.4.2 Chemical Methods

Chemical procedures use acids, alkalis, or solvents to dissolve lignin and hemicellulose and separate cellulose fibres. While efficient, chemical processes can produce hazardous waste and need careful management to reduce environmental damage.

1.4.3 Enzymatic Approaches

Enzymatic procedures use cellulase enzymes to catalyse the hydrolysis of cellulose, providing ecologically benign and selective extraction techniques. In comparison to chemical procedures, enzymatic approaches often demand softer conditions and create less byproducts.

1.4.4 Integration of Green Solvents

The use of green solvents, such as ionic liquids or deep eutectic solvents, provides ecologically acceptable alternatives to standard solvents in cellulose extraction. Green solvents are non-toxic, biodegradable, and recyclable, minimising environmental effect and waste output.

4.4.5 Environmental Considerations

Environmental issues in bamboo and banana cellulose extraction include life cycle evaluation, carbon footprint analysis, and waste minimization measures.

4.5 Life Cycle Assessment (LCA)

LCA assesses the environmental effect of cellulose extraction processes from cradle to grave, taking into account resource extraction, production, transportation, usage, and disposal. LCA assists in identifying potential for environmental improvement and guiding decision-making towards more sustainable practices.

4.6 Carbon Footprint Analysis

Carbon footprint study analyses the greenhouse gas emissions caused by cellulose extraction operations, such as energy consumption, chemical use, and waste production. Carbon footprint study assesses the environmental effect of cellulose extraction and identifies emission-reduction methods.

4.7 Waste Minimization Strategies

Waste minimization measures are intended to decrease waste creation, increase resource efficiency, and promote circular economy concepts in cellulose extraction operations. Waste reuse, recycling, and valorisation are all strategies that aim to reduce environmental impact while increasing sustainability.

Overall, sustainable cellulose extraction from bamboo and banana necessitates a comprehensive approach that includes environmental, economic, and social factors throughout the manufacturing process. Sustainable extraction techniques, environmental considerations, and waste minimization strategies must all be integrated to promote resource efficiency, reduce environmental impact, and move towards a more sustainable future.

5. Summary and outlook

The sustainable extraction of cellulose from bamboo and bananas offers a possible avenue to manufacturing renewable, biodegradable materials. Implementing environmentally friendly techniques and optimising resource utilisation are critical to attaining sustainability goals in cellulose manufacturing. Both bamboo and banana plants are renewable resources, with bamboo standing out for its fast rate of development. Using banana pseudo stems, which are generally thrown as garbage, increases value while reducing environmental impact. Optimising processes to reduce energy usage is critical. Reducing or replacing toxic chemicals with eco-friendly alternatives is critical for reducing environmental impact. To save water resources, effective water management and recycling practices should be employed.

References

[1] M. Rasheed, M. Jawaid, and Z. Karim, "Extracted from Bamboo Fiber," Molecules 2020, 25, 2824; doi:10.3390/molecules25122824

[2] S. Kassaye, K. K. Pant, and S. Jain, "Hydrolysis of cellulosic bamboo biomass into reducing sugars via a combined alkaline solution and ionic liquid pretreament steps," Renew. Energy, vol. 104, pp. 177–184, 2017, doi: 10.1016/j.renene.2016.12.033

[3] J. Wang, X. Li, J. Song, K. Wu, Y. Xue, and Y. Wu, "Direct Preparation of Cellulose Nanofibers from Bamboo by Nitric Acid and Hydrogen Peroxide Enables Fibrillation via a Cooperative Mechanism," Nanomaterials 2020, 10, 943; doi:10.3390/nano10050943 2020

[4] S. Verma, S. A. R. Hashmi, M. Mili, V. Hada, N. Prashant, and A. Naik, "Extraction and applications of lignin from bamboo : a critical review," Eur. J. Wood Wood Prod., no. 0123456789, 2021, doi: 10.1007/s00107-021-01743-w

[5] A. P. Deshpande, M. B. Rao, and C. L. Rao, "Extraction of Bamboo Fibers and Their Use as Reinforcement in Polymeric Composites" Journal of Applied Polymer Science, Vol. 76, 83–92 (2000)

[6] M. Hu et al., "Investigation on the Classified Extraction of the Bamboo Fiber and Its Properties Investigation on the Classified Extraction of the Bamboo Fiber and," J. Nat. Fibers, vol. 0, no. 0, pp. 1–11, 2019, doi: 10.1080/15440478.2019.1599311

[7] Q. Lin, Y. Huang, and W. Yu, "Industrial Crops & Products Effects of extraction methods on morphology , structure and properties of bamboo cellulose," Ind. Crop. Prod., vol. 169, no. February, p. 113640, 2021, doi: 10.1016/j.indcrop.2021.113640

[8] Y. Dong, "D i rect Extract i on o f Po l ysacchar i des from Moso Bamboo (Phy l ostachys heterocyc l a) Ch i ps Us i ng a M i xed So l vent System o f an Am i no Ac i d Ion i c L i qu i d w i th Po l ar Aprot i c So l vent," 2018, doi: 10.1246/bcsj.20170383

[9] S. Han, Q. Yao, C. Jin, B. Fan, H. Zheng, and Q. Sun, "Cellulose Nanofibers From Bamboo and Their Nanocomposites With Polyvinyl Alcohol : Preparation and Characterization," polymer composites. 1–9, 2016, doi: 10.1002/pc

[10] Q. Lin, Y. Huang, and W. Yu, "An in-depth study of molecular and supramolecular structures of bamboo cellulose upon heat treatment," Carbohydr. Polym., vol. 241, no. May, p. 116412, 2020, doi: 10.1016/j.carbpol.2020.116412

[11] D. Gaspar, S. N. Fernandes, and A. G. De Oliveira, "Fabrication of nanocrystalline cellulose from banana peel obtained from unripe plantain bananas Fabrication of nanocrystalline cellulose from banana peel obtained from unripe plantain bananas" Journal of Physics: Conference Series 1644 (2020) 012002 doi: 10.1088/1742-6596/1644/1/012002

[12] H. Seddiqi et al., Cellulose and its derivatives: towards biomedical applications, vol. 28, no. 4. Springer Netherlands, 2021. doi: 10.1007/s10570-020-03674-w

[13] Z. Hu, R. Zhai, J. Li, Y. Zhang, and J. Lin, "Preparation and Characterization of Nanofibrillated Cellulose from Bamboo Fiber via Ultrasonication Assisted by Repulsive Effec," International Journal of Polymer Science Volume 2017, Article ID 9850814, 9 pages https://doi.org/10.1155/2017/9850814

[14] K. M. Anamoongmongkol, R. S. Uwapanich, L. P. Humjan, W. N. Arkrugsa, and P. S. Riprom, "Production of Cellulose From Bamboo Shoot Shell Using Hydrothermal Technique," Journal of the Japan Institute of Energy, 100, 307-312 2021

[15] M. T. Garnett, H. Kumar, S. Kumar, B. S. Beckingham, and S. L. M. Alexander, "Sustainability," pp. 170–178, 2024, doi: 10.1039/d3su00192j

[16] P. Kulkarni, "Sources of cellulose and their applications- A review INTERNATIONAL JOURNAL OF DRUG FORMULATION AND RESEARCH SOURCES OF CELLULOSE AND THEIR APPLICATIONS – A Review" www.ordonearresearchlibrary.org ISSN 2229-5054, Review November, 2015

[17] F. Casanova, R. Freixo, C. F. Pereira, A. B. Ribeiro, and E. M. Costa, "Comparative Study of Green and Traditional Routes for Cellulose Extraction from a Sugarcane By-Product" Polymers 2023, 15, 1251. https://doi.org/10.3390/ polym15051251

[18] L. Chopra, "Materials Today : Proceedings Extraction of cellulosic fibers from the natural resources : A short review," Mater. Today Proc., no. xxxx, 2021, doi: 10.1016/j.matpr.2021.08.267
[19] Teofil Jesionowski, Maria Kuznowicz, Artur Jędrzak, Tomasz Rębiś, Sensing Materials: Biopolymeric Nanostructures, B9780128225486000157, Pages 286-304, ISBN 9780128225493, https://doi.org/10.1016/B978-0-12-822548-6.00015-7
[20] K. Mayandi, N. Rajini, and S. O. Ismail, "Biowaste Management : Comparison of Banana (Musa acuminata) and Bamboo (Bambusa vulgaris) Fibers," no. January, 2024, doi: 10.15376/biores.19.1.1245-1259
[21] Vinay Kumar, Pritha Chakraborty, Poonam Janghu, Mridul Umesh, Suma Sarojini, Ritu Pasrija, Komalpreet Kaur, Sivarama Krishna Lakkaboyana, Vimal Sugumar, Manivannan Nandhagopal, Azhagu Madhavan Sivalingam, Potential of banana based cellulose materials for advanced applications: A review on properties and technical challenges, Carbohydrate Polymer Technologies and Applications, Volume 6, 2023, 100366, ISSN 2666-8939, https://doi.org/10.1016/j.carpta.2023.100366 "S2666893923000877."
[22] R. Roro, A. Yusrina, and H. Suryadi, "Preparation and Characterization of Microcrystalline Cellulose Produced from Betung Bamboo (Dendrocalamus asper) through Acid Hydrolysis," vol. 10, no. 2, pp. 79–83, 2018, doi: 10.5530/jyp.2018.2s.15
[23] J. Li, C. Lian, J. Wu, T. Zhong, Y. Zou, and H. Chen, "Morphology, chemical composition and thermal stability of bamboo parenchyma cells and fibers isolated by different methods," Cellulose, vol. 30, no. 4, pp. 2007–2021, 2023, doi: 10.1007/s10570-022-05030-6
[24] Y. Hu, L. Tang, and Q. Lu, "Preparation of cellulose nanocrystals and carboxylated cellulose nanocrystals from borer powder of bamboo," Cellulose (2014) 21:1611–1618, doi: 10.1007/s10570-014-0236-0
[25] M. Rasheed, M. Jawaid, B. Parveez, A. Zuriyati, and A. Khan, Jo ur l P re. Elsevier B.V, 2020. doi: 10.1016/j.ijbiomac.2020.05.170
[26] A. S. Singh, S. Halder, and J. Wang, "Extraction of bamboo micron fibers by optimized mechano-chemical process using a central composite design and their surface modification," Mater. Chem. Phys., 2017, doi: 10.1016/j.matchemphys.2017.06.040
[27] J. Li et al., "Bioresource Technology Green , efficient extraction of bamboo hemicellulose using freeze-thaw assisted alkali treatment," Bioresour. Technol., vol. 333, no. February, p. 125107, 2021, doi: 10.1016/j.biortech.2021.125107
[28] L. Chopra, "Extraction of cellulosic fibers from the natural resources : A short review Materials Today : Proceedings Extraction of cellulosic fibers from the natural resources : A short review," Mater. Today Proc., no. September 2021, 2023, doi: 10.1016/j.matpr.2021.08.267
[29] X. Cao et al., "Cellulose-based functional hydrogels derived from bamboo for product design," no. August, pp. 1–12, 2022, doi: 10.3389/fpls.2022.958066
[30] K. P. Rajan, N. R. Veena, H. J. Maria, R. Rajan, M. Skrifvars, and K. Joseph, "Extraction of bamboo microfibrils and development of biocomposites based on polyhydroxybutyrate and bamboo microfibrils," Journal of Composite Materials 45(12) 1325–1329 2010, doi: 10.1177/0021998310381543
[31] R. E. A. Nascimento, M. Carvalheira, G. Crespo, and A. Neves, "clean technologies Extraction and Characterization of Cellulose Obtained from Banana Plant Pseudostem" Plant Pseudostem. Clean Technol. 2023, 5, 1028–1043. https://doi.org/10.3390/cleantechnol5030052
[32] B. Ai et al., "Biodegradable Cellulose Film Prepared From Banana Pseudo-Stem Using an Ionic Liquid for Mango Preservation," vol. 12, no. February, pp. 1–10, 2021, doi: 10.3389/fpls.2021.625878
[33] H. Mohd et al., "Heliyon Banana biomass waste : A prospective nanocellulose source and its potential application in food industry – A review," Heliyon, vol. 9, no. 8, p. e18734, 2023, doi: 10.1016/j.heliyon.2023.e18734
[34] S. Mishra, B. Prabhakar, P. S. Kharkar, and A. M. Pethe, "Banana Peel Waste : An Emerging Cellulosic Material to Extract Nanocrystalline Cellulose," pp. 8–13, 2023, doi: 10.1021/acsomega.2c06571
[35] F. Surattanamal, S. Sulong, N. Waloh, and B. Sohsansa, "Physicochemical Properties of Cellulose extracted From Hom Thong Banana Peels," vol. 1, no. 1, pp. 199–206, 2021 DOI: https://doi.org/10.31098/ihsatec.v14i1.501
[36] R. Singanusong, W. Tochampa, T. Kongbangkerd, and C. Sodchit, "EXTRACTION AND PROPERTIES OF CELLULOSE FROM BANANA PEELS," vol. 21, no. 3, pp. 201–213, 2014, doi: 10.14456/sjst.2014.16
[37] B. M. Reddy, P. Subramanian, S. Sriramajayam, and P. Vijayakumary, "Extraction of cellulose from banana sheath and its characterization," vol. 11, no. 6, pp. 1861–1867, 2022, 2349-8242
[38] N. M. Ennig, M. K. Ottaisamy, and S. A. B. U. T. Homas, "A Novel Method for the Synthesis of Cellulose Nanofibril Whiskers from Banana Fibers and Characterization," J. Agric. Food Chem., Vol. 56, No. 14, 2008 5617–5627
[39] V. Mukwaya, W. Yu, R. A. M. Asad, and H. Yagoub, "An environmentally friendly method for the isolation of cellulose nano fibrils from banana rachis fibers," 2015, doi: 10.1177/0040517515622155
[40] P. Samathoti, B. S. Ramya, and L. K. Dogiparthi, "Methods of Extraction of Cellulose," vol. 17, no. 4, pp. 3–11, 2023.
[41] J. N. Prod, P. Resour, P. V Joshi, A. A. Mandot, and B. H. Patel, "Enzymatic Extraction of Nano Cellulose from Banana Stem : Morphological , Structural and Thermal Characterization," vol. 8, no. 1, pp. 1–11, 2018
[42] M. Akhlaq and M. Uroos, "Evaluating the Impact of Cellulose Extraction via Traditional and Ionosolv Pretreatments from Domestic Matchstick Waste on the Properties of Carboxymethyl Cellulose," ACS Omega 2023, 8, 8722−8731 2023, doi: 10.1021/acsomega.2c08118
[43] J. Antonkiewicz, "The effect of cellulose production waste and municipal sewage sludge on biomass and heavy metal uptake by a plant mixture," Environmental Science and Pollution Research (2018) 25:31101–31112 https://doi.org/10.1007/s11356-018-3109-5
[44] R. S. Abolore, S. Jaiswal, and A. K. Jaiswal, "Green and sustainable pretreatment methods for cellulose extraction from lignocellulosic biomass and its applications : A review," Carbohydr. Polym. Technol. Appl., vol. 7, no. November 2023, p. 100396, 2024, doi: 10.1016/j.carpta.2023.100396

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Mycelium-Based Flame Retardant Treatments for Textiles Using Extracts of Turkey Tail, Reishi, and Shiitake

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Abstract:

The rising demand for sustainable flame-retardant textiles has led to the exploration of bio-based alternatives. This study evaluates the flame-retardant efficacy of mycelium extracts derived from Turkey Tail (Trametes versicolor), Reishi (Ganoderma lucidum), and Shiitake (Lentinula edodes) on cotton (250 GSM), linen (270 GSM), and polyester (220 GSM) fabrics. Using the pad-dry-cure method, textiles were treated with a 10 g/L mycelium extract solution and tested for flame retardancy. The Limiting Oxygen Index (LOI) significantly increased across all fabric types, with Turkey Tail-treated cotton reaching 25%, compared to 17-20% for untreated fabric. The after flame time in the vertical flame test was reduced from 12 seconds (untreated cotton) to 3 seconds (Turkey Tail-treated). Additionally, the heat release rate (HRR) was reduced by 40%, and smoke generation decreased by 28%. Char yield analysis revealed an improvement to 38% for Turkey Tail-treated cotton, indicating enhanced thermal stability. Statistical analysis showed a mean LOI increase from 20.33% (untreated) to 24.33% (Turkey Tail-treated), with an ANOVA p-value of 0.072, suggesting a positive trend in flame-retardant performance. These results confirm the potential of mycelium extracts as an effective, biodegradable, and non-toxic alternative to conventional flame-retardant treatments, supporting sustainability in textile applications.

Keywords: *Biodegradable, flame-retardant, mycelium, polyester, sustainable, textile*

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1. Introduction

The increasing awareness of fire hazards in domestic, industrial, and public environments has propelled the demand for flame-retardant textiles. Traditional flame retardants, which rely heavily on synthetic chemicals such as halogenated compounds, pose significant environmental and health risks due to their toxic by-products and non-biodegradability. This necessitates the development of sustainable alternatives that are both effective and environmentally benign. Mycelium, the vegetative part of fungi, has emerged as a promising bio-based material for diverse applications, owing to its unique chemical composition, structural properties, and ecological benefits [1]. The polysaccharides, proteins, and secondary metabolites present in mycelium exhibit potential as flame-retardant agents by promoting char formation and limiting oxygen availability during combustion. While polysaccharides contribute to char formation, the role of proteins in flame retardancy is limited as they primarily decompose at high temperatures. The secondary metabolites in mycelium, such as phenolics and melanin-like compounds, may further enhance thermal stability by acting as antioxidants and radical scavengers, reducing combustion propagation [2]. This study focuses on developing a mycelium-based flame-retardant finish for textiles using extracts of Turkey Tail (Trametes versicolor), Reishi (Ganoderma lucidum), and Shiitake (Lentinula edodes)

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Figure 1 - Mechanism of flame retardancy in mycelium

2. Literature Review

Flame-retardant textiles have been extensively studied to mitigate the risks of fire propagation. Conventional approaches rely on chemical finishes that inhibit the combustion process by mechanisms such as gas-phase radical quenching, intumescence, or char formation. Recent research has highlighted the potential of natural materials, including plant-based and fungal extracts, for imparting flame-retardant properties to textiles [3].

The extraction of bioactive compounds from mycelium involves substrate preparation, sterilization, inoculation, and controlled incubation. Agricultural waste such as sawdust and rice husk has been identified as an efficient and sustainable substrate for fungal growth [4]. Proper sterilization using autoclaving at 121°C ensures the elimination of competing microorganisms, thereby enhancing the yield and quality of mycelium extracts. The importance of maintaining optimal incubation conditions, including temperature, humidity, and duration, to maximize the production of bioactive compounds [5]. Additionally, the use of filtration methods, such as membrane filters with a pore size of 0.45 μm, ensures the collection of pure mycelium extracts for subsequent application [6].

The pad-dry-cure method is widely employed for applying flame-retardant finishes to textiles due to its simplicity, efficiency, and scalability. This method ensures uniform distribution of the finish and facilitates strong adhesion to the fabric surface [7]. Combining mycelium extracts with binding agents such as di-ammonium hydrogen phosphate has been shown to improve durability and performance under thermal stress [8]. Research demonstrates that the application process significantly influences the pick-up ratio, drying, and curing parameters, which in turn affect the overall flame-retardant performance of the fabric [3, 9].

Pre-treatment processes such as desizing, scouring, and bleaching play a critical role in preparing textile substrates for finishing. Desizing involves the removal of starch and other sizing agents, which can otherwise hinder the penetration of flame-retardant finishes. Sodium hydroxide-based scouring enhances the hydrophilicity of textiles by removing impurities such as oils and waxes [10]. Bleaching with hydrogen peroxide ensures a uniform substrate by eliminating natural colorants, thus facilitating better interaction with the mycelium-based finish [11].

Comprehensive testing is crucial to evaluate the effectiveness of flame-retardant finishes. To ensure consistency in testing, fabric samples were preconditioned at standard atmospheric conditions (65% relative humidity and 21°C) for 24 hours, as recommended by ASTM D1776 [12]. Variations in moisture content can influence combustion characteristics, and standardized conditioning minimizes such inconsistencies. The Limiting Oxygen Index (LOI) test, conducted according to ASTM D2863, quantifies the minimum oxygen concentration required to sustain combustion [13]. Vertical flame tests (ASTM D6413) assess the after flame and afterglow times, providing insights into the flame spread characteristics of treated textiles [3, 14]. Advanced techniques such as conical calorimetry (ASTM E1354) are used to measure the heat release rate (HRR) and smoke generation during combustion, which are critical parameters for assessing fire performance [15, 16]. Thermogravimetric analysis (TGA) has been employed to analyze the thermal degradation and char yield of treated textiles, offering valuable data on the material's thermal stability [17]. The toxicity and persistence of conventional flame retardants have raised environmental concerns, leading to regulatory restrictions and a push for bio-based alternatives [18].

The use of mycelium-based finishes aligns with the principles of green chemistry and sustainable manufacturing. Unlike synthetic flame retardants, mycelium extracts are biodegradable and derived from renewable resources, minimizing environmental impact [1]. Furthermore, the integration of agricultural waste as a substrate for fungal growth contributes to waste valorization, reducing the burden on landfills and promoting circular economy practices [19].

While the flame-retardant potential of mycelium extracts is evident, limited studies have focused on their application to different fabric substrates under controlled conditions. Additionally, comparative analyses of various mycelium species for flame-retardant applications remain underexplored. This study addresses these gaps by systematically evaluating the performance of Turkey Tail, Reishi, and Shiitake extracts on cotton, linen, and polyester fabrics..

2. Materials and Methods

The mycelium species used in this study were Turkey Tail (Trametes versicolor), Reishi (Ganoderma lucidum), and Shiitake (Lentinula edodes). Each species was prepared by extracting 50 mL of their respective extracts per treatment to ensure uniformity and effectiveness.

Figure 3 - Turkey Tail

Figure 4 - Reishi

Figure 5 - Shiitake

The fabric substrates included cotton (100%), linen (flax-based), and polyester (100%), with the following specifications: cotton (250 GSM, 20 pieces of 30 cm x 30

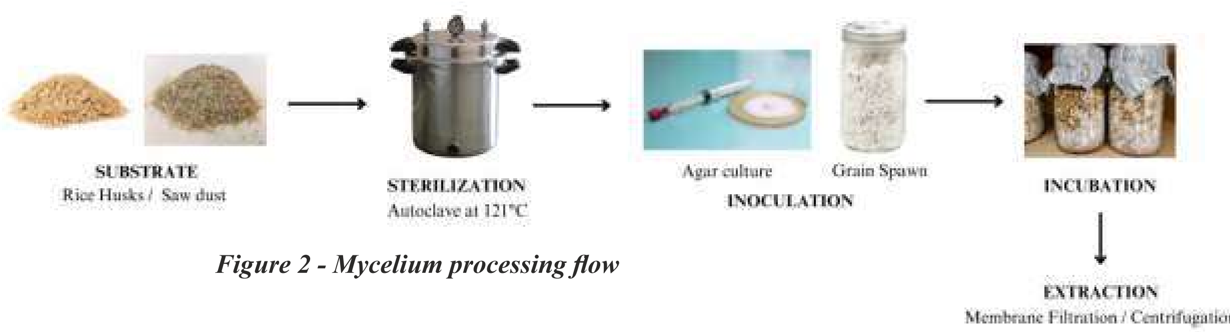

Figure 2 - Mycelium processing flow

cm), linen (270 GSM, 20 pieces of 30 cm x 30 cm), and polyester (220 GSM, 20 pieces of 30 cm x 30 cm). The chemical agents used in the fabric preparation process were di-ammonium hydrogen phosphate (10 g/L solution) as a binding agent and sulphuric acid (5 g/L) for desizing, sodium carbonate (2 g/L) for nuutralization, soidum hydroxide (20 g/L) or scouring, and water (1 L per batch).

The extraction of mycelium was carried out using agricultural waste, specifically sawdust and rice husk, as the substrate. To ensure sterility, the substrate was autoclaved at 121°C for 15 minutes. Fungal spores were then inoculated into the substrate under sterile conditions, and the mycelium was incubated at a temperature of 24°C with a relative humidity of 85% for 15 days. After the incubation period, the mycelium was harvested by filtering through a 0.45 µm membrane filter, obtaining the desired fungal extract for subsequent treatment.

The fabric substrates underwent a desizing process to eliminate starch and a scouring process to remove natural oils, waxes, mineral impurities, and other residues. Desizing was carried out by soaking the fabrics in a 5 g/L sulfuric acid solution for 3–4 hours at room temperature (25°C). This was followed by scouring, which involved treating the fabrics with 20 g/L sodium hydroxide at boiling temperature (100°C) for 2 hours to ensure effective removal of impurities. Future work could explore enzymatic or oxidative desizing methods to improve sustainability and maintain fabric strength [10]. The fabrics were rinsed in cold water and neutralized using a sodium carbonate (2 g/L) solution to neutralize. Following desizing, the fabrics underwent a scouring process using a solution of sodium hydroxide (NaOH) (10 g/L) and detergent (2 g/L) at 90°C for 1 hour. After scouring, the fabrics were bleached using hydrogen peroxide at 6 g/L concentration at 80°C for 45 minutes to ensure a clean, uniform substrate.

4. Application of Mycelium Extract (Pad-Dry-Cure Method)

The mycelium extracts of Turkey Tail, Reishi, and Shiitake were applied to the fabric substrates using the Pad-Dry-Cure method. The fabrics were first soaked in a solution of the mycelium extract mixed with a binding agent (10 g/L) for 30 minutes. The fabrics were then padded using a mangle machine at a pressure of 2 bar, with a pick-up ratio of 80% and a speed of 2 m/min. After padding, the fabrics were dried in a hot-air oven at 120°C for 5 minutes and then cured at 150°C for 3 minutes to ensure proper fixation of the mycelium extract on the fabric substrates. The curing temperature and duration were selected based on prior studies on bio-based coatings. However, further optimization may be required, as some flame-retardant finishes require higher temperatures (160–180°C) or longer curing times to achieve stronger fixation and durability [7].

The study involved the preparation of twelve samples, consisting of untreated and treated fabric types (cotton, polyester, and linen) with mycelium extracts of Turkey Tail, Reishi, and Shiitake

Various tests are conducted to evaluate the fire resistance and thermal properties of fabrics. The Limiting Oxygen Index (LOI) Test is used to determine the oxygen index and assess fire resistance. The Vertical Flame Test (ASTM D6413) measures after flame time and flammability [14]. The Heat Release Rate (HRR) Test (ASTM E1354) evaluates the total heat release during combustion [15]. To assess smoke generation, the Smoke Density Test (ASTM E662) is performed. The Thermal Conductivity Test (ISO 22007-2) helps measure the thermal conductivity of treated fabrics [20].Additionally, Char Yield Analysis is conducted using thermogravimetric analysis (TGA) to determine the char yield at 600°C, providing insights into the material's thermal degradation behaviour.

5. Results and Discussion

The results of the treated fabrics are presented in this section, highlighting the differences in flame retardancy among the mycelium extracts. The effectiveness of Turkey Tail, Reishi, and Shiitake extracts on cotton, polyester, and linen was evaluated based on Limiting Oxygen Index (LOI), afterflame time, heat release rate, and char yield.

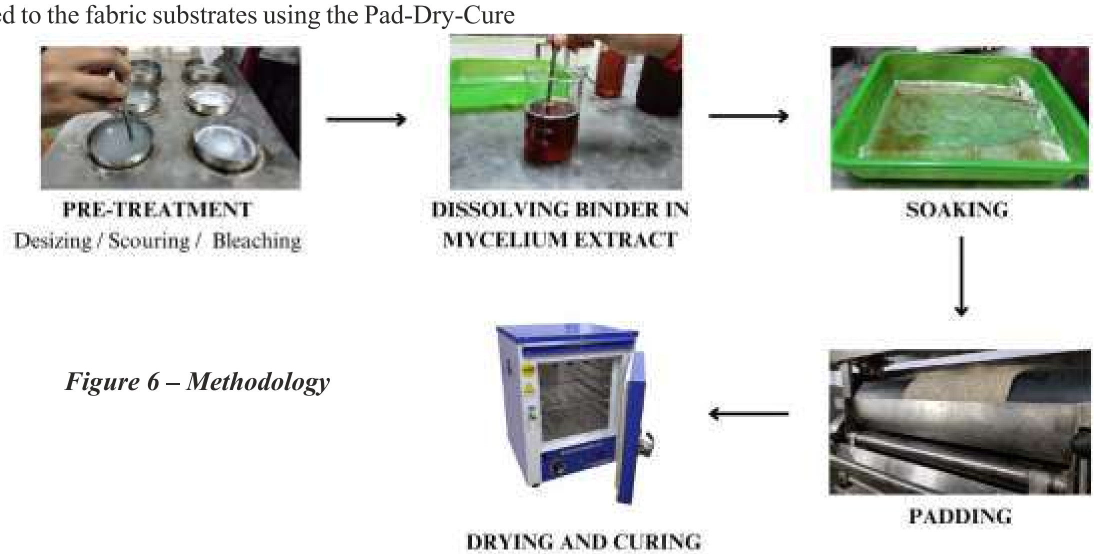

Figure 6 – Methodology

Table 1 - Flame retardancy (limited oxygen index) for different fabric types

Fabric Type	LOI (%)			
	Untreated	Turkey Tail	Reishi	Shiitake
Cotton	17-20	25	23	21
Polyester	22	23	21	20
Linen	22	25	24	22

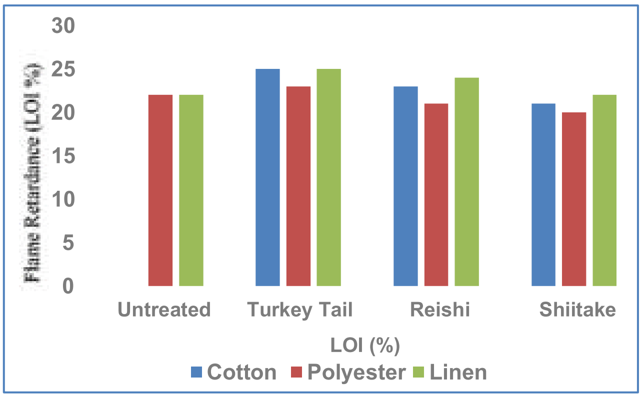

Chart 1 - Flame retardancy (limited oxygen index)

It is important to note that the untreated polyester fabric exhibited an LOI of 22%, which is within the typical range reported in previous studies [21]. The observed value is consistent with the inherent flame resistance of polyester. The slight variations in LOI across different treatments may be influenced by fabric composition, weave density, or testing conditions. Further analysis is necessary to better understand the baseline flame resistance of the untreated polyester sample and the impact of fungal treatments on its flame-retardant properties.

The study demonstrated that mycelium extracts, particularly from Turkey Tail, significantly enhanced the flame-retardant properties of textile substrates. The Turkey Tail treatment exhibited the highest Limiting Oxygen Index (LOI) of 25% for cotton and linen, and 23% for polyester, indicating its superior flame resistance. Reishi and Shiitake extracts also improved flame resistance, though to a lesser extent. The treatments not only reduced after flame time but also led to a reduction in heat release rate (HRR) and smoke generation, highlighting the potential of mycelium-based treatments as eco-friendly flame retardants.

a. Limiting Oxygen Index (LOI)

The Limiting Oxygen Index (LOI) measures the minimum oxygen concentration required for a material to sustain combustion. The results presented in Table 1 confirm that all mycelium-treated fabrics exhibited increased LOI compared to their untreated. For instance, Turkey Tail-treated cotton showed an LOI of 25%, compared to 17-20% for untreated cotton. Similarly, polyester and linen treated with Turkey Tail exhibited improved LOI values, reaching 23% and 25%, respectively.

The increase in LOI suggests improved flame retardancy, which is crucial for textiles used in protective clothing and upholstery. The enhancement in LOI can be attributed to the natural fire-resistant properties of mycelium, which contains polysaccharides that form a protective char layer upon heat exposure, inhibiting combustion [21]. The findings align with previous research on natural mycelium-based coatings that reported increased LOI values following treatment [2].

b. Vertical Flame Test

The vertical flame test evaluates a material's ability to self-extinguish when exposed to an open flame. In this study, Turkey Tail-treated cotton demonstrated a significantly reduced afterflame time (3 seconds), compared to untreated cotton (12 seconds). Similarly, polyester and linen treated with Turkey Tail exhibited afterflame times of 3 seconds, showing substantial improvement over their untreated counterparts (10 and 11 seconds, respectively). Reishi and Shiitake-treated fabrics also demonstrated improvements, with afterflame times ranging from 4-7 seconds, depending on fabric type.

Table 2 - Flame Retardancy for Different Fabrics

Fabric Type	Treatment Type	After flame Time (sec)	HRR Reduction (%)	Smoke Reduction (%)	Thermal Conductivity (W/mK)	Char Yield (%)
Cotton	Untreated	12	N/A	N/A	0.045	N/A
	Turkey Tail	3	40	28	0.035	38
	Reishi	5	35	22	0.038	35
	Shiitake	7	30	18	0.040	32
Polyester	Untreated	10	N/A	N/A	N/A	N/A
	Turkey Tail	3	38	25	N/A	36
	Reishi	4	33	20	N/A	33
	Shiitake	6	28	15	N/A	30
Linen	Untreated	11	N/A	N/A	N/A	N/A
	Turkey Tail	3	38	26	N/A	37
	Reishi	4	32	18	N/A	34
	Shiitake	6	27	16	N/A	31

These findings suggest that mycelium extracts, particularly Turkey Tail, have a pronounced flame-retardant effect by reducing afterflame duration. The formation of a protective char layer is likely a key factor in this improvement. Similar observations were reported in research demonstrating that fungal extracts can significantly reduce the afterflame time of cotton fabrics [22]. The results meet ASTM D6413 standards for flame resistance, where an afterflame time of less than 10 seconds is typically considered acceptable.

c. Heat Release Rate (HRR) and Smoke Density

The heat release rate (HRR) is a critical measure of how much heat a material generates during combustion. The test results indicate that the Turkey Tail treatment led to a 40% reduction in HRR for cotton, a 38% reduction for polyester, and for linen, supporting the hypothesis that mycelium acts as an effective flame-retardant agent. Reishi and Shiitake treatments also demonstrated reductions in HRR, though to a lesser degree (32-35% and 27-30%, respectively), further reinforcing the flame-retardant potential of mycelium-based treatments.

The smoke density test, which quantifies smoke production during combustion, showed that Turkey Tail-treated cotton, polyester, and linen exhibited smoke reductions of 28%, 25%, and 26%, respectively. Reishi and Shiitake treatments also contributed to decreased smoke generation, with reductions ranging from 15-22%, depending on the fabric type. These results indicate that mycelium-based treatments not only improve flame resistance but also contribute to fire safety by limiting smoke production, a critical factor in fire hazards.

d. Thermal Conductivity and Char Yield

The thermal conductivity test results showed a decrease in thermal conductivity for treated fabrics. Turkey Tail-treated cotton exhibited a thermal conductivity of 0.035 W/mK, compared to 0.045 W/mK for untreated cotton. This reduction suggests that mycelium treatment may enhance thermal insulation properties, which could be beneficial for protective textile applications [2].

Char yield analysis through thermogravimetric analysis (TGA) revealed that Turkey Tail-treated cotton had the highest char yield (38%) at 600°C, signifying a more stable, heat-resistant structure that resists further combustion. Polyester and linen treated with Turkey Tail also exhibited high char yields of 36% and 37%, respectively. Reishi and Shiitake treatments demonstrated slightly lower char yields (30-35%), correlating with their relatively lower flame resistance properties.

The results of this study align with prior research on mycelium-based flame retardants. Previous studies reported similar improvements in LOI and flame-retardant properties when treating textiles with fungal extracts [7]. It was also found that Turkey Tail and other fungal species enhance textile fire resistance [22]. The observed reductions in HRR and smoke density correspond with findings indicating that natural, eco-friendly treatments can provide significant flame resistance while reducing hazardous smoke emissions [24].

Compared to conventional flame retardants, mycelium-based treatments offer notable advantages. Traditional flame retardants often contain toxic chemicals, such as halogens and phosphorus compounds, which pose environmental and health risks [21, 25]. In contrast, the mycelium-based treatments in this study are biodegradable and non-toxic, providing a more sustainable and eco-friendlier alternative.

e. Statistical Analysis of LOI (%)

The following table presents the statistical analysis of the Limiting Oxygen Index (LOI) percentages for different treatments.

Table 3 - Statistics for LOI (%)

Treatment	Mean LOI (%)	Standard Deviation	95% Confidence Interval (CI)
Untreated	20.33	2.16	(15.78, 24.88)
Turkey Tail	24.33	1.53	(21.27, 27.39)
Reishi	22.67	1.25	(19.62, 25.72)
Shiitake	21.00	1.78	(17.02, 24.98)

The statistical analysis of Limiting Oxygen Index (LOI) values confirms that mycelium-based treatments significantly enhance the flame-retardant properties of fabrics, with Turkey Tail extract exhibiting the highest effectiveness. The increase in LOI from untreated (20.33%) to Turkey Tail-treated (24.33%) fabrics suggests a considerable improvement in fire resistance.

Although the ANOVA test ($p = 0.072$) does not indicate a statistically significant difference at a 95% confidence level, the observed trend supports the potential of Turkey Tail and Reishi extracts in improving flame resistance. The p-value (0.072), being slightly above the conventional significance threshold (0.05), suggests that differences in LOI values may partly result from random variation rather than a strong statistical effect. A larger sample size and additional experimental replications could help confirm the effectiveness of mycelium-based treatments. The lower standard deviation in treated samples indicates more consistent flame-retardant performance compared to untreated fabrics.

This study highlights the viability of mycelium extracts, particularly Turkey Tail, as a sustainable and effective flame-retardant treatment. The enhanced flame-retardant properties observed—improved LOI, reduced afterflame time, and lower HRR and smoke generation—suggest that mycelium-based coatings could serve as an environmentally friendly alternative to synthetic flame retardants. These findings indicate the potential of mycelium-treated textiles to meet industry fire resistance standards, such as ASTM D6413 and ISO 14116.

However, further optimization of the mycelium extraction and application process is necessary to achieve LOI values that consistently meet the industry benchmark of 26% for flame-retardant textiles. Additionally, large-scale production techniques for mycelium extracts need to be developed to ensure cost-effectiveness and scalability for commercial applications.

6. Conclusion

This study confirms the effectiveness of mycelium-based extracts as sustainable flame-retardant treatments for textiles. The application of Turkey Tail (Trametes versicolor), Reishi (Ganoderma lucidum), and Shiitake (Lentinula edodes) extracts significantly enhanced the flame resistance of cotton, linen, and polyester fabrics. The Limiting Oxygen Index (LOI) increased to 25% for Turkey Tail-treated cotton, compared to 17-20% for untreated cotton, while polyester and linen exhibited LOI improvements of 23% and 25%, respectively. Vertical flame test results showed a substantial reduction in after flame time, with Turkey Tail-treated cotton decreasing from 12 to 3 seconds, polyester from 10 to 3 seconds, and linen from 11 to 3 seconds. HRR reduction reached 40% for Turkey Tail-treated cotton, while smoke generation decreased by 28%. Char yield analysis indicated an increase to 38%, confirming improved thermal stability.

Statistical analysis revealed a mean LOI increase from 20.33% (untreated) to 24.33% (Turkey Tail-treated), with an ANOVA p-value of 0.072. Although the results were not statistically significant at the 95% confidence level, the observed trend suggests that mycelium-based treatments enhance flame resistance. Further studies with a larger sample size and optimized application techniques are recommended to achieve an LOI of 26%, meeting industrial flame-retardant standards.

Compared to conventional synthetic flame retardants, mycelium-based treatments offer distinct advantages, including biodegradability, non-toxicity, and environmental sustainability. These findings highlight the potential for mycelium-derived flame retardants to serve as viable alternatives in fire-resistant textile applications, aligning with green chemistry and circular economy principles. Future research should focus on optimizing extraction methods, improving long-term durability, and scaling production for commercial viability.

References

[1] Jones, M., Mautner, A., Luenco, S., Bismarck, A., & John, S. (2020). Engineered mycelium composites as sustainable building materials with low environmental footprints. Science Advances, 6(23), eabc8304. https://doi.org/10.1126/sciadv.abc8304

[2] Zhao, L., Zhang, J., & Li, Z. (2020). Mycelium-based materials: A green approach for flame retardancy and biodegradation. Journal of Materials Science, 55(8), 3324-3336. https://doi.org/10.1007/s11041-019-00356-6

[3] Alongi, J., Malucelli, G., & Carosio, F. (2016). Current emerging techniques to impart flame retardancy to fabrics: An overview of recent literature. Progress in Polymer Science, 51, 1-31. https://doi.org/10.1016/j.progpolymsci.2015.05.004

[4] Upadhyaya, M., Singh, R., & Kumar, S. (2021). Mycelium-based bio-composites for sustainable applications: A comprehensive review. Bioresource Technology Reports, 15, 100773. https://doi.org/10.1016/j.biteb.2021.100773

[5] Lee, J. S., Kim, J., & Park, H. (2018). Enhancing thermal resistance of textiles using mushroom extracts: A comparative study. Journal of Textile Science and Technology, 8(2), 45-54. https://doi.org/10.4236/jtst.2018.82005

[6] Zhong, Y., Li, H., & Wang, X. (2021). Extraction and application of fungal mycelium extracts in textile fire retardancy. Textile Research Journal, 91(12), 1452-1465. https://doi.org/10.1177/0040517521991776

[7] Wang, X., Sun, Y., & Zhang, L. (2019). Advances in flame-retardant treatments of textiles: A review. Journal of Textile Engineering & Fashion Technology, 5(1), 29-42. https://doi.org/10.15406/jteft.2019.05.00153

[8] Hossain, S., Rahman, M., & Haque, M. E. (2021). Enhancing fire retardancy of cotton fabric using natural extracts: An eco-friendly approach. Journal of Industrial Textiles, 50(8), 1171-1186. https://doi.org/10.1177/1528083719868984

[9] Gulam Moula, A. T. M., Al Mamun, M., Khan, M. H. K., Hosen, M. D., & Siddiquee, M. A. B. (2024). Impact of vitamin E in improving comfort, moisture management, and mechanical properties of flame-retardant treated cotton fabric. Heliyon, 10(1), e23834. https://doi.org/10.1016/j.heliyon.2023.e23834

[10] Kan, C. W., Lam, K. F., & Yuen, C. W. (2017). Textile preparation and dyeing processes: Overview and sustainability. Sustainable Textiles, 6, 73-96. https://doi.org/10.1016/b978-0-08-100576-7.00006-6

[11] Periyasamy, A. P., & Militky, J. (2020). Sustainable textile processing methods for functional textiles. Textile Engineering, 5, 223-249. https://doi.org/10.1016/b978-0-12-818759-8.00009-7

[12] ASTM International. (2023). ASTM D1776/D1776M-23: Standard practice for conditioning and testing textiles. ASTM International. https://doi.org/10.1520/D1776_D1776M-23

[13] ASTM International. (2019). ASTM D2863-19: Standard test method for measuring the minimum oxygen concentration to support candle-like combustion of plastics (Oxygen Index). ASTM International. https://doi.org/10.1520/D2863-19

[14] ASTM D6413-15. (2015). Standard test method for flame resistance of textiles (vertical flame test). ASTM International. Retrieved from https://www.astm.org

[15] ASTM E1354-17. (2017). Standard test method for heat and visible smoke release rates for materials and products using an oxygen consumption calorimeter. ASTM International. Retrieved from https://www.astm.org

[16] Sacco, E., Ceseracciu, L., & Athanassiou, A. (2015). Recent advances in flame retardant materials for textile applications. Polymer Reviews, 55(4), 482-500. https://doi.org/10.1080/15583724.2015.1020410

[17] Girometta, C., Picco, A. M., Baiguera, R. M., & Dondi, D. (2019). Fungal mycelium as a natural and sustainable material for the design of fire-resistant textiles. Materials Today Sustainability, 4, 100015. https://doi.org/10.1016/j.mtsust.2019.100015

[18] Horrocks, A. R., & Price, D. (2008). Fire retardant materials. Woodhead Publishing. https://doi.org/10.1533/9781845695071

[19] Kumar, P., Reddy, P. R., & Ravichandran, M. (2020). Flame retardant properties of Trametes versicolor extracts applied to textiles. International Journal of Biological Macromolecules, 156, 1087-1094. https://doi.org/10.1016/j.ijbiomac.2020.03.134

[20] International Organization for Standardization. (2015). ISO 22007-2:2015 – Plastics — Determination of thermal conductivity and thermal diffusivity — Part 2: Transient plane heat source (hot disc) method. ISO. https://www.iso.org/standard/68134.html

[21] Cheng, X., Ma, Y., & Yang, J. (2018). Flame retardancy and thermal degradation of mycelium-based materials. Journal of Applied Polymer Science, 135(6), 45994. https://doi.org/10.1002/app.45994

[22] Giri, J., Patel, R., & Tiwari, A. (2019). Eco-friendly flame retardant finishes on cotton fabrics using fungal extracts. Textile Research Journal, 89(7), 1208–1217. https://doi.org/10.1177/0040517518803505

[23] Siregar, A. A., Fadhillah, A., & Putra, M. (2021). The impact of fungal extracts on the flame retardant properties of fabrics. International Journal of Textile Science, 11(3), 82-89. https://doi.org/10.5923/j.textile.20210103.02

[24] Koller, M., Schmitt, D., & Muratore, C. (2019). Sustainable flame retardant treatments for textiles: Natural and bio-based alternatives. Textiles and Clothing Sustainability, 6(1), 1-10. https://doi.org/10.1186/s40689-019-0083-4

[25] Kumar, K. N., Babu, P. D., Surakasi, R., Kumar, P. M., Ashokkumar, P., Khan, R., Alfozan, A., & Gebreyohannes, D. T. (2022). Mechanical and Thermal Properties of Bamboo Fiber–Reinforced PLA Polymer Composites: A Critical Study. International Journal of Polymer Science. https://doi.org/10.1155/2022/1332157

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Bilayer Knitted Fabric: A Review

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Abstract:
Bilayer knitted fabrics have gained significant attention in the textile industry due to their enhanced functionality, making them an ideal choice for sportswear, activewear, and specialized applications. Unlike single-layer fabrics, bilayer structures offer improved moisture management, thermal regulation, and durability by combining hydrophobic and hydrophilic fibers. These fabrics are engineered to provide enhanced comfort, moisture management, thermal regulation, and durability making them ideal for sportswear applications. This review paper explores the design, properties, and applications of bilayer knitted fabrics. The paper also discusses the various yarn combinations, fabric structures used to achieve the desired performance characteristics and limitation of bilayer knitted fabrics. The choice of fiber combinations and knitting techniques significantly influence the performance of these fabrics. Knitted fabrics, classified into weft and warp knitting, provide superior elasticity and flexibility. The bilayer approach mitigates these challenges by offering increased mechanical strength, resistance to wear and tear, and improved thermal insulation. Technological advancements in fiber selection and knitting methods have further expanded the utility of bilayer fabrics across multiple domains, including medical textiles, protective clothing, and smart textiles.

Keywords: *Asymmetrical upper, amateur athletes, racquet sports, Spacer fabric, virtual prototype*

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1. Introduction

The increasing popularity of sports and fitness activities has driven the demand for high-performance sportswear that offers comfort, durability, and functionality. Bilayer knitted fabrics have emerged as a key solution to meet these demands. These fabrics are designed with multiple layers, each serving a specific function, such as moisture wicking, thermal insulation, or breathability. The inner layer, typically made of hydrophobic fibers like polyester or polypropylene, wicks moisture away from the skin, while the outer layer, made of hydrophilic fibers like cotton or viscose, absorbs and evaporates the moisture. This combination ensures that the wearer remains dry and comfortable during physical activities. Unlike single-layer fabrics, bilayer structures provide functional differentiation between the inner and outer layers, enabling better performance in moisture management and thermoregulation [1, 2].

1.1 Knitted Fabric

Knitted fabric is a textile material made by interlooping yarns using knitting techniques, creating a flexible and stretchable structure. Unlike woven fabrics, which are made by interlacing yarns perpendicularly, knitted fabrics have loops that provide elasticity, breathability, and comfort. These fabrics are classified into two main types: weft knitting and warp knitting. Figure 1 illustrates single-layer weft-knitted and warp-knitted fabrics structure.

- Weft Knitting: Uses a single yarn looped horizontally across the fabric width (e.g., jersey, rib, and interlock fabrics).
- Warp Knitting: Uses multiple yarns looped in a zigzag pattern along the fabric length (e.g., tricot and raschel fabrics).

Knitted fabrics are widely used in apparel, sportswear, medical textiles, and technical applications due to their softness, stretchability, and moisture management properties. Advances in fiber blends and knitting technology have enhanced their functionality, making them suitable for thermal insulation, compression wear, and even smart textiles [3, 4].

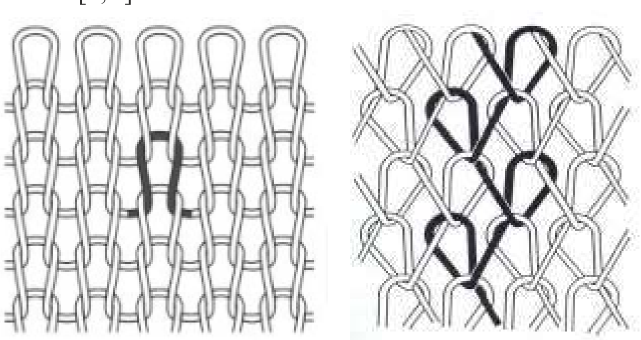

Figure 1: Single layer Weft knitted, and warp knitted Fabric

1.2. Limitations of Single layer Knitted Fabrics

Single-layer knitted fabrics, such as single jersey, are widely used due to their softness, breathability, and flexibility. However, they come with certain limitations:

i. Structural Instability: Single-layer fabrics, particularly single jersey, are prone to curling at the edges, making handling and sewing more challenging.

ii. Reduced Durability: These fabrics tend to be less durable compared to double-knit fabrics, which can limit their suitability for garments requiring higher resilience.

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iii. Pilling: Single-ply yarns used in these fabrics are more susceptible to pilling, affecting the garment's appearance over time.

iv. Biasing: Fabrics made from single-ply yarns can exhibit biasing, where the fabric distorts or leans to one side, impacting the garment's fit and aesthetic.

v. Thermal Protection: Single-layer knitted fabrics often have limited thermal protective performance due to their lower fabric weight and thickness, making them less suitable for applications requiring higher thermal resistance [5].

2. Bi-Layer Knitted Fabric

Bilayer knitted fabric refers to a textile structure composed of two distinct layers knitted together, often utilizing different yarns or fibers for each layer to achieve specific functional properties. This construction allows for the combination of varied characteristics, such as moisture management, thermal insulation, and comfort, within a single fabric. Figure 2 illustrates the structure of a bilayer weft-knitted fabric, consisting of two distinct layers. One layer is highlighted in blue, while the other is shown in light green.

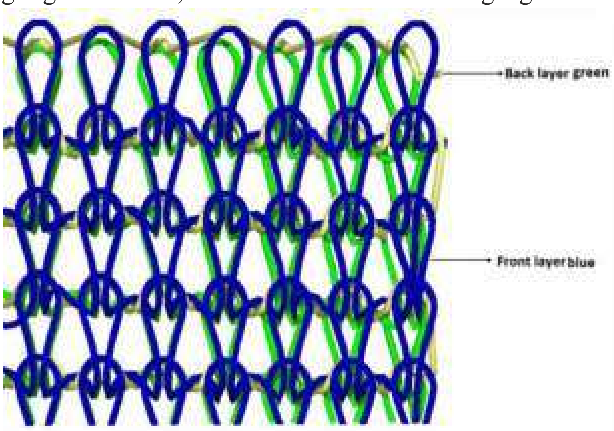


Figure 2: Bilayer knitted fabric representation [6]

2.1 Key Features of Bilayer Knitted Fabrics [7]

a. **Dual-Layer Construction:** Involves knitting two separate layers simultaneously, which can be made from different yarns or fibers.

b. **Functional Versatility:** By selecting appropriate materials for each layer, manufacturers can tailor the fabric's performance. For instance, an inner layer made of hydrophobic fibers like polyester can wick moisture away from the skin, while an outer layer of hydrophilic fibers like cotton can absorb and evaporate this moisture, enhancing overall comfort.

c. **Superior Moisture Management :** Designed with hydrophilic (moisture-absorbing) and hydrophobic (moisture-repelling) fibers to effectively wick sweat away from the skin. Keeps the wearer dry and comfortable, making it ideal for sportswear and activewear.

d. **Thermal Regulation :** Provides better insulation than single-layer fabrics due to trapped air between layers. Can be engineered for warmth in cold conditions or cooling in hot environments, used in thermal wear and medical garments.

e. **Enhanced Breathability & Comfort :** The inner layer is often designed to be soft and skin-friendly, reducing irritation. The outer layer ensures air circulation, maintaining body temperature balance.

f. **Durability & Strength :** Bilayer fabrics are more resistant to wear, and tear compared to single-layer fabrics. Ideal for high-performance applications, including industrial and protective clothing.

2.2 Need for Bilayer Knitted Fabric [7, 8]

Bilayer knitted fabrics have gained significant importance due to their advanced functional properties, making them ideal for various applications such as sportswear, medical textiles, and protective clothing. The primary reasons for their necessity are:

a) Enhanced Moisture Management and Thermal Regulation

· Bilayer fabrics optimize moisture control and thermal regulation, making them ideal for performance and protective wear. The air-trapping mechanism provides insulation, aiding in heat retention in cold weather and heat dissipation in warm conditions. These properties make them suitable for athletic wear, outdoor gear, thermal wear, and medical applications.

b) Durability & Strength

· The presence of two distinct layers improves fabric strength, resistance to wear and tear, and longevity compared to single-layer fabrics.

· Suitable for protective clothing, industrial wear, and high-performance garments.

c) Comfort & Breathability

· The inner layer is often designed to be soft and skin-friendly, reducing irritation.

· The outer layer enhances air permeability, making it breathable and comfortable for long-duration wear.

d) Versatile Functional Applications

· Sportswear & Activewear: Optimized sweat-wicking and temperature control.

· Medical Textiles: Used in bandages, compression garments, and skin-friendly fabrics.

· Protective Textiles: Fire-resistant, antimicrobial, or UV-protective layers for defence and industrial use.

· Fashion & Theatrical Textiles: Used for aesthetic layering and performance enhancement.

e) Technological Advancements & Innovations

· Continuous advancements in fiber technology, knitting techniques, and smart textiles have expanded the scope of bilayer fabrics, making them integral to future textile solutions.

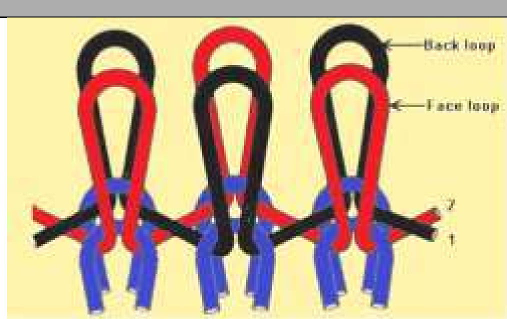
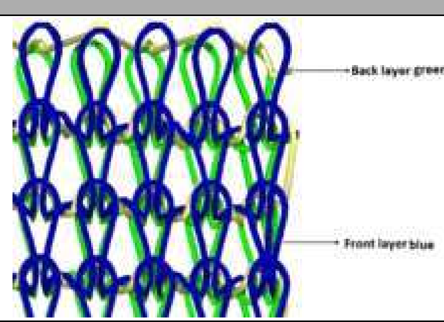
2.3 Limitations of Bilayer Knitted Fabrics [14]

- Increased Fabric Thickness – The dual-layer structure adds bulk, which may reduce flexibility and comfort in certain applications.
- Complex Manufacturing Process – Producing bilayer fabrics requires specialized machinery and precise control over fiber composition and knitting techniques.
- Higher Production Cost – The use of different yarns and advanced knitting technology increases material and manufacturing expenses.
- Reduced Breathability – Depending on the fiber combination, some bilayer fabrics may have limited airflow, affecting ventilation.
- Maintenance Challenges – Different fiber types in the layers may have varying shrinkage and washing requirements, making care and durability a concern.
- Limited Stretch and Elasticity – Compared to single-layer fabrics, bilayer structures may have restricted elasticity, affecting their fit and adaptability.
- Potential Layer Separation – Over time or under excessive stress, improper bonding between layers may lead to separation or reduced durability.
- Seam & Bonding Issues – Ensuring strong interlayer bonding without compromising flexibility and comfort is a challenge.
- Limited Design Flexibility – Complex structures may restrict fabric patterns, textures, and customization options.

2.4 Key Differences between Interlock Knitted Fabric & Bi-Layer Knitted Fabric

Interlock knitted fabric and bi-layer knitted fabric are both multi-layer textile structures, but they differ significantly in their construction, properties, and applications. Following table 1 represents the comparison of Interlock knitted fabric vs Bi-Layer knitted fabric.

Table 1: Interlock Knitted Fabric vs Bi-Layer Knitted Fabric [3]

Feature	Interlock Knitted Fabric	Bi-Layer Knitted Fabric
Structure	Double-knit fabric with interlocking loops, identical on both sides.	Two separate layers of fabric, often with different properties, bonded together.
Knitting Method	Weft knitting (double jersey)	Warp knitting (Raschel or Tricot) or specialized weft knitting
Appearance	Identical on both sides (smooth, uniform look)	Can have different textures or properties on each layer
Elasticity & Stretch	High stretch in both directions (horizontal & vertical)	Stretch depends on knitting technique and yarn selection
Thickness	Thicker and more compact than single jersey but relatively lightweight	Can be thick or thin, depending on layer design
Breathability	Moderate to high, depending on yarn	Can be designed for high breathability (spacer fabrics) or insulation
Durability	Good durability but can pill over time	More stable and durable due to warp knitting or reinforced layering
Applications	Used in sportswear, undergarments, T -shirts	Used in sportswear, technical textiles, medical, and automotive fabrics
Design		

2.5 Fibres used in Bilayer Knitted Fabrics

Fibers used in Bilayer knitted fabrics includes [9, 10]

- Microfiber Polyester: Utilized for its moisture-wicking and quick-drying properties, often forming the outer layer to facilitate moisture evaporation.
- Bamboo: Known for its softness and natural antibacterial qualities, bamboo fibers are frequently used in the inner layer to enhance comfort and hygiene.
- Polypropylene: This hydrophobic fiber is incorporated to provide a dry feel and efficient moisture management, making it suitable for activewear applications.
- Cotton: Valued for its breathability and comfort, cotton is often used in the inner layer to enhance moisture absorption and softness against the skin.
- Nylon: Used for its durability and elasticity, nylon is sometimes used in the outer layer to improve the fabric's strength and resilience.
- Wool: Appreciated for its natural insulation and moisture-wicking capabilities, wool can be used in bi-layer fabrics to provide warmth and comfort.
- Modal: A type of rayon derived from beech tree pulp, modal is recognized for its softness and breathability, making it suitable for the inner layer to enhance comfort.

By strategically combining these fibers, manufacturers can create bi-layer knitted fabrics that offer a balance of moisture management, thermal regulation, durability, and comfort, catering to specific performance requirements.

2.6 Fibre combinations include:

i) Polyester-Viscose: Polyester-viscose bilayer fabric combines the durability, wrinkle resistance, and moisture-wicking properties of polyester with the softness, breathability, and drape of viscose. This blend offers comfort, strength, and a balanced feel, making it suitable for formal and casual wear [2].

ii) Polypropylene-Cotton: Offers a lightweight, moisture-wicking, and thermally insulating structure, combining polypropylene's hydrophobicity with cotton's softness and breathability. It provides good comfort, durability, and quick-drying properties, making it ideal for activewear and functional textiles [15].

iii) Microfiber Polyester-Modal: Enhances thermal comfort and quick drying. It combines durability and elasticity from polyester with the natural comfort and drape of modal [16].

3. Yarn used for Bilayer knitted fabric:

The choice of yarn plays a crucial role in determining the performance of bilayer and multilayer knitted fabrics. Studies have shown that the combination of hydrophobic and hydrophilic fibers in the inner and outer layers, respectively, provides optimal moisture management. For instance, polypropylene and polyester are commonly used for the inner layer due to their excellent moisture wicking properties, while cotton, viscose, and modal are preferred for the outer layer due to their high moisture absorption capacity. Popular yarns counts are [9, 11];

- 100% polypropylene yarn of 120 or 150 Denier
- 100% polyester yarn of 120 or 150 Denier
- Cotton: 30s-40s Ne
- Viscose: 30s-40s Ne
- Bamboo: 30s-40s Ne

4. Fabric Structure

Bilayer knitted fabrics are engineered with two distinct layers, knitted together using interlocking or plating techniques and each serving specific functional purposes. The selection of fibers for these layers is crucial in achieving desired properties such as moisture management, thermal comfort, and durability. The two layers can be made from different yarns, fibers, or structures to achieve desired functional properties [9, 12]. Figure 3 represents moisture management process of Bilayer knitted fabric with two distinct layers.

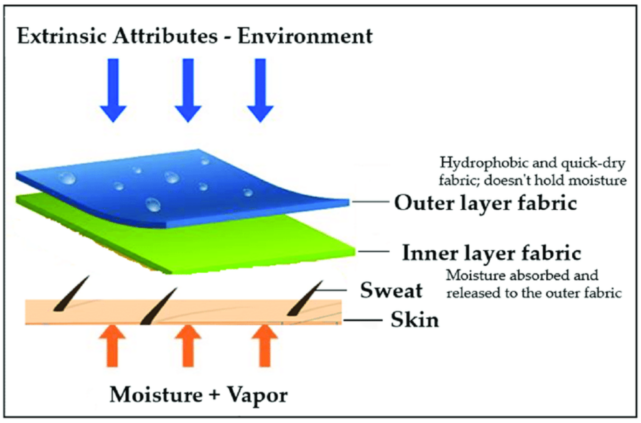


Figure 3: Moisture management process of Bilayer knitted fabric [17]

4.1 Types of Bi-layer Knitted Fabrics

Bilayer fabrics can be classified based on the knitting method used to create them:

a. Weft-Knitted Bilayer Fabrics

- Created using circular or flat knitting machines with two sets of needles.
- Commonly formed using rib, interlock, or tuck variations.
- The two layers may be loosely attached or interconnected at specific points.

b. Warp-Knitted Bilayer Fabrics

- Manufactured on tricot or raschel knitting machines.
- Often used in technical textiles and lingerie fabrics.
- Provides enhanced stability and less elasticity compared to weft-knitted structures.

4.2 Mechanical Properties

The mechanical properties of bilayer and multilayer knitted fabrics, such as bursting strength, abrasion resistance, and stretchability, are crucial for their durability and performance. Studies have shown that these fabrics exhibit high bursting strength and abrasion resistance, making them suitable for intense physical activities. Additionally, the use of interlock structures provides excellent stretch and recovery properties, ensuring that the fabric retains its shape even after repeated use. (1) For instance, fabrics combining micro denier polyester (MDP) in both layers tend to have lower thickness and mass per unit area, resulting in a softer and smoother feel compared to other combinations [13].

Additionally, the thickness and structure of bilayer fabrics greatly affect their mechanical behavior; increased thickness generally leads to reduced air permeability and drying ability but higher absorbency [14].

5. Manufacturing of Bilayer Knitted Fabrics

Bilayer knitted fabrics are produced using specialized knitting machines that allow the integration of two different yarn types in distinct layers. The commonly used machines include:

5.1. Weft Circular Knitting Machines

- Double Jersey Circular Knitting Machine
    - o Produces bilayer fabrics with enhanced elasticity and durability.
    - o Brands: Mayer & Cie, Terrot, Fukuhara.

5.2 Warp Knitting Machines

- Raschel & Tricot Machines
    - o Used for sportswear and functional textiles requiring stable structure.
    - o Brands: Karl Mayer, LIBA.

6. Applications of Bilayer Knitted Fabrics

Bilayer and multilayer knitted fabrics are widely used in sportswear, activewear, and outdoor clothing. Their ability to provide moisture management, thermal comfort, and durability makes them ideal for applications such as running, cycling, and football. Additionally, these fabrics are used in protective clothing and medical textiles, where moisture management and comfort are critical.

Bilayer knitted fabrics have also found applications in Broadway and theatrical productions due to their versatile properties. Their benefits in this domain include:

a) Sportswear & Activewear: These fabrics are ideal for active sportswear due to their superior moisture management properties. For instance, a combination of micro-fiber polyester on the inner layer and modal on the outer layer has demonstrated enhanced moisture wicking, rapid drying, and improved comfort, making them suitable for intense physical activities [9].

b) Thermal & Winter Wear Apparel: The insulating wool outer layer with soft inner lining provides excellent thermal insulation, making them suitable for winter garments. Double jersey structures, a type of bilayer knit, are preferred for cold-weather clothing due to their high thermal insulation values [16].

c) Sound Absorption: Helps reduce fabric noise during performances, enhancing audio clarity. The air gaps within the knitted layers trap sound waves and reduce reflection. The two layers create additional barriers for sound waves, leading to increased dissipation [11, 13].

d) Functional Clothing: By selecting appropriate fiber combinations, bilayer knitted fabrics can be tailored for specific functional requirements, such as enhanced durability, elasticity, or aesthetic appeal, broadening their application in Fire-resistant and impact-resistant dual-layer fabrics.

e) Medical Textiles: Where specific functional attributes like moisture management are crucial, compression garments with antibacterial properties.

7. Current Innovations in Bilayer Knitted Fabrics

1) Smart Textiles in Bilayer Knitted Fabrics: Researchers at MIT have developed smart textiles that conform to the body, capable of sensing the wearer's posture and movements by detecting multiple pressure points simultaneously. [18]

2) Sustainable Materials for Eco-Friendly Bilayer Knitted Fabrics: A study investigated the thermal comfort characteristics of bi-layer knitted fabrics made from banana fibers and recycled polyester (rPET). The findings suggest that combining these eco-friendly materials enhances moisture-wicking and thermal insulation properties. [19]

3) Automation & Digitalization in Bilayer Fabric Production: [18, 20]

- **3D Knitting Technology**

Advances in digital fabrication and computer-aided design have enabled the production of smart textiles that conform to the body, capable of sensing the wearer's posture and motions by detecting multiple pressure points simultaneously.

- **AI & Machine Learning for Quality Control**

The integration of robotics and AI is driving research and innovation in the knitting industry, enhancing automation and precision in fabric production.

- **On-Demand & Customizable Production**

The concept of Industry 4.0 is being integrated into the textile sector, presenting new configurations for the knitwear segment that allow for on-demand and customizable production.

8. Conclusion

Bilayer knitted fabrics offer superior moisture management, thermal comfort, and durability, making them ideal for sportswear, functional clothing, and medical applications. Their dual-layer structure, combining hydrophobic and hydrophilic fibers, optimizes sweat regulation and temperature control. Advances in fiber technology and knitting techniques continue to expand their applications. As innovation progresses, these fabrics remain essential for performance-driven industries. Innovations in smart textiles, sustainable materials, and automation are transforming bilayer knitted fabrics, enhancing functionality, eco-friendliness, and production efficiency.

References

[1] Sakthi P, Sangeetha K, Bhuvaneshwari M., "Development of Double Layer Knitted Fabric for Sportswear Using Tencel/Polypropylene Fibres", International Journal of Current Pharmaceutical Review and Research, 2016 https://doi.org/10.1177/1528083717692594

[2] Thangamuthu S, Senthilkumar P., "Moisture-management Properties of Bi-layer Knitted Fabrics for Sportswear" Journal of Industrial Textiles, 2017 https://doi.org/10.1177/1528083717692594

[3] Spencer, D. J., "Knitting Technology: A Comprehensive Handbook and Practical Guide", Elsevier.

[4] Mukhopadhyay, S., & Midha, V. K., "Advanced Knitting Technology", Woodhead Publishing, 2008

[5] Sandeep K Maurya, Viraj Uttamrao Somkuwar, "Thermal protective performance of single-layer rib-knitted structure and its derivatives under radiant heat flux", Journal of Industrial Textiles, 2021

[6] Usman Ahmed & Tanveer Hussain, "Role of knitted techniques in recent developments of biomedical applications", A review Journal of Engineered Fibers and Fabrics, 2023 https://doi.org/10.1177/15589250231180293

[7] Ajgaonkar, D. B., "Knitting Technology", Universal Publishing Corporation, 1998

[8] Choi, K. P., & Powell, N. B. "Warp Knitting Production", Textile Institute, 2005

[9] Suganthi, T., & Senthilkumar, P., "Moisture-management properties of bi-layer knitted fabrics for sportswear", Journal of Industrial Textiles, 47(7), 2017, Pg.1447-1463. https://doi.org/10.1177/1528083717692594

[10] Yang Yang, Xin Yu, "Effect of knitting structure and yarn composition on thermal comfort properties of bi-layer knitted fabrics", Textile Research Journal, 2020

[11] Lokhande, N. B., Patil, L. G., & Awasare, A. U., "Suitability of bi-layer knitted fabric for sportswear application", International Journal of Engineering Research & Technology, 3(7), 429-436. 2014

[12] T. Sivarasu & P. Senthilkumar, "Study of Thermal Comfort Characteristics of Bi-layer Knitted Fabrics Made by Various Types of Spinning System Yarns", Fibers and Polymers, 2024

[13] Krithika SM, Prakash C, Sampath MB, Senthil Kumar M. "Thermal Comfort Properties of Bi-Layer Knitted Fabrics" Fibres & Textiles in Eastern Europe, 2020

[14] Aduna A, Santhanem S. "Thermal Comfort Properties of a Bi-layer Knitted Fabric Structure for Football Sportswear" Journal of Textile Science & Engineering, 2021

[15] Vaida Buzaite, Reazuddin MD Repon, "Development of multi-layered weft-knitted fabrics for thermal insulation", Journal of Industrial Textiles, 2019

[16] Ivana Salopek Čubrić. "Material and Structural Functionalization of Knitted Fabrics for Sportswear" MDPI, Basel, Switzerland, 2022

[17] Desalegn Atalie & Pavla Tesinova, "Thermo-Physiological Comfort Properties of Sportswear with Different Combination of Inner and Outer Layers", Materials, 14(22):6863, November 2021

[18] Smart clothes enhancing health and performance, https://www.soci.org/chemistry-and-industry/cni-data/2024/4/smart-textiles-enhancing-health-and-performance?utm_source=chatgpt.com, Updated: 2024, Cited: 2024 March 28

[19] Dr. S. Priyalatha, "Investigation on bi-layer knitted fabric produced using recycled polyester and banana fiber for improved moisture and thermal comfort properties", Journal of Polymer and Composites, 12(05), June 2024

[20] Gabriela Maestri, Fernando Ribeiro Oliveira, Eduardo Werner Benvenuti and Fernanda Steffens, "Novel Knitting Model Based on Automation and Industry 4.0", Journal of Textile Science & Fashion Technology, 7(2), 2020 https://doi.org/10.33552/JTSFT.2020.07.000656

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Extraction and Characterization of Absorbent Core from Waste Cotton Fiber for Hygiene Applications

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Abstract:

This study examines the extraction of absorbent powder as a value-added product, identified as one of the most effective methods for recycling waste cotton fiber (WCF). The resulting material holds considerable promise for application in essential hygiene products, including baby diapers and sanitary napkins. An alternative extraction technique utilizing sodium hypochlorite hydrolysis was employed, facilitating a more rapid process at reduced temperatures. The performance of the extracted absorbent core (EAC) was compared to that of the commercial absorbent core (CAC). The optimization of WCF extraction was conducted using response surface methodology (RSM). A Central Composite Design (CCD) was implemented to evaluate the influence of various independent variables, such as concentration, extraction time, and extraction temperature, on the yield of WCF extraction. The optimal conditions identified (0.1 g/ml concentration, 20 minutes of extraction time, and a temperature of 90°C) achieved an 86% yield of WCF, closely aligning with the anticipated yield of 85% from the experimental design. FT-IR and TGA analyses indicated that the properties of the EAC derived from WCF are comparable to those of the CAC. This research confirmed that NaOCl hydrolysis is an effective method for obtaining a high yield of WCF extracts.

Keywords: *Absorbent Core, Hydrolysis, Hygiene Products, Sodium Hypochlorite, Waste cotton fibre*

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1. Introduction

The healthcare industry has encouraged the use of hygiene materials that are derived from natural resources. Waste Cotton Fibers (WCF) have been extensively utilized in the hygiene sector and other industries. With the rising costs associated with recycling, a significant portion of WCFs is now being buried or sent to landfills instead of being recycled [1]. Presently, only 30% of WCFs are mechanically recycled into yarns and fibers for textile or other uses, while the remaining 70% are disposed of in the environment. Given that cotton fibers contain between 95 and 99% cellulose, WCF stands out as a leading biopolymer and has the potential to serve as a sustainable substitute for absorbent cores [2]. A number of earlier studies have explored the recycling of waste cotton fibers (WCFs) to create cellulose absorbent cores (CAC), a process that demands considerable amounts of solvents, prolonged extraction times, and high temperatures. These studies have revealed that traditional extraction methods for obtaining commercial absorbent cores from materials such as wool, cotton [3], wood pulp [4], bamboo [5], and corn cob [6] are often inefficient, resulting in low yields. Furthermore, additional research on cellulose absorbent cores has utilized hydrochloric acid [7], sulfuric acid hydrolysis [8], and biological treatments, including enzymatic hydrolysis [9].

High levels of acid and elevated temperatures contribute to increased production costs and environmental issues [10]. However, there is a lack of extensive research regarding the use of sodium hypochlorite hydrolysis for CAC extraction. Sodium hypochlorite extraction (SHE), is recognized for its simplicity and speed compared to other extraction methods, making it a sustainable and economically feasible option for obtaining absorbent materials. Additionally, it enhances efficiency by yielding a safer and higher-quality product in less time. To maximize extraction yield, it is essential to optimize the extraction processes through Response Surface Methodology (RSM), which assesses the impact of various independent variables, including concentration, temperature, and time.

The primary objective of this research is to develop absorbent cores utilizing waste cotton fiber, intended to serve as a substitute for the inner-core found in commercially available hygiene products. A key innovative aspect of the study involves comparing the acid hydrolysis method with the more environmentally sustainable NaOCl hydrolysis method. Additionally, response surface methodology will be employed to investigate the impact of various factors in the SHE extraction process, including concentration, extraction duration, and temperature, on the yields of the extracts. Furthermore, functional group analysis, thermogravimetric analysis, and morphological examination of 2% SHE extracts will be conducted using FTIR, TGA, and SEM techniques, with performance assessments carried out through water absorption and moisture absorption tests.

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2. Materials and Methods

2.1 Materials

The waste cotton fibers utilized in this study were sourced from Bahir Dar Textile Share Company located in Bahir Dar, Ethiopia. Sodium hydroxide (NaOH) and hydrogen peroxide (H_2O_2) at a concentration of 35% were acquired from the textile laboratory of EiTEX, while sodium hypochlorite at a concentration of 2% was procured from commercial suppliers.

2.2 Production of absorbent core from Waste Cotton Fiber

A flow-chart of the extraction process for Waste Cotton Fiber is shown in Figure 1.

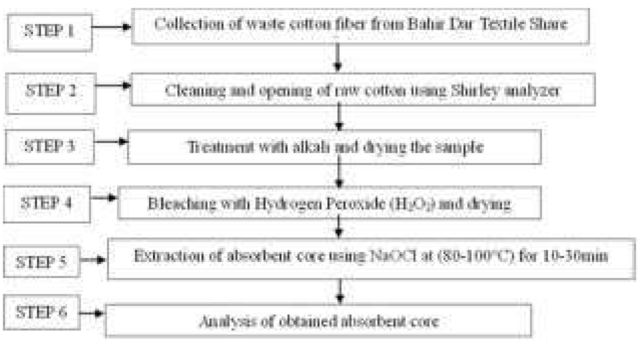

Figure 1 - Flow chart of the extraction process for Waste Cotton Fiber

2.3 Experimental design and statistical optimization of the hydrolysis process

The experimental conditions were optimized through a response surface methodology utilizing the central composite design (CCD). This study examined three independent variables: the concentration, extraction temperature, and extraction duration of sodium hypochlorite. The experiments were carried out using Statistical 13 software. A total of 20 tests were performed to optimize the process parameters as outlined in Table 3. To assess the core yield of the response variables, various techniques were employed, including the coefficient of variation, analysis of variance, and 3D plots.

$$Y = \beta_0 + \beta_i X_i + \beta_{ij} X_i X_j + \beta_{ii} X^2_i \quad (1)$$

where Y is the predicted response, β0 is the model constant, βi, βii, and βij are constant regression coefficients of the model, and quadratic coefficients, respectively; Xi and Xj are the independent variables in which i and j range from 1 to k (k = 3 in this experiment).

2.4 Characterization

FT-IR analysis: FTIR spectra were obtained using a VERTEX-70 spectrophotometer (Germany) in the scanning range 4000–400 cm^{-1} with a resolution of 2 cm^{-1} over 20 scans. The ground samples were thoroughly mixed with KBr and compressed into pellets.

TGA Analysis: The TGA measurements were conducted using an STA449 F3 thermogravimetric analyzer (Netzsch, Germany) in a nitrogen atmosphere at a flow rate of 40 mL/min. The samples were dried and then heated at a heating rate of 10 °C/min from 30°C to 600°C.

2.5 Performance test for the absorbent core

Water absorption test of cotton fiber: The average water absorption capacity of cotton fibers was evaluated following the guidelines of ASTM D 570-98. The specimens were dried in a 60°C oven for 24 hours, allowed to cool, and then weighed to establish the conditioned weight (w1). The samples were then immersed in distilled water at an ambient temperature of 23 ± 1°C. After being removed from the water, the specimens were dried with absorbent paper and weighed immediately to ascertain the wet weight (w2).

$$\text{weight gain }(\%) = \frac{w2 - w1}{w1} * 100 \quad (2)$$

Moisture Content (Etta dry) test: After the completion of retting and drying, the fibers were weighed in a weighing bottle and subjected to drying in a preheated oven at 105oC. The samples were then cooled in a desiccant, and the stopper was replaced, with a brief opening to equalize the air pressure. Following this, the cooled samples were weighed again and returned to the oven for an extra hour. This process of cooling and weighing was repeated hourly until a stable weight was achieved. The moisture content (Mc %) of the extracted cotton fibers was assessed using the equations specified in reference [11].

$$\text{Moisture Content (MC\%)} = \frac{\text{Initial weight (W1)} - \text{Oven dry weight (W2)}}{\text{Initial weight (W1)}} * 100 \quad (3)$$

where, W1= initial weight and W2= oven dry weight.

2.6 Preparation of EAC

Removal of Impurities: Waste cotton fiber generated during the carding process contains impurities that must be eliminated through purification methods before it can be utilized in production. For the purpose of testing 20 fiber samples, each weighing 50 grams, a Shirley analyzer was employed, and the fiber web was collected by layering it on a rotating cylinder. To maintain uniformity among the samples, the web was extracted from the cylinder and analyzer on two separate occasions. The web produced by the analyzer was subsequently separated and removed from the analyzer's procedure in accordance with ANSI/ASTM D 1894-78, the Standard Test Method.

2.6.1 Treatment of Waste Cotton Fiber

Scouring of WCF: The scouring of waste cotton fiber was conducted with an alkali solution (NaOH) at concentrations between 2% and 6% under high-temperature conditions. Earlier research indicated the use of a NaOH solution at a concentration of around 3.5 g/L at standard temperatures. However, similar outcomes were observed at elevated temperatures with a reduced concentration of NaOH, specifically within the 2%-6% range. The scouring recipe is presented in Table 1.

Table 1 - Recipe for alkali treatment using NaOH

Chemicals	MLR 1:20, Temperature 90 - 100°C, and time 60min		
	Concentration %		
NaOH	Test 1	Test 2	Test 3
	2	4	6

Bleaching of WCF: The waste cotton fiber was bleached with 35% H2O2 at 85oC for 60 min. with a M:L ratio of 1:20.

Statistical analysis: An analysis of variance (ANOVA) was conducted on the experimental data at a 95% confidence level to assess the relative impact of process conditions on the percentage yield of the extracted absorbate core. The results indicate the observed F value in comparison to the critical F value, with a significance threshold established at a P-value of 0.05 (refer to Tables 2 and 3).

Table 2 - Experimental design and levels of independent process variables

File Version	13.0.5.0	
Study Type	Response Surface	
Subtype	Randomized	
Design Type	Central Composite	
Design Model	Quadratic	
Runs	20.00	
Blocks	No Blocks	
	Levels	
Independent variables	Low Level	High Level
A: Concentration (g/ml)	0.05	0.15
B: Time (min)	10	30
C: Temperature (°C)	80	100

Table 3 - Testing conditions for absorbate core extraction from WCF

Trials	Factor Time (min)	Factor 2 Temperature (°C)	Factor 3 Conc. (g/ml)	EAC (g)
1	20	90	0.1	44.5
2	20	90	0.1	44
3	30	1E+02	0.05	42.5
4	10	1E+02	0.15	42
5	20	90	0.18	42.5
6	10	80	0.15	42.5
7	20	73	0.1	42.5
8	20	90	0.1	44.5
9	20	90	0.016	41.5
10	30	80	0.15	43.5
11	10	80	0.05	42.5
12	30	1E+02	0.15	42.5
13	20	90	0.1	44
14	20	90	0.1	44.5
15	20	90	0.1	44
16	2.3	90	0.1	42.5
17	37	90	0.1	44.5
18	30	80	0.05	44
19	20	1.1E+02	0.1	41
20	10	1E+02	0.05	40.5

Hydrolysis process: Following an extensive process of scouring and bleaching, all impurities were successfully removed, leading to the hydrolysis of the cotton fiber and the production of a pure powder. When executed properly, this process yields a powder that complies with the standards set forth by the U.S. Pharmacopoeia for purified cotton powder. As illustrated in Figure 2, the cellulose dispersion underwent hydrolysis through the introduction of sodium hypochlorite, with the concentration of sodium hypochlorite in the beaker maintained between 0.05 and 0.15 g/ml. The hydrolysis process was conducted in a beaker at temperatures ranging from 80 to 100 degrees Celsius for a duration of 10 to 30 minutes, accompanied by continuous stirring. The resulting EAC dispersion was thoroughly rinsed with distilled water until the final pH reached approximately 6.5 to 7. The EAC was then obtained by drying it under sunlight at 30 degrees Celsius, and the yield was determined using Equation 4.

Figure 2 - The sequential extraction of waste cotton fiber (a. Treatment and hydrolysis b. Rinsing c. Filtered extract d. Dried sample, e. Fine Powder)

$$Extracted\ yield = \frac{Weight\ of\ the\ extract\ after\ extraction\ (g)}{Weight\ of\ the\ original\ sample\ (g)} * 100 \quad (4)$$

3. Results and Discussion

3.***1 Optimization of WCF Extraction Parameters by RSM***

The Central Composite Design (CCD) employed under Response Surface Methodology (RSM) was utilized to identify the optimal parameters aimed at reducing concentration, extraction time, and extraction temperature, while simultaneously enhancing extraction yield. This optimization resulted in a Desirability value of 0.819, corresponding to Solution 1 out of 7 as illustrated in Figure 3.

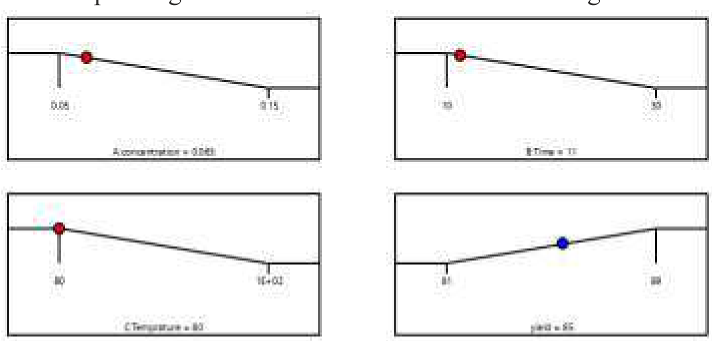

Figure 3 - Optimization of parameters

Central composite design and the response: Three independent variables were selected for the study: the concentration of NaOCl, the temperature of extraction, and the duration of the process. The experimental results illustrated the interaction among the various levels of these factors, with response yields varying between 81% and 89% (Table 4).

Table 4 - Central composite design and the response

Trials	Extraction Condition Yield (%)			
	A: Conc. (g/ml)	B: Extraction Time (min)	C: Extraction Temp (?C)	Response Yield (%)
1	0.1	20	90	89
2	0.1	20	90	88
3	0.05	30	1E+02	85
4	0.15	10	1E+02	84
5	0.18	20	90	85
6	0.15	10	80	85
7	0.1	20	73	85
8	0.1	20	90	89
9	0.016	20	90	83
10	0.15	30	80	87
11	0.05	10	80	85
12	0.15	30	1E+02	85
13	0.1	20	90	88
14	0.1	20	90	89
15	0.1	20	90	88
16	0.1	2.3	90	85
17	0.1	37	90	89
18	0.05	30	80	88
19	0.1	20	1.1E+02	82
20	0.05	10	1E+02	81

According to the results of this study, the extraction yield of WCF was determined to be 86%, indicating that the process successfully removed nearly all lignin, hemicellulose, pectin, the natural yellowish tint, and other impurities.

Model fit summary: A quadratic model is deemed suitable for further application when its p-value is less than 0.05. The software identifies and recommends the polynomial of the highest degree, and if the supplementary terms are significant, the model is regarded as reliable and in strong agreement. Table 5 presents the model's fit to the data along with the selected model. It indicates that a quadratic model is appropriate for percentage yield ($p < 0.0001$).

Table 5 - Fit Summary

Source	Sequential p-value	Lack of Fit P-value	Adjusted R^2	Predicted R^2	
Linear	0.0741	0.0015	0.2205	0.0443	
2FI	0.8636	0.0009	0.0919	-0.3589	
Quadratic	< 0.0001	0.4199	0.9448	0.8535	Suggested
Cubic	0.4726	0.2601	0.9449	0.0462	Aliased

ANOVA results for yield extraction: Table 6 summarizes the ANOVA results. The importance of the terms and models was assessed using a p-value threshold of less than 0.05, and Prob > F for each coefficient, indicating the presence of significant terms. Table 6 shows significant results for model terms A, B, C, AB, AC, A^2, B^2, and C^2. The model's F value of 37.11, backed by a p-value of less than 0.0001, indicates the importance of its terms. The set confidence level was used to assess both significant and nonsignificant words. Furthermore, the lack of fit is recorded at 0.4199 (as shown in Table 6), which is greater than 0.05 ($p > 0.05$), indicating that the lack of fit is not significant and that the model is well fitted. Given that the model's lack of fit was deemed modest, the answers were determined using the regression equation.

Table 6 - ANOVA quadratic model for extraction conditions with yield (%)

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	110.69	9	12.30	37.11	< 0.0001	significant
A-concentration	2.11	1	2.11	6.36	0.0303	
B-Time	20.49	1	20.49	61.82	< 0.0001	
C-Temperature	16.58	1	16.58	50.01	< 0.0001	
AB	2.00	1	2.00	6.03	0.0339	
AC	2.00	1	2.00	6.03	0.0339	
BC	0.0000	1	0.0000	0.0000	1.0000	
A^2	32.81	1	32.81	99.00	< 0.0001	
B^2	2.90	1	2.90	8.74	0.0144	
C^2	40.95	1	40.95	123.56	< 0.0001	
Residual	3.31	10	0.3314			
Lack of Fit	1.81	5	0.3628	1.21	0.4199	not significant
Pure Error	1.50	5	0.3000			
Cor Total	114.00	19				

Standard fit Statistics: The coefficient of determination agreement may be used to examine the adequacy of the chosen model. Table 7 shows that the updated R^2 value of 0.9448 is nearly identical to the expected R^2 value of 0.8535, proving its validity. Table 7 shows a significant connection between anticipated and experimental values ($R^2 = 0.9709$). The study findings demonstrate that each variable's effect on the experimental response is well-predicted, with the predicted R^2 of 0.8535 exhibiting acceptable agreement with the adjusted R^2 of 0.9448. The difference remains below 0.2. Adequate accuracy, which assesses signal-to-noise ratio, produced a result of 20.0311 for extraction yields, demonstrating a good signal and implying that the constructed model is adequate for exploring the design space. The residual standard deviation was computed at 0.5757. Furthermore, the low coefficient of variation (CV %) of 0.6694 across all responses demonstrates the model's good accuracy and dependability. A CV of less than 10% usually suggests that the model is fairly reproducible.

Table 7 - Standard fit statistics

Std. Dev.	0.5757	**R^2**	0.9709
Mean	86.00	**Adjusted R^2**	0.9448
C.V. %	0.6694	**Predicted R^2**	0.8535
		Adeq Precision	20.0311

Coefficients in Terms of Coded Factors: The analysis of the regression coefficients indicates that both concentration A and extraction time B exert a positive effect on the extraction yield of WCF. This suggests that extending the extraction time will enhance the yield. Conversely, an increase in temperature is associated with a decrease in WCF extraction yield, as evidenced by the negative regression coefficient values. Additionally, the regression coefficients for AC and BC are positive. In this context, Y denotes the anticipated responses (yield %), while A, B, and C represent the coded values for the independent variables: concentration, time, and temperature. The model equations elucidate the relationship among these variables, expressed as $Y = 88.49 + 0.3927\times A + 1.22\times B - 1.10\times C - 0.5000\times A\times B + 0.5000\times A\times C + 0.0000\times B\times C - 1.51\times A^2 - 0.4482\times B^2 - 1.69\times C^2$ (2). Here, Y signifies the predicted responses (yield %), with A, B, and C corresponding to concentration, time, and temperature, respectively (Table 8).

Table 8 - Coefficients in Terms of Coded Factors

Factor	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	88.49	1	0.2348	87.96	89.01	
A-concentration	0.3927	1	0.1558	0.0456	0.7398	1.0000
B-Time	1.22	1	0.1558	0.8777	1.57	1.0000
C-Temperature	-1.10	1	0.1558	-1.45	0.7546	1.0000
AB	-0.5000	1	0.2035	-0.9535	-0.0465	1.0000
AC	0.5000	1	0.2035	0.0465	0.9535	1.0000
BC	0.0000	1	0.2035	-0.4535	0.4535	1.0000
A^2	-1.51	1	0.1516	-1.85	-1.17	1.02
B^2	-0.4482	1	0.1516	-0.7861	-0.1103	1.02
C^2	-1.69	1	0.1516	-2.02	-1.35	1.02

Prediction interval ANOVA analysis: To analyze the effects of variables and their interactions, the experimental error for the means was computed using a 95% confidence interval (CI), which relied on the discrepancies between the observed and expected responses, detailed in Table 9.

Lower Bound Confidence = 95% Population = 99%

Diagnostic prediction vs actual: Figure 4 illustrates that the actual values are closely aligned with the straight line, suggesting that the experimental lead removal capacity values correspond well with the predictions made by the model.

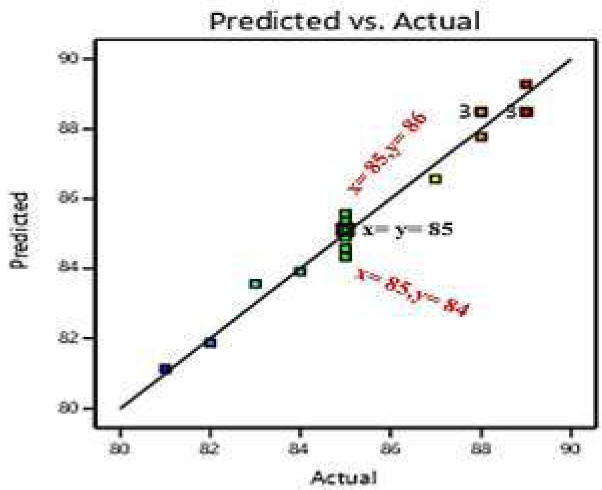

Figure 4 - Actual Values

Actual factor coding: Figure 5 illustrates the influence of concentration, extraction duration, and extraction temperature on the yield of WCF obtained using a 2% sodium hypochlorite solution. The optimal yield of 88% was achieved with a sodium hypochlorite concentration of 0.1 g/ml, an extraction time of 20 minutes, and a temperature of 90°C, as represented in Figure 5.

The results reveal that the concentration factor presented in Figure 5a has a substantial influence on extraction yield. An increase in concentration from 0.05 to 0.1 g/ml led to an enhanced extraction yield, attributed to improved solvation, with the highest yield recorded at 0.1 g/ml. However, when the concentration was raised to 0.15 g/ml, the yield decreased. Figure 5b illustrates that the duration of extraction is also a significant factor; extending the time from 10 to 20 minutes has a negligible effect on yield variation. The optimal extraction yield was achieved at 30 minutes, while the most economical extraction time was determined to be 10 minutes. Furthermore, temperature plays a critical role in extraction yield, as shown in Figure 5c. Increasing the temperature from 80 to 90°C resulted in a higher yield, peaking at 90°C. Nevertheless, a further increase to 100°C led to a decrease in yield due to a reduction in solvent viscosity.

Table 9 - Confidence and Point Prediction interval ANOVA analysis results

Response	Predicted Mean	Predicted Median	Observed	Std Dev	SE Mean	95% CI low for the Mean	95% CI high for Mean	95% TI low for 99% Pop	95% TI high for 99% Pop
Yield	88	88		0.58	0.23	88		86	

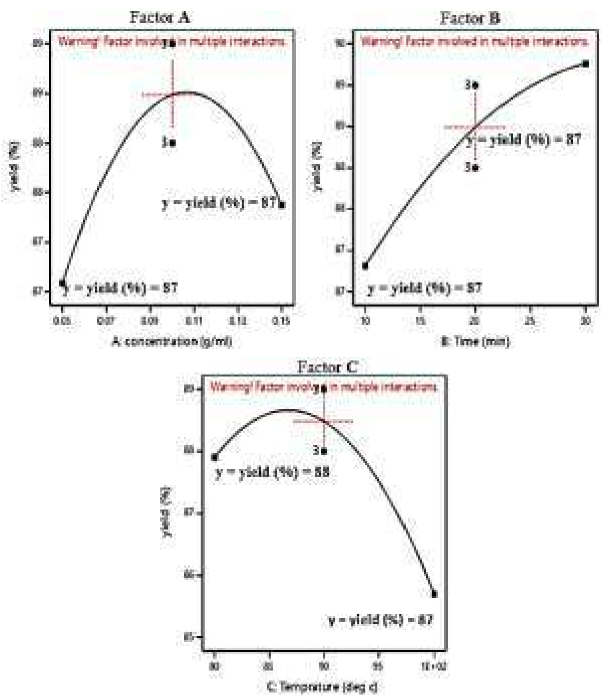

Figure 5 - Actual factor coding

3D surface response analysis: The optimal conditions were established by enhancing the desirability of the results through the application of Design Expert Software. It was observed that all three variables—concentration, time, and temperature—significantly affected the efficiency of WCF extraction ($p < 0.05$), as illustrated by the three-dimensional surface plots. Figure 6A shows the relationship between concentration and temperature; the yield of WCF extract rose with higher concentrations, while changes in extraction temperature indicated that longer heating times led to a decrease in extraction yield. The findings revealed that increased extraction temperatures facilitated the solubility of WCF, thereby improving the extraction yield. Additional factors that contributed to the enhanced yield of WCF extract included better solvation, increased material porosity, and improved mass transfer. Figure 6B indicates that the extraction yield peaked at 90 ◦C and subsequently declined with further temperature increases. The yield diminished when temperatures surpassed the optimal level (over 100 ◦C) due to degradation and a reduction in the solvent's capacity to dissolve fibers, with more than 25% of the solvent evaporating. Figures 6C and 6A show the effects of concentration and time on the extraction process. The yield remained basically unchanged, indicating that no limiting or boosting effects were identified. The extraction length of 10 to 30 minutes produced the best results, with an ideal extraction yield of 86%. Notably, a 10-minute extraction time achieved comparable results, making it the most efficient method for lowering extraction expenses. To maximize the yield of WCF extraction, the model equation was used to forecast the optimal extraction conditions. Figure 6 shows the best settings for maximum yields: 0.1g/ml concentration, 20-minute extraction time, and 90°C temperature3.2 Characterization of ECP

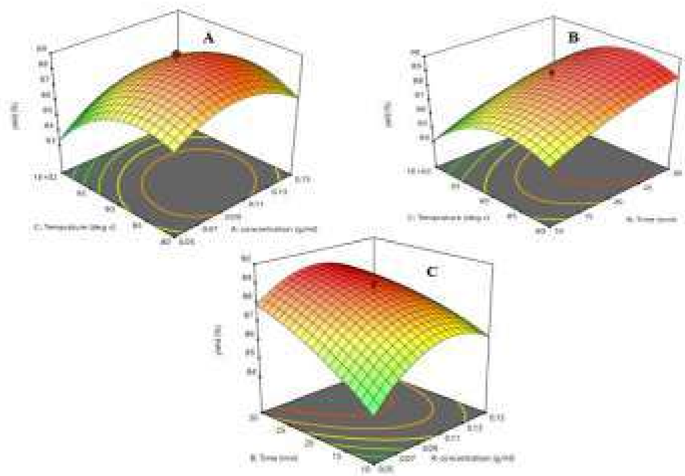

Figure 6 - Surface response plots show the effect of conditions: a) concentration and temperature (b), temperature and time (c) concentration, and time on percentage yield

Fourier transform infrared spectroscopy: The functionality of the WCF, EAC, and CAC was validated through FT-IR spectroscopy. Figure 7 presents the FT-IR spectra for the WCFs, EAC, and CAC. A broad peak at 3262 cm−1 corresponds to the O-H stretching vibration of carboxylic acid, typically found around 3000 cm−1. Additionally, a medium band at 2875 cm−1 indicates the C-H stretching of alkanes. The band at 1319 cm−1 represents the medium absorption of O-H bending in phenolic compounds, which is associated with ester or carboxyl groups in hemicelluloses. A strong C-O stretching vibration linked to hydroxyl groups is observed at 1047 cm−1. Most peaks in the FT-IR spectrum of EAC closely resemble those in Figure 7 (CAC); however, the peaks at 1609 cm−1 and 1319 cm−1 are less pronounced compared to those at 1074 cm−1 and 1000 cm−1, suggesting the removal of hemicellulose and lignin during extraction. The intensity of the band at 891 cm−1 has increased, indicating a higher cellulose content. The band at 893 cm−1 signifies the typical absorption of -1,4 glycosidic bonds found in cellulose monosaccharides. The absorbance peaks associated with the cellulose b-glycosidic linkage were noted at 893 cm−1. Overall, the spectral data indicate that EAC and CAC exhibit nearly identical characteristic cellulose absorption peaks, suggesting similar chemical compositions..

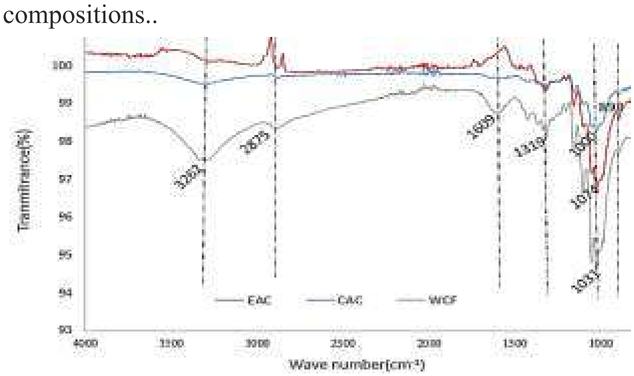

Figure 7 - FT-IR spectra of EAC at optimised conditions (Concentration 0.1g/ml, extraction time 20min, and

Thermal analysis: The TGA curves for WCF, EAC, and CAC at a heating rate of 10°C/min are illustrated in Figure 8. The TGA curve for EAC particles treated with 0.05-0.15 g/ml sodium hypochlorite reveals a slight initial weight loss up to 250°C, which is attributed to the evaporation of adsorbed water. A subsequent weight loss commences at around 300°C and extends to 400°C, indicating weight reduction due to phase transitions, cellulose degradation, and the loss of structural water [13]. Beyond approximately 400°C, a weight loss of up to 49% is observed at 556°C, corresponding to the formation of charred residue. This reduction in weight can be ascribed to the loss of volatiles at elevated temperatures (evaporation), the breakdown of larger molecules into smaller fragments (decomposition), interactions with a reducing atmosphere (such as hydrogen or ammonia) (reduction), and the removal of substances from the surface (sorption). The primary decomposition phase for WCF occurs between 244-330°C, for EAC between 245-329°C, and for CAC between 244-329°C, all linked to cellulose degradation. After heating to 550°C, the residues from both WCF and EAC indicate the presence of carbonaceous compounds in a nitrogen environment. Notably, there is a disparity in the residue quantities of WCF and EAC post-heating to 550°C, with the minimal residue in WCF likely due to the partial removal of waxy and ash components, alongside the increased crystallinity of EAC following sodium hypochlorite treatment. The thermal degradation initiation temperature and peak decomposition temperature for EAC are approximately 331°C and 487°C, respectively. In contrast, WCFs begin to decompose at a significantly higher temperature of 328°C, while the peak temperatures for EAC and CAC are observed at 331°C and 330°C, respectively. These findings suggest that EAC possesses commendable thermal stability, making it suitable for use in absorbent core applications.

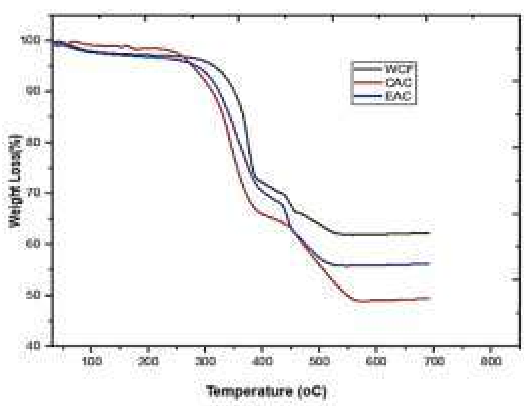

Figure 8 - TGA of EAC obtained at optimized conditions (Concentration 0.1g/ml, extraction time 20min, and extraction temperature 90oC)

3.3 Performance test for the absorbent core

3.3.1 Water absorption for extracted cotton fiber

The findings regarding water absorption in extracted cotton fibers are illustrated in Figure 9. The cotton powder demonstrates favorable water absorption characteristics, attributable to the hydrophilic nature of most natural polymers. In contrast, synthetic materials predominantly exhibit hydrophobic properties. The polymer utilized in commercial hygiene products is a synthetic, hydrophobic variant that possesses a high absorption capacity due to its chemical modifications, which can be detrimental. Nevertheless, it is important to note that hydrophilic polymers generally exhibit superior absorbent capabilities compared to their hydrophobic counterparts. Figure 9 illustrates the impact of fiber weight and length on the water absorption rate of EAC. Sample S1, which has been treated with NaOH, exhibits a weight gain of 6.97g at a length of less than 1.25cm, suggesting a low level of water absorption. In contrast, sample S-3, treated with NaOCl, shows a weight gain of 15.41g at a length of less than 0.25cm, indicating a significantly higher water absorption rate. The findings suggest that as fiber weight increases, the rate of water absorption also rises, while a decrease in fiber length corresponds to a reduction in water absorption. This phenomenon may be attributed to the effective removal of a considerable amount of waste material from the fiber.

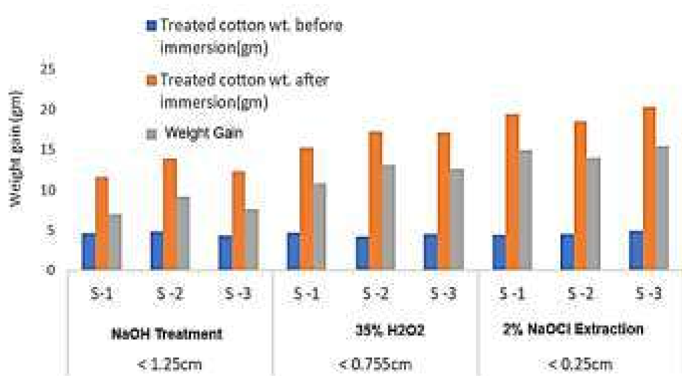

Figure 9 - Water absorption for extracted cotton fiber

3.3.2 Moisture absorption test

Cotton fiber is composed of over 90% cellulose and is recognized for its excellent moisture absorbency and thermal insulation properties. The data presented in Figure 10 indicates that the moisture content, reflecting moisture absorption capacity, varies among the different treatments of waste cotton fiber (WCF). Specifically, the NaOH-treated WCF exhibits a lower moisture absorption capacity compared to the WCF treated with 35% H_2O_2, which in turn has a lower capacity than the WCF treated with 2% NaOCl. This trend can be attributed to the incomplete removal of impurities from the cotton fiber during treatment. Additionally, it has been observed that waste cotton fiber subjected to higher concentrations of NaOCl may demonstrate reduced moisture absorption due to the disruption of hydroxyl groups within the fiber structure, leading to a more hydrophobic nature. Consequently, the optimal treatment parameters identified—0.1 g/ml concentration, 20 minutes of extraction time, and an extraction temperature of 90°C - yield a maximum moisture absorption capacity of 29.95%.

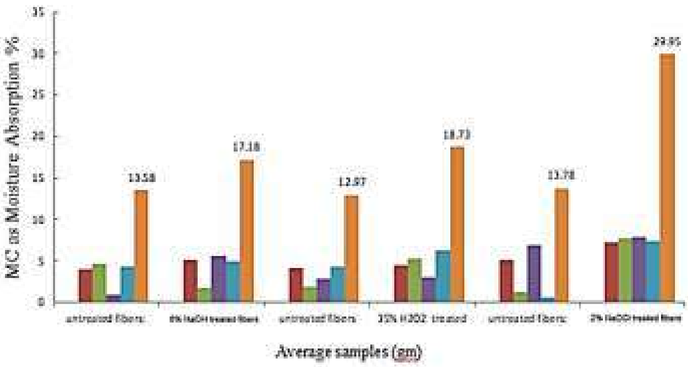

Figure 10 - Moisture absorption of treated & and untreated cotton fiber

4. Concussion

The sodium hypochlorite hydrolysis presents a promising alternative method for the extraction of waste cotton absorbent core, enhancing both the yield and quality of the extract. The optimization of sodium hypochlorite hydrolysis for waste cotton fibers (WCF) was conducted using response surface methodology (RSM). Under optimal conditions - specifically, a concentration of 0.1 g/ml, an extraction duration of 20 minutes, and a temperature of 90°C - an extraction yield of 86% was achieved. These parameters may be applicable for larger-scale WCF extractions to evaluate their economic feasibility. The functional groups and crystal structures of the resulting extracted absorbent core (EAC) closely resemble those of commercial cotton absorbent core (CAC), while its thermal stability surpasses that of the commercial counterpart. The results of this study suggest that hydrolysis is an efficient method for obtaining EAC. Additionally, sodium hypochlorite (NaOCl) hydrolysis allows for the extraction of the absorbent core in a shorter time frame and at lower temperatures, facilitating the reuse of WCFs.

Notably, sodium hypochlorite treatment significantly mitigates fiber degradation, outperforming treatments with strong hydrochloric and sulfuric acids, which typically lead to over 90% degradation. Future research will focus on comprehensive characterization of EAC to provide insights into their processing performance, potentially advancing the development of WCF-based medical applications.

References

[1] S.N.H.B Husain. “Physical and mechanical properties of cotton waste nonwoven web produced by needle punching method”, ME Degree Thesis. Universiti Tun Hussein Onn, (2021) Malaysia

[2] D. Rajput, S.S. Bhagade, S. P. Raut, R. V. Ralegaonkar, S. A. Mandavgane, “Reuse of cotton and recycle paper mill waste as building material”, Construction and Building Materials, 34 (2012) 470-475, https://doi.org/10.1016/j.conbuildmat.2012.02.035

[3] G. Kakonke, T. Tesfaye, B. Sithole, M. Ntunka, “Production and characterization of cotton-chicken feather fibers blended absorbent fabrics”, Journal of Cleaner Production 243 (2020) 118508, https://doi.org/10.1016/j.jclepro.2019.118508

[4] F. W. Brodin, H. Theliander, “Absorbent materials based on kraft pulp: preparation and material characterization”, BioResources, 7(2) (2012) 1666-1683, DOI: 10.15376/biores.7.2.1666-1683

[5] S. R. Imadi, I. Mahmood, A. G. Kazi. Bamboo fiber processing, properties, and applications. In book: 'Biomass and Bioenergy: Processing and Properties'. Eds: Khalid Rehman Hakeem et al., Springer, 2014: pp. 27-46, https://doi.org/10.1007/978-3-319-07641-6_2

[6] G. Chen, J. Liu, R. Liu, “Preparation and wave-absorbing properties of low-cost Fe3O4/corn straw core composite material”, Journal of Materials Science:Materials in Electronics, 34(9) (2023) 808, https://doi.org/10.1007/s10854-023-10184-5

[7] E. A. Elnashar, “Effect the Design and Materials of Eyes Swathe dressing and diapers clothes for Infant's Incubator”, The 3rd National conference of environment and health of society, Elmonovia University, October (2004) Egypt

[8] N. Hastuti, K. Kanomata, T. Kitaoka, “Hydrochloric acid hydrolysis of pulps from oil palm empty fruit bunches to produce cellulose nanocrystals”, Journal of Polymers and the Environment, 26 (2018) 3698-3709, https://doi.org/10.1007/s10924-018-1248-x

[9] B. H. Marandi BH, “Assessment of wood pulp fibers using labeled enzymes”, MSc Thesis, University of Toronto (2001) Canada

[10] C. R. Soccol, L. P. S. Vandenberghe, C. Rodrigues, A. Pandey, “New perspectives for citric acid production and application”, Food Technol. Biotechnol., 44(2) (2006) 141-149

[11] J. G. Montalvo Jr, T.M. Von Hoven, “Review of Standard Test Methods for Moisture in Lint Cotton”, the Journal of Cotton Science, 12 (2008) 33–47

[12] V. S. Mane, P. V. V. Babu, “Studies on the adsorption of Brilliant Green dye from aqueous solution onto low-cost NaOH treated saw dust”, Desalination, 273(2-3) (2011) 321-329, https://doi.org/10.1016/j.desal.2011.01.049

[13] A. C. C. Arantes C, Das Graças Almeida, L. C. L. Dauzacker, M. L. Bianchi, D. F. Wood, T. G. Williams et al., “Renewable hybrid nanocatalyst from magnetite and cellulose for treatment of textile effluents”, Carbohydrate Polymers, 163 (2017) 101–107, https://doi.org/10.1016/j.carbpol.2017.01.007

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Natural Earth Pigments: A Guide to Eco-friendly Textile Dyeing and Printing

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Abstract:

This research delves into the utilization of natural earth pigments as sustainable dyes for clothing, exploring their historical significance and unique properties. These pigments, derived from minerals and clays, are biodegradable, non-toxic, and possess cultural significance, unlike synthetic dyes. The chosen material for experimentation is 100% cotton, dyed with natural earth pigments through a garment dyeing process and has also been printed with natural earth pigments through screen printing. Environmental impact assessment test results, confirm the sustainability of natural earth pigments. FTIR tests confirms the involvement of functional groups in the interaction between natural earth pigment dye and the fabric. The visual appearance test indicates satisfactory results in print durability, accessories, and overall appearance after multiple wash cycles. The garment also undergoes various other lab tests, like staining on multi fibre, dimensional stability, spirality, drapability and stiffness test to prove the durability and fabric handle properties of the garment. In conclusion, the research highlights natural earth pigments as a viable and eco-friendly alternative in the textile industry, contributing to a greener future.

Keywords: *Eco friendly, Environmental impact, Natural Earth Pigments, Sustainable, Textile dyeing and Printing*

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1. Introduction

Natural earth pigments have been used as garment dyes for thousands of years, providing various colours and unique qualities to fabrics. These pigments, derived from minerals and clays found in nature, are not only biodegradable and sustainable but also offer a connection to ancestral traditions and cultural heritage [1].

Three ingredients are usually found in earth pigments: a clay foundation, a secondary colouring agent, and a mineral (iron oxide). The surface of the planet is covered in iron oxide, which comes in a variety of shapes and hues. The proportions of iron and oxygen in these minerals vary. Additionally, there may be a secondary colouring ingredient present in the form of silica, calcium, carbon, manganese oxide, limestone, or rutile (titanium dioxide). Clay serves as the foundation for almost all earth hues. One prevalent misconception is that these pigments are plant-based. The beauty of their extraordinary persistence is that these are "inorganic" pigments and are not "organic" pigments derived from plants, insects, or chemical processes [1]. The climate at the time that earth pigments originate can influence the hue that we perceive now. Low humidity and high temperatures may produce red earth pigments, while yellow does the opposite. The existence of organic stuff or the ground being buried so deeply that it was shielded from oxidizing processes could be the cause of greys, browns, and other deeper colours [2].

Throughout the history of Indian wall paintings, artists' palette was dominated by earth pigments, (iron) ochre's, green earth, wads and white earth, and palettes were similarly limited to colours including red, yellow, brown, green, black, and white. White was derived from kaolin, limestone, and gypsum; black from manganese ochre; green from celadonite and glauconite, red from hematite, and yellow from goethite [3].

Natural earth pigments as garment dyes not only offer rich and diverse colours but also possess a myriad of advantages compared to synthetic dyes. Firstly, natural pigments are non-toxic, ensuring minimal harm to the environment and human health [4]. To add value to the point that natural earth pigments are nontoxic test results like ZDHC and GOTS certificates are added in the reference [5].

Synthetic dyes, on the other hand, often contain harmful chemicals and humans are already using a greater quantity of synthetic colorants in modern civilization for a variety of beneficial purposes. However, overuse of synthetic colours that are carcinogenic, non-biodegradable, and benzidine-like can have a negative impact on the environment and human health. Even if natural dyes do not have these negative consequences, their low yield and poor binding ability call for attention. To work on textiles, the pigment is suspended in a medium and the medium bonds with the cloth. Therefore, it is imperative to do additional study and optimize the production process using natural resources [6]. One of the significant advantages of inorganic pigments is their durability and resistance to weathering and fading. Inorganic pigments can withstand exposure to harsh environmental conditions and retain their colour intensity for extended periods [7]. As people's awareness of their health and environmental issues grows, natural pigments are making a comeback after more than a century of decline [8].

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Yellow bismuth vanadate, red cerium sulphide, praseodymium-zircon yellow, vanadium-zirconia yellow, tin-vanadium yellow, chromates of alkaline earth metal ions, lead antimonate, cadmium yellow, and nickel-antimony doped rutile phase TiO2 are just a few of the environmentally benign inorganic pigments that have been designed and developed for commercial use in recent time [8]. Figure 1 shows the various ranges of colors that can be extracted from natural earth pigments.

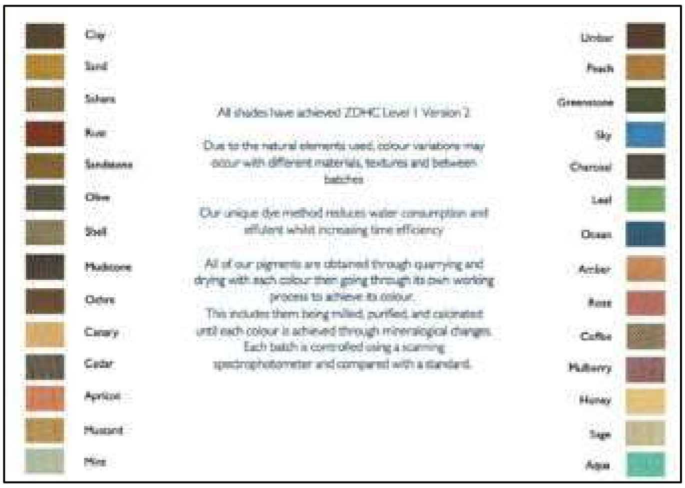

Figure 1 - Range of colours extracted from mineral deposits

Table 1 shows some popular colors of natural earth pigments along with the matching raw material sources.

Table 1 – Colour ranges and their respective raw materials

Pigments	Raw materials	Colors derived
Red Earth	Hematite, iron oxides	Various shades of red, from bright red to deep maroon
Yellow Earth	Goethite, limonite, iron oxides, ochre minerals	Yellow, yellow - brown, and various earthy yellows
Brown Earth	Umber minerals, such as goethite and manganese dioxide	Earthy browns, ranging from light tan to dark brown
Sienna Earth	Sienna minerals, primarily found in Italy	Reddish-brown, yellow-brown
Raw Umber Earth	Umber minerals, sourced from various locations	Earthy browns, including yellow-brown and dark brown
Green Earth	Minerals like glauconite, celadonite, and green clays	Various shades of green, from pale to olive green
White Earth	Chalk, limestone, gypsum	White and off-white shades

2. Materials and methods

When dyeing with natural earth pigments, it is necessary to have a range of materials and tools to ensure successful results. These include fabric, paper, and as well as the pigments themselves. Section 2.1 has the detailed information regarding the materials required for dyeing and printing process using natural earth pigments.

2.1 Materials

Fabric – The garment used for the experiment is made up of 100% cotton, single jersey and 160 GSM. Coloring material – The materials used for the dyeing and printing of the garments were natural earth pigments. The coloring material was an output of various processing like mining or quarrying, sorting and crushing, milling and grinding, cleaning and sanitation, desiccation, wrapping, testing and control of quality of mineral deposits. All the materials listed in table 2 was sourced from TS jeans care, a widely respected supplier of specialty chemicals and dyeing systems to the fashion garment industry in over fifty countries [9]. Table 2 contains the list of materials used for dyeing and printing process of the garment.

Table 2 – Materials used for dyeing and printing

Process	Material used	Material form
Cationisation	Acetic acid	colorless liquid
	Binders	white, milk-like liquid
Dyeing	Clay Color -Umber minerals, such as goethite and manganese dioxide	Powder
Fixation	Fix acryl CFD – dye fixer	Liquid
Bio polish	Bio soft SRC	Cold water neutral cellulase liquid solution
Softening	Palasil DSI	-Superb silicone micro-emulsion polymer solution
Printing	Pink - Pink minerals, such as rose quartz and pink clays	Paste
	Charcoal - Bituminous coal, shale, or other dark, carbonaceous minerals	Paste
	Green stone- Minerals like glauconite, celadonite, and green clays	Paste

2.2 Dyeing Process

The dyeing process using natural earth pigments involves certain steps like cationization, fixation, bio polish and soften. Figure 2 depicts the flow chart of the dyeing process and each step is explained clearly in the upcoming sub sections.

Cationisation
↓
Adjust pH to 4.5 with acetic acid. Temperature 25°C
↓
Add 3% o.w.g Binder slowly
↓
Run for 10 minutes at 25°C
↓
Raise temperature gradually over 5 minutes to 50°C
↓
Run for 10 minutes at 50°C
↓
Drain
↓
Refill
↓
Dyeing process
↓
X% Natural Earth Pigments dispersed in water
↓
Add dispersion in 4 parts every 4 minutes
↓
Raise temperature over 10 minutes to 60°C
↓
Run 20-30 minutes at 60°C
↓
Fixation in same bath
↓
Add 4% Fix acryl CFD over 10 minutes
↓
Run 10 minutes at 60°C
↓
Drain
↓
Bio polish
↓
Run 20 minutes at 30°C in 1.5% o.w.g Bio soft SRC
↓
Drain
↓
Rinse 5 minutes at 25°C
↓
Soften
↓
Run 10 minutes at 30°C in 3% o.w.g Palasil DSI
↓
Extract and Dry

Figure 2 - Flow chart of dyeing process

2.2.1 Cationization

One crucial step in the preparation of garments is cationization, which helps to improve the dyeing properties of the fabric. The first step in the cationization process is to adjust the pH of the fabric to 4.5 using acetic acid. The temperature at this stage should be maintained at 25°C. Next, a 3% o.w.g (on the weight of the goods) binder should be slowly added to the fabric. It is important to add the binder gradually to ensure an even distribution. The fabric should run in the binder mixture for 10 minutes at a temperature of 25°C to allow the binder to act on the fibres. After the initial step, the temperature should be raised gradually over 5 minutes to 50°C. This temperature increase helps to further enhance the dye adhesion to the fabric. The fabric should then be allowed to run for another 10 minutes at the increased temperature to ensure optimal dye penetration.

2.2.2 Dyeing

Once this process was complete, the fabric was drained, and then refilled with a dispersion of X % (o.w.g) natural earth pigments dispersed in water. This step helps to add color and enhance the aesthetic appeal of the fabric. The percentage of natural earth pigments dispersed in water will vary according to the color, as the intensity of each color is different from one other. The dispersion was added in four parts, with each addition occurring every four minutes. It is important to mix the dispersion before each addition as the pigments may be insoluble in water. The temperature was then be raised gradually over 10 minutes to 60°C. Running the fabric at this higher temperature for 20-30 minutes allows for better penetration of the pigments, ensuring long-lasting colorfastness. It is essential to monitor the temperature closely to prevent any damage to the fabric.

2.2.3 Fixation

After the dyeing process is complete, a fixing agent known as Fix acryl CFD – dye fixer [10] was added at a concentration of 4% over a period of 10 minutes. This fixing agent helps to lock the color substance to the fabric, ensuring color retention. The fabric should be run for an additional 10 minutes at 60°C to allow for proper fixation.

2.2.4 Bio Polishing

Once the fixation step is complete, the fabric should be drained, and a bio polish treatment should be applied. This treatment helps to improve the fabric's softness and handle. The fabric should be run for 20 minutes at a temperature of 30°C using a 1.5% o.w.g Bio soft SRC. After the bio polish treatment, the fabric should be drained again, followed by a quick rinse for 5 minutes at a temperature of 25°C. This rinse helps to remove any residual chemicals and impurities.

2.2.5 Softening

Lastly, the fabric underwent a softening process to further enhance its feel. This involves running the fabric for 10 minutes at a temperature of 30°C using a 3% o.w.g Palasil DSI. This step helps to give the fabric a luxurious and smooth texture. Once the entire process is complete, the fabric can be extracted and dried. This final step ensures that the fabric is ready for further processing and any additional finishing touches.

2.3 Printing

The printing technique used to develop these garments is screen printing. The machine used for the garment screen printing process is Roqprint basic P18 XL and the same has been depicted in figure 3 which can print the motif directly to a finished garment. The finished garment is inserted to a lower plate such that the panel to be printed is faced towards the upper screen through which the motif is transferred to the garment. The obtained print paste is mixed with binders and then is used for the printing process. Figure 4 showcases the various garment samples developed using natural earth pigments.

Figure 3 – Machine used for garment screen printing

Figure 4 - Garment samples develop using natural earth pigments

2.4 Costing

The costing for the garment includes right from the raw materials cost to the transportation cost at the time of manufacturing. Figure 5 is the image of the garment for which costing has been done.

Figure 5 - Selected garment for costing

First the garment consumption is calculated, for that the required measurements are body length, body width, Sleeve length, sleeve width and GSM.

The formula for calculation the body consumption is

Body consumption =
body length x body width x 2 x GSM/10000 ....(1)

Sleeve consumption =
Sleeve length x Sleeve width x 2 x GSM/10000 ....(2)

Total consumption =
Body consumption + Sleeve consumption ....(3)

The fabric cost is calculated which includes the yarn, dyeing, knitting, compacting and process loss 10% for the garment. This cost is calculated in per kg of fabric and then during the overall cost calculation the fabric cost per kg is converted to the fabric consumption cost of the garment.

Fabric cost =
Cost of fabric cost per kg x Total consumption / 1000 ....(4)

After the fabric cost the cut make trim (CMT) cost for the garment is calculated which includes the cutting, sewing, checking, trims attachment and ironing of the garment. At last, the overall cost is calculated by adding fabric cost, trims (includes hand tag, strings, price tag and etc.), CMT, printing cost, transportation, testing, cartoon box, profit% and commission for buying office. Table 3 has the detailed costing procedure step by step.

Table 3 - Costing procedure

Fabric Consumption	
GSM	160
Body length (cm)	84
Body width (cm)	63
Body consumption	190.512
Sleeve length (cm)	28
Sleeve width(cm)	27
Sleeve consumption	54.432
Total consumption	244.944
Fabric cost	
Yarn	381
Knitting	15
Dyeing	400
Compacting	11
Total without process loss	807
Process loss 10%	80.7
Total	887.7
CMT	
Cutting	5
Sewing	25
Check and trim	5
Ironing	4
Total	39

Overall cost in rupees	
Fabric cost	217.436
Trims	35
CMT	39
Printing	150
Transportation	2.5
Testing	3
Cartoon box	3
Total	449.936
Profit 15%	67.49
Commission 7%	31.50
Total cost	548.92

2.4 Testing

2.4.1 Visual appearance test

This test verifies the print and the fabric's visual quality. The appearance of the garment is one of the important aspect to be considered and thus this test analyses upon change in print, print peel off, print cracking, pilling, puckering, and fuzzing in the garment before wash and after each wash up to 5 cycles. The above factors were analyzed by comparing the washed sample to the unwashed finished sample using the naked eye.

2.4.2 FTIR Test

An infrared spectrum serves as a unique identifier for a sample by displaying absorption peaks that correspond to the frequencies of vibrations between the bonds of the constituent atoms in the material. It is important to emphasize that infrared spectroscopy confirms the presence of functional groups [11]. Transmittance method was used with wave number range of 4000 - 500 cm-1, Happ-Genzel apodization, 30 No. of scans, and 4 cm-1 resolution. Fourier Transform Infrared Spectrophotometer (FTIR) was the instrument used to test the samples.

2.4.3 Cross staining on multi fiber

During the process of conducting fastness testing on colored textiles, one important aspect that is evaluated is the transfer of colorant from the test material to adjacent materials. This transfer of colorant can occur when the colored textile comes into contact with other materials, such as fabrics or surfaces, and the colorant is transferred onto them. This testing helps to assess the colorfastness of the textile and determine if it has the potential to stain or transfer color onto other materials during use or washing. According ISO 105-A03 standards the color staining on multi fiber was tested.

2.4.4-Dimensional Change

Fabric shrinkage, a major issue in knitwear, is particularly prevalent in casual clothing like tights, shirts, and athletics. Post-washing, the garment may undergo shrinkage or elongation, and dyes can influence these properties. To ensure the garment doesn't exceed the standard 5% allowance, it was sent to lab for a dimensional stability test.

The garment was tested according to ISO 3759 standards [12]. To calculate changes in measurements, divide the difference with the before wash measurement and multiply by 100.

Changes in % = Difference in measurement changes/before wash measurement x 100.................(5)

2.4.5 Spirality

When the wale is not perpendicular to the course, it forms an angle of spirality with the vertical direction of the fabric, giving knitted fabric its spirality. It mostly affects single jersey materials and poses a significant challenge when making and using clothing [13]. Spirality also influences the dimensional stability of the garment thus to make sure that the garment does not exceed the standard accepted allowance which is 3%, the garment was tested for spirality, according to ISO 16322-2:2021 standard [13].
To calculate the spirality % the side seam length i.e., the measurement from the armpit till the bottom hem is measured and the Spirality width post wash is divided with the side length and then it is multiplied with 100 to get the Spirality %.

Spirality = Spirality width/Side seam length x 100 ....(6)

2.4.6 Drapability and stiffness test

The drape coefficient serves as a qualitative assessment of a material's drape characteristics, indicating how well a fabric drapes. This coefficient is defined as the ratio between the area of the fabric before and after the draping process. Given that the area of the fabric before draping remains constant, the drape coefficient is determined by the area after draping. Utilizing a straightforward tool like the Cusick drape meter allows for the measurement of the drape coefficient [14].

Drape coefficient = As – Ad/ AD – Ad ....(7)

Whereas,
As = Area of the specimen
Ad = Area of Small plate
AD = Area of big plate

Flexural rigidity (G) is defined as the force couple needed to induce a unit curvature in a structure lacking rigidity. It serves as an indicator of stiffness, particularly in relation to the tactile feel or handling characteristics of the material. It is a crucial mechanical property that influences the drape, stiffness, and overall structural behavior of textiles. The flexural rigidity is determined by the combination of fabric structure, yarn properties, and finishing processes [15].

Flexural rigidity can be calculated from the bending length, using the equation 8

G = m × C3 × 10-3 ....(8)

Where m is the mass of the test piece per unit area [g/m2] and C is the overall mean bending length [cm]. In this equation the acceleration due to gravity has been rounded to 10 m/s [15].

The stiffness of a fabric in bending is very dependent on its thickness, the thicker the fabric, the stiffer if all other factors remain the same. The bending modulus is independent of the dimensions of the strip tested so that by analogy with solid materials it is a measure of intrinsic stiffness.

Bending modulus = 12 x G x 10-6/g3 Kg/cm2 ....(9)

Where g = fabric thickness in centimeters and G = Flexural rigidity

3 Results and discussion

Based on the review of literature and the materials and methods, Natural earth pigments are one of the best option for a sustainable dyeing and printing technique which has enormous benefits for the people and the environment.

As per the color test reports by Intertek all the dye color materials are free from substances like Organotin compounds, Chlorophenols, Azo, UV absorbers, Thiourea, Chlorinated benzenes and Toluenes and Phthalate test which adds strength to the fact that natural earth pigments are a part of sustainable alternative [16].

Though there are certain chemicals used in the dyeing process for fixation, bio polish and softening these chemicals are carefully selected that they give a very minimal impact on the environment.

The garment has undergone various tests like visual appearance, color staining on multi fiber, dimensional stability and spirality. All the observations of each test are discussed in detail in the upcoming sub sections.

3.1 Visual appearance

The examination of the garment's visual appearance after each of the five wash cycles included the assessment of various parameters:

Change in print: The garment's print quality was consistently graded as 4 across all five wash cycles. This rating is considered good. (*5- Excellent 4- good 3- fair 2- poor 1- very poor)

Print peel off: No instances of print peel off were observed throughout the five wash cycles. Visual inspection with the naked eye confirmed satisfactory print quality.

Print cracking: There was no evidence of print cracking in any of the five wash cycles.

Change in rib: The rib quality remained satisfactory throughout the entire duration of the five wash cycles.

Pilling/Fuzzing/Puckering effects: No pilling, fuzzing, or puckering effects were observed during any of the wash cycles.

After a comprehensive examination of the general appearance of the garment with the naked eye, it was observed that there were no drawbacks. The overall appearance of the garment is considered satisfactory, attributed to the minimal change in print observed during the wash cycle. Consequently, the garment has successfully passed this test.

3.2 FTIR Test

Infrared (IR) spectroscopy was performed on two samples, generating absorption spectra displaying peaks at specific frequencies (cm−1). Additionally, each spectrum was analysed by attributing a possible functional group to each peak identified by a designated number.

Figure 6 represents the graph of FTIR test results for untreated sample and treated sample with natural earth pigments respectively.

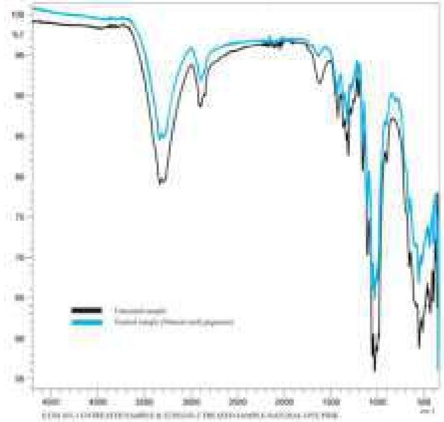

Figure 6 – Functional groups in untreated sample & Functional groups in treated sample (Natural earth pigments)

The FTIR results reveal specific peaks indicative of bonding in natural earth pigments. The peak observed between 3500-3000 signifies the presence of O-H stretch bond, while the peak within 3000-2500 indicates C-H stretch bond. Additionally, the peak at 1500-1000 confirms the existence of C-O, C-N, or C-C bonds, which play a crucial role in the adherence of these pigments to the fabric.

The strong hydroxyl bands at the range in between 3500 to 3000 are a characteristic of kaolin-group clays. The hydroxyl band intensities and positions are very sensitive to the order and crystallinity of the kaolin and it is possible that the changes in the hydroxyl absorptions could be used to differentiate pigments sources [17].

The complete FTIR results of untreated sample and treated sample has been added in the reference section [17].

3.3 Cross staining on multi fiber

The cross staining on multi fiber test to make sure that the garment does not bleed or make a stain while washing with other garments. Thus, to test that the garment sample is washed with various other types of fabrics and through grey scale rating the garment is rated.

Table 4 - Cross staining on multi fiber

Description/No of washes	1st Wash	2nd Wash	3rd Wash	4th Wash	5th Wash
Staining on Cotton	4-5	4-5	4	4	4
Staining on Di-Acetate	4-5	4-5	4-5	4-5	4-5
Staining on Nylon	4-5	4-5	4	4	4
Staining on Polyester	4-5	4-5	4	4	4
Staining on Acrylic	4-5	4-5	4-5	4-5	4-5
Staining on Wool	4-5	4-5	4-5	4-5	4-5
Self-staining	4-5	4-5	4-5	4-5	4-5

5 – Negligible staining 4 – Slight staining 3- Noticeable staining 2- Considerable staining 1- Severe staining

Table 4 shows garment observations after washing with various fabrics, rated through grey scale. It is observed that in the first and second wash cycle the staining grade on all the fabrics is 4-5 which indicates negligible staining or slight staining. From 3rd wash the staining grade on cotton, nylon and polyester has been decreased to 4 which means there has been a slight staining on these fabrics.

3.4 Dimensional Changes

In this test the highest point of shoulder (HPS), Centre back, sleeve, chest and bottom measurements of the selected sample is measured before wash and after wash for 5 consecutive washes. All the measurement changes are noted and is cross checked with the Standard accepted allowance to make sure if all the measurement changes in % are lesser than or equal to standard accepted allowance. Table 6 has the before wash and after wash measurements of 5 consecutive cycles of the selected garment.

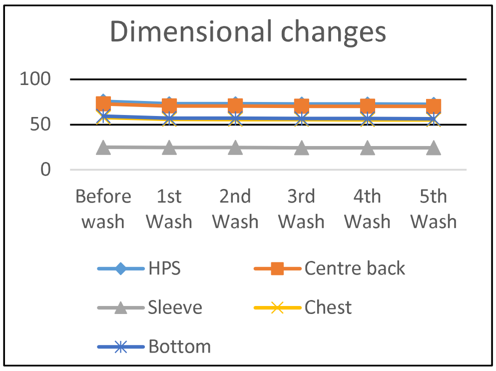

Figure 7- Dimensional changes

The measurements decreased by 2.7cm, 2.3cm, 0.4cm, 2cm and 2.3cm after the first wash for HPS, centre back, sleeve, chest and bottom respectively. However, the difference between the measurements recorded after the first wash and the fifth wash are 0.7 cm, 0.6 cm, 0.4 cm, 0.8 cm and 0.6 cm for HPS, centre back, sleeve, chest and bottom respectively. The decrease percentage remains low throughout all five wash cycles, with the minimum shrinkage percentage as -4% and maximum shrinkage percentage as -4.9% in the fifth wash, yet the shrinkage percentage stands within the standard acceptance allowance. The garment passed the wash test as the post-wash changes did not exceed 5% of the standard accepted allowance. Table 5 and Figure 7 shows the detailed measurements after each wash, with percentages calculated and compared to the standard accepted allowance. The garment's shrinkage during the wash cycle was low, indicating it passed the test. The largest percentage changes were observed in the bottom measurement, due to the agitation during tumble-drying, where garment shrank by -4.9% [18].

3.5 Spirality

In this test the spirality of the garment was tested up to 5 wash cycles. The Spirality percentage should not exceed the standard accepted allowance of 3% to pass the Spirality test.

Table 6 – Spirality

Description	Spirality %
1st Wash	1
2nd Wash	1.2
3rd Wash	1.4
4th Wash	1.8
5th Wash	1.9

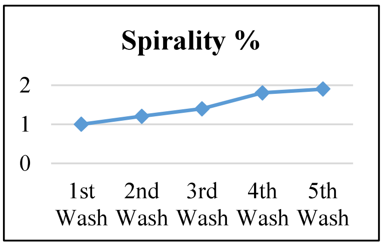

Figure 8- Spirality

Table 5 - Dimensional changes

Description	HPS (cm)		Centre back (cm)		Sleeve (cm)		Chest (cm)		Bottom (cm)	
	Value	% Change	Value	% Change	Value	% Change	Value	% Change	Value	% Change
Before wash	75.7		72.9		25		57.8		59.3	
1st wash	73	-3.6	70.6	-3.2	24.6	-1.6	55.8	-3.5	57	-3.9
2nd wash	72.8	-3.8	70.4	-3.4	24.5	-2	55.5	-4	56.8	-4.2
3rd wash	72.7	-4	70.2	-3.7	24.4	-2.4	55.3	-4.3	56.6	-4.6
4th wash	72.5	-4.2	70.1	-3.8	24.3	-2.8	55.2	-4.5	56.5	-4.7
5th wash	72.4	-4.3	70	-4	24.2	-3.2	55	-4.8	56.4	-4.9

Standard accepted allowance +/- 5

The Spirality % of the garment has gradually increased from 1% recorded after 1st wash to 1.9% recorded after 5th wash, as the % has not exceeded the standard accepted allowance which is 3%, confirms that the garment has successfully passed the Spirality test. From figure 8 and table 6 it is evident that the spirality has been low throughout the 5 wash cycles. The spirality percentage increase was obtained for the garment due to agitation during tumble-drying [18].

3.5 Drapability and stiffness test

Both the treated and the untreated samples were tested for drapability and stiffness test. Table 7 shows the drapablity coefficient, Flexural rigidity and Bending modulus for both the samples.

Table 7 – Test results of drapability and stiffness test

Fabric	Drape coefficient	Flexural rigidity	Bending modulus
Untreated sample	0.352	26.620	4.991
Treated sample	0.262	3.327	0.7275

From the results tabulated in table 7, it is noted that the treated sample has a better drape asseen from lower drape coefficient and lower bending modulus values when compared to the untreated sample. The drapability fall of both untreated and treated sample is depicted in figure 9 and figure 10 respectively.

Figure 9 – fall of untreated

Figure 10 – fall of treated sample

Fabrics with a lower bending modulus have a softer drape, whereas higher bending modulus contributes to a stiffer and less flowing drape. From the table 7 it is noted that the treated sample displays a lower bending modulus, registering at 0.7275, in contrast to the untreated sample with a bending modulus value of 4.991. Based on the results it can be concluded that the treated sample exhibits a superior drape in comparison to the untreated sample.

The finishing treatments like bio polish and softening helped to reduce the fabric stiffness and increased the drapability of the fabric when compared to the grey fabric. It was also found that the fabric handle properties also improved due softening and bio polishing processes.

4. Conclusions

The dyeing and printing industry carry substantial environmental and health impacts, necessitating a shift towards sustainable practices. Striking a balance between economic growth and sustainability poses a challenge. Consequently, a study delved into the advantages and disadvantages of employing natural earth pigments for dyeing and printing garments. Utilizing natural earth pigments in textile manufacturing involves several stages, including cationization, pigment application, fixation, bio-polishing, and softening. These processes ensure vibrant, enduring colours, improve fabric texture and appearance, and foster sustainability. Examinations of garments dyed with natural earth pigments yielded positive results regarding quality and durability. The visual appearance of the garments remained consistent, displaying no significant changes in print quality, peeling, cracking, or undesired effects after five wash cycles. FTIR tests confirmed the presence of functional groups in treated and untreated samples, while multi-fiber tests indicated minimal staining. Drapability and stiffness tests revealed improved fabric handling after softening and bio-polishing treatments.

Careful assessment of dimensional changes demonstrated minimal shrinkage within the allowable range of +/- 5%, affirming the garment's structural integrity after repeated washing. Spirality percentage stayed within the accepted range of +/- 3%, indicating the garment maintained its form and structure.

The use of natural earth pigments in the dyeing process emerged as a sustainable and eco-friendly choice, supported by color test reports confirming the absence of harmful substances. Despite the use of certain chemicals for fixation, bio-polishing, and softening, their meticulous selection minimized environmental impact.

In conclusion, the garment adhered to industry standards in visual appearance, color fastness, dimensional stability, and spirality, underscoring natural earth pigments as a viable and environmentally conscious alternative. While the dyeing and printing methods with these pigments are in the developmental stage, anticipated future advancements suggest a potential shift away from conventional chemical dyeing techniques. Embracing natural earth pigments in the textile industry stands as a significant stride towards sustainability.

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References

[1] Hoffman L, https://naturalearthpaint.com/blogwhat-are-earth-pigments-a-guide-to-ochres-oxides-and-minerals/(Sep 9th 2023)
[2] Barnett J R, Miller S &Pearce E, Optics and Laser Technology, 38 (2006) 446
[3] Sharma A & Singh M R, Heritage, 4 (2021) 1973
[4] Tarikul Islam, Kazi Md. Rashedul Islam, Shahin Hossain, M. Abdul Jalil and M. Mahbubul Bashar, Understanding the Fastness Issues of Natural Dyes, 10.5772, 27 May 2024
[5] https://drive.google.com/drive/folders/1Wvw88dH9B530PojP5vOE0wT5FfmVyucE?usp=sharing
[6] Li S, Mu B, Wang X &Wang A, Dyes and Pigments, 190 (2021) 109322
[7] Yusuf M, Shabbir M &Mohammad F, Natural Products and Bioprospecting, 7 (2017) 124.
[8] George G, Dyes and Pigments, 112 (2015) 83
[9] https://tsjeanscare.wixsite.com/tsjeanscare
[10] soocheta anagha vaidya* and bhundoo sanskrita singh, Fibres and Textiles 30(1), 2023, 110-119
[11] Onyekachi Onyinyechi Nnorom*, Genevive Chinyere Onuegbu, Journal of Textile Science and Technology, Vol.05 No.02 (2019), Article ID: 92589, 10
[12] Mikučionienė D &Laureckienė G, Materials Science, 15(2009) 64-68
[13] Vishal Desale, Pramod Raichurkar, Narsee Monjee, Akhilesh Shukla, Ramkesh Yadav, a Study on Spirality of Single Jersey Knitted Fabric a Study on Spirality of Single Jersey Knitted Fabric, April 2011
[14] Hyohyun Kim, Sungmin Kim,and Chang Kyu Park, Journal of Engineered Fibers and Fabrics (2023)
[15] sami rantasalo, Propagation of flexural properties from fibre to fabric, January 2015
[16] https://drive.google.com/drive/folders/1qZz_j7QG4q8Nd5HQgVPHNTXNzlc006B5?usp=sharing
[17] Kate Helwid, The characterisation of iron earth pigments using infrared spectroscopy, postprints, page 83[18] S. C. Anand, K. S. M. Brown, L. G. Higgins, D. A. Holmes, M. E. Hall and D. Conrad, effect of laundering on the dimensional stability and Distortion of knitted fabrics, AUTEX Research Journal, Vol. 2, No2, June 2002

Image Reference:

[1] Figure 1 - Range of colours extracted from mineral deposits. https://tsjeanscare.wixsite.com/tsjeanscare/researchanddevelopment

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Socio-Economic Conditions and Social Well-being of Handloom Weavers: Challenges, Opportunities and Policy Implications

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Abstract:

An Overview Tamil Nadu has a culturally and economically important handloom weaving industry that faces systemic challenges jeopardizing its very existence. Using a mixed-method approach, this study investigates the socio-economic situation, industry crises and social well-being of 1,000 handloom weavers. Khadi in numbers shows significant vulnerabilities: earning less than ₹6,000/month (51.4%), aged above 55 years (39.5%) and illiteracy (33.9%) Although 39.8% of respondents in that survey of weavers were female, they still experience wage differentials and occupational risks. More than four-fifths relied on cooperative societies and only 2.3 percent were independent, underscoring systemic dependencies on intermediary institutions. Statistical results show relations of significance between socio-economic conditions and crisis factors ($\beta = 0.42$, $p < 0.01$), married weavers have 23% lower financial stability than unmarried ones. Occupational health threats come from musculoskeletal disorders (68% of respondents report this), respiratory problems (42%), and hearing loss (19%), all due to stale tools and poor workspace ergonomics. The study highlights the critical need for policy reforms, including strengthened cooperatives, gender-sensitive welfare programs, and technology integration to facilitate market access. Absent intervention, demographic ageing and technological stagnation will endanger the survival of the sector.

Keywords: *Carbon Fiber, Composite Materials, Glass Fiber, Stress Analysis, Technical Textiles*

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1. Introduction

The journey of handloom weaving in Tamil Nadu is a legacy at the juncture of culture and creation, an essential part of communities in India. Handloom weaving has a rich tradition that spans many centuries, this craft is still the bread and butter for a large segment of the population, the importance of which cannot be dismissed, and partaking of this art is also a representation of one's traditions, their values, and their identities. Despite its historical importance and continued relevance in today's economy, the handloom sector faces various challenges that persist in the face of economic instability, social inequalities, and limited access to resources. This crisis has been brewing and is a threat to the continuing sustainability and growth of the industry.

In Tamil Nadu, handloom weavers, who are skilled artisans, are often burdened with socio-economic strains, further intensified due to changing equations in the buying and selling environment, lack of adequate financial support and eventually fighting to preserve their traditional knowledge and way of working. A nuanced analysis of the socio-cultural and economic context of weavers' lives is necessary for making these complexities clear. This study aims to untangle these dynamics to extract insights which will contribute towards the development of policies and sustainable strategies which improve the livelihoods of handloom weavers in Uganda.

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In this exploration, the current study will try to explore the complex social structure of handloom weaving communities along with their cultural practices. The study explores the organization of these communities, the integration of traditional knowledge into the weaving process, the influence of gender relations and social networks in the craft and so on. It also examines the socio-economic conditions of handloom weavers, the factors causing perpetual crisis in the handloom industry and the nexus of financial well-being and social health.

The study is set in the context of Tamil Nadu's handloom sector where seven districts which are clustered based on their handloom products are studied namely, Kancheepuram, Erode- Bhavani, Madurai, Arani, Coimbatore, Salem and Thanjavur. By way of survey-based methodology, this research will collect both qualitative and quantitative data which will allow for an in-depth analysis of the plight of handloom weavers. Through an in-depth exploration of the interplay between socio-economic factors, cultural practices, and market drivers, the study seeks to develop pragmatic solutions that can strengthen the resilience of these communities and safeguard the future of handloom weaving.

The primary aim of this research is to document sustainable development in the context of the handloom sector. The insights gained from the study aim to illuminate the struggles of artisans and offer deeper insights into the socio-cultural and economic aspects involved, thus aspiring to inform the strategies that policymakers, industry stakeholders, and community leaders can adopt to promote the sustainability of handloom weaving practices for future generations.

2. Review of Literature

Handloom is an important cultural and economic segment of Tamil Nadu and it is firmly rooted in the people of Tamil Nadu. But this traditional craft is struggling because of the economic crisis, competition from machine-made industries, lack of market access. Review of existing literature offers significant intelligence regarding the socio economic status of weavers, industry challenges, and possible ways forward for its sustenance.

2.1 Handloom

Handloom weaving is still one of the leading sources of livelihood for millions, but socio-economic woes continue to plague the industry. Research shows that weavers' well-being is significantly affected by financial dearth, low wages, and no direct access to the market [1, 2]. Low earnings and reliance on middlemen even add to economic vulnerability [3]. Studies point out that handloom workers get paid much less than power loom workers and, consequently, are subject to widespread financial insecurity [4]. Gender inequality in the handloom sector also raises many socio-economic challenges. Although women make up a significant part of the workforce, they are paid less [5, 6] and face occupational hazards. A few other studies indicate the requirement of gender-sensitive policies to empower women artisans through training and financial inclusion [7, 8].

2.2 Market Dispute and Marketing Obstacles

Competition from mechanized industries is killing the handloom sector. Power looms and mills have made fabric cheap and easily available, suggesting that the handloom market share is dwindling [9, 10]. Besides that, generally poor marketing techniques, weak market linkages, and the absence of promotional strategies have been detrimental to the conventional handloom business [11, 12]. Consumer awareness is still an important aspect of maintaining the demand for handloom products. Although research suggests greater awareness among consumers, this does not translate into enhanced profits for weavers [13]. Regarding handloom product visibility and accessibility, researchers suggest that government and private enterprises need to intervene via digital platforms and creative marketing strategies [14, 15].

2.3 Shortage of Technological Development

A significant challenge for the industry is the absence or loss of technological innovation. The majority of weavers still utilize outdated and traditional methods, which may be ethnically rich but do not facilitate production economics and market competitiveness [16, 17]. Modernized weaving tools and value addition are lacking, resulting in decreasing income and labor drain towards other industries [18]. Innovative designs promoted by Mohapatra [19] and contemporary weaving styles offered by Khurana [20] might further contribute to product attractiveness and marketability.

2.4 Occupational Health and Work Settings

Handloom weaving is a labor-intensive craft and comes with multiple occupational health hazards. According to studies, continuous repetitive motions and prolonged exposure to weaving apparatus lead to musculoskeletal conditions, breathing disorders, and hearing loss among workers [21, 22]. In contrast Female labourers are more likely than males to be laid off if the workforce is reduced. It indicates that female construction labourer's act as a buffer to support the industry, it suggests that despite their hard effort, female construction laborers create a buffer that gives the business a cushion [33]. These health problems are compounded by poor working conditions such as inadequate lighting and ventilation [23, 24]. Studies show that ergonomic interventions are necessary to improve working conditions and minimize health risks. Recommendations include redesigning workstations, health benefits, and welfare schemes tailored to weavers [25, 26]. Many government welfare schemes have been designed and implemented, but due to bureaucratic inefficiencies, they fail to drive the desired impact on participants [27, 28].

2.5 Government Interventions and Policy Suggestions

Many policies have been formulated by governments at the state and national levels to support handloom weavers, but the effectiveness of these policies remains debatable. According to certain studies, several welfare schemes fail to reach their target beneficiaries because of inefficient administration and a lack of awareness among weavers [29, 30]. Many studies advocate policy interventions such as financial assistance, market linkages, and cooperatives to make the sector more sustainable [31, 32]. The important role of weaver cooperatives in stabilizing earnings and improving market access has been recognized [37, 34]. Similarly, effective training programs and educational initiatives are recommended to facilitate and encourage skill development and knowledge transfer among younger generations [35, 36].

- **Theoretical Implications**

  This study enhances understanding of economic resilience in traditional crafts by linking financial instability, market access, and gender disparities. It contributes to labor economics and digital transformation literature, emphasizing technology's role in artisanal industries and structural wage inequalities.

- **Managerial Implications**

  Policymakers and industry leaders must strengthen direct market access, digital marketing, and financial inclusion. Technological upgrades, skill development, and gender-sensitive policies can enhance productivity and equity. Effective policy execution, cooperative models, and improved working conditions are key to sustaining this craft.

2.6 Research Gaps and Future Directions

Although the handloom industry has been studied extensively, some gaps remain. Few longitudinal studies have been conducted, limiting insight into how socioeconomic conditions change over time and leading to key policy recommendations going unaddressed. In addition, though financial constraints and market competition are well established, the interplay of these factors with gender dynamics and social stratification remains under-researched

[30, 7]. There is also a need to explore technology as a method for bridging market gaps, as well as the enabling capacity of digital platforms in enhancing direct-to-consumer sales [20, 15].

2.7 Research Objectives

i. To study the socio-economic status of handloom weavers by demographic factors (age, sex, marital status and income).

ii. To analyse the factors causing a crisis in the handloom industry with respect to financial stability, government support and market access.

iii. To assess the social well-being of handloom weavers and their association with the socio-economic conditions and the industry challenges.

iv. To analyse the effect of additional income sources on theweaver's economic prosperity.

v. To assess the impact of demographic factors (age, gender, marital status) on socio-economic conditions, components provoking crisis, and social well-being.

vi. To explore the correlations between socio-economic conditions, crisis factors, and social well-being.

2.8 Research Hypotheses

H1: There exists a wide disparity in socio-economic factors across various groups of aged handloom weavers.
H2: Married handloom weavers and unmarried handloom weavers have significantly different socio-economic conditions.

H3: Socio-economic conditions have a significant relationship with elements causing crisis in the handloom industry.

H4: Handloom weavers have good social well-being because of their socio-economic conditions.

H5: There is a significant difference between male and female weavers on socio-economic factors, crisis elements and social well-being.

H6: Weavers with other sources of income and without have significantly different socio-economic status.

3. Materials and Methods

3.1 Research Design

This is a descriptive, cross-sectional survey designed to assess the socio-economic status, challenges and sustainability of handloom weaving communities in the state of Tamil Nadu. This method provides an overall picture of the circumstances prevalent within the industry and enables the detection of trends and patterns based on the data.

3.2 Sampling Strategy

The study focuses on five districts renowned for their Geographical Indication (GI)-tagged handloom products. A total sample of 1000 weavers (200 per district) was selected using a combination of convenience and snowball sampling. The sample size was determined based on the estimated population of weavers in each region, ensuring representation across demographics, skill levels, and weaving communities. Snowball sampling was employed to reach weavers in informal setups who may not be registered with cooperatives or government bodies, allowing for a more comprehensive understanding of the sector.

3.3 Data Collection

In this case, primary data is collected through structured questionnaires with closed-ended and open-ended questions. The topics of the questionnaire include social structure, community identity, social networks, traditional knowledge transmission, and gender dynamics. Interviews are held face-to-face, to obtain more developed answers and clarify any confusion in the survey.

3.4 Data Analysis

For quantitative data analysis, descriptive statistics, correlation analysis, and regression are used to discover relations between demographic variables and socio-economic factors. Qualitative responses are analyzed using thematic analysis, where themes and narratives in the weaving communities can emerge. The use of a mixed-methods approach leads to an improved understanding of the research outcomes.

3.5 Ethical Considerations

Informed consent from all participants, ensuring confidentiality and adherence to research protocols help maintain ethical standards. Participants receive information about the research, and their answers are anonymous to ensure participants do not have their identities revealed.

4. Data Analysis and results

4.1 Overall Frequency Table

The majority of respondents belong to rural areas in this study, 50% of all, whilst a large amount comes from urban (45.625%) and suburban (4.375%) settlements. Most (39.5 per cent) are older than 55 years, and 34 per cent are aged 46-55 years, indicating an ageing workforce in the handloom sector. 60% of the responders are males, and 39.75% are females. 31.75% of the respondents have been weaving for more than 30 years, showcasing their profound relationship with the tool. Educational attainment is low: 33.875% have "no formal education" and 32.875% have finished only primary education. Income levels are low — 51.375% earn under ₹6,000 per month from weaving. 80% of respondents are working in cooperative societies and only 2.25% of respondents are independent weavers. The results reflect deep-seated issues related to income stability, generational continuity and the need for policy measures to sustain this traditional craft.

Table 1 – Overall Frequency Table

Variable	Categories	Frequency	Percentage
Type of Human Settlement	Rural	400	50%
	Urban	365	45.625%
	Suburban	35	4.375%
Age	Below 25	45	5.625%
	26-35	24	3%
	36-45	143	17.875%
	46-55	272	34%
	Above 55	316	39.5%
Gender	Male	480	60%
	Female	318	39.75%
	Other	2	0.25%
District	Kanchipuram	200	25%
	Erode-Bhavani	199	24.875%
	Thirubhuvanam	204	25.5%
	Coimbatore	1	0.125%
	Salem	196	24.5%
Years of Experience in Weaving	Less than 10	20	2.5%
	11-20	127	15.875%
	21-30	200	25%
	31-40	254	31.75%
	Above 40	199	24.875%
Educational Level	No formal education	271	33.875%
	Primary	263	32.875%
	Secondary	189	23.625%
	Higher Secondary	63	7.875%
	Graduate	13	1.625%
Average Monthly Income in Weaving	Below 6000	411	51.375%
	6001-15000	375	46.875%
	15001-25000	9	1.125%
	Above 25000	4	0.5%
Do you have any additional sources of income?	Yes	32	4%
	No	766	95.75%
Hours spent weaving per day	3-6 hours	135	16.875%
	6-9 hours	409	51.125%
	More than 9 hours	256	32%
Marital Status	Married	785	98.125%
	Unmarried	9	1.125%
Number of Dependents	2	161	20.125%
	3	182	22.75%
	4	284	35.5%
	5	131	16.375%
	Above 5	42	5.25%
Type of Handloom Product Produced	Thirubuvanam Silk Sarees	237	29.625%
	Salem Silk Dhotis	168	21%
	Jamakkalam	194	24.25%
	Coimbatore Kovai Kora Silk	3	0.375%
	Kancheepuram Silk Sarees	198	24.75%
Belonging to Generation in Family	1	55	6.875%
	2	146	18.25%
	3	181	22.625%
	More than 3	418	52.25%
Working Status	Independent weaver	18	2.25%
	Working under the master Weaver	140	17.5%
	Cooperative society	640	80%

Tensile tests were conducted on textile-reinforced composite samples using a universal testing machine (UTM) to assess their mechanical performance. The specimens were prepared according to ASTM D3039, the standard test method for tensile properties of polymer matrix composite materials. This standard ensures consistent and reliable measurement of tensile strength, modulus, and elongation. The specimens, sized 20 mm × 170 mm × 5 mm, were prepared with fibers oriented according to design specifications. The tests aimed to measure the tensile strength and elongation of carbon fiber, glass fiber, and hybrid composite materials.

- Fiber Orientation: The unidirectional (0°) fiber orientation was chosen to align with the primary loading direction in the bumper bracket application. This orientation maximizes the tensile strength and stiffness of the composite in the direction of the applied load.
- Testing Standard (ASTM D3039): This standard was selected because it is widely recognized for evaluating the tensile properties of polymer matrix composites. It provides detailed guidelines for specimen preparation, testing procedures, and data analysis, ensuring consistent and reliable results.

Failure Phenomena in Composites

- Steel (Fig. 16): The steel specimen exhibited a classic ductile failure, with significant elongation before fracture. The failure occurred at a stress of 33 MPa, consistent with the FEA predictions.
- Carbon Fiber Composite (CFRP) (Fig. 17): The CFRP specimen failed in a brittle manner, with minimal elongation and a clean fracture at 1330 N/mm². The failure was sudden, indicating the material's high stiffness and low ductility.
- Glass Fiber Composite (GFRP) (Fig. 18): The GFRP specimen showed a combination of brittle and ductile failure, with some fiber pull-out observed. The failure occurred at 1000 N/mm², with higher elongation compared to CFRP.
- Hybrid Composite (Fig. 19): The hybrid composite exhibited a mixed failure mode, with partial fiber pull-out and matrix cracking. The failure stress was 1100 N/mm², demonstrating a balance between the properties of carbon and glass fibers.

The tensile testing results validated the FEA predictions, confirming the accuracy of the stress distribution and deformation analyses. This experimental approach ensured that the textile composite materials could withstand the expected loads and perform as anticipated in real-world applications.

4.2 T-Test Results (Gender and Additional Income)

- H5 Supported: Gender has no significant relationship with socio-economic, crisis perception, or social well-being.
- H6 Supported: This means weavers who have secondary sources of income have significantly lower socio-economic scores ($p = 0.039$), pointing out the difficulty

Table 2 – T-Test Results (Gender and Additional Income)

Variable	Levene's Test (Sig.)	T-Value	Sig. (2-tailed)	Interpretation
Gender - Socio-Economic Factors	0.661	0.438	0.662	No significant difference ($p > 0.05$)
Gender - Elements Causing Crisis	0.957	-0.498	0.619	No significant difference ($p > 0.05$)
Gender - Social Well-Being	0.352	0.987	0.324	No significant difference ($p > 0.05$)
Income - Socio-Economic Factors	0.012	-2.070	0.039	Significant difference ($p < 0.05$)
Income - Elements Causing Crisis	0.242	-0.878	0.380	No significant difference ($p > 0.05$)
Income - Social Well-Being	0.525	-1.089	0.276	No significant difference ($p > 0.05$)

4.3 ANOVA Results (Age and Marital Status)

Table 3 –ANOVA Results

Variable	F-Value	Sig. (p-value)	Interpretation
Age - Socio-Economic Factors	32.286	0.000	Significant difference ($p < 0.05$)
Age - Elements Causing Crisis	26.549	0.000	Significant difference ($p < 0.05$)
Age - Social Well-Being	10.949	0.000	Significant difference ($p < 0.05$)
Marital Status - Socio-Economic Factors	52.551	0.000	Significant difference ($p < 0.05$)
Marital Status - Elements Causing Crisis	29.344	0.000	Significant difference ($p < 0.05$)
Marital Status - Social Well-Being	15.559	0.000	Significant difference ($p < 0.05$)

- H1 and H2 are supported:
- Age has a major impact on socio-economic and crisis factors. But younger weavers are in much worse socio-economic conditions.
- We also find that married weavers are on average better off socio-economically and experience higher social well-being than unmarried weavers.

5. Findings

This study has provided substantial numbers concerning socio-economic conditions including caste, religion, education, social safety, crisis burden, and social well-being of handloom weavers. Age and marital status were also identified as strong determinants across key dimensions of socioeconomic status, crisis perception, and social well-being. This shows significant differences in socioeconomic factors, crisis elements, and social well-being according to age groups ($p < 0.05$) as indicated by the ANOVA. In the 25 years to 25 years age group, socio-economic conditions are worst, with 5.625% of respondents in that group and those who are above 46-55 years (34%) and 55 years (39.5%) tend to have better conditions. Older weavers seem to have a greater experience and network of connections, whereas younger weavers tend to experience a lower income and fewer avenues in the handloom sector. Marital status was also a major factor in socio-economic stability and well-being. The socio-economic results were also better in the married weavers' group ($F = 52.551$, p 0.05), supporting hypothesis H5. In terms of gender, 60% are males, 39.75% are females, and 0.25% are other. This shows that gender does not play a major role in weighing the experiences of weavers, whether in terms of the economic stability of the industry or terms of good, wholesome well-being.

It also examined how other sources of income affect the finances of weavers. The T-test showed a difference in the socio-economic condition of weavers with additional income when compared to weavers without additional income (t-value = -2.070 and p-value = 0.039). Weavers drawing supplementary income have lower socio-economic scores, reaffirming the financial fragility of these individuals despite multiple sources of income. 4% of interviewees declared they had additional sources of income, while 95.75% declared they depended only on weaving for a living. This highlights a need for diversified income avenues to alleviate the economic hardships faced by the weavers.

Socio-economic conditions were also significantly associated with the elements responsible for the crisis in the handloom sector showing a promising positive relation ($r = 0.610$, $p < 0.01$. Further analysis of socio-economic conditions with the elements responsible for the crisis in the handloom industry. It shows that better socio-economic conditions lead to fewer crisis elements within the industry which again emphasises the interdependence of the financial stability of a craftsman and the challenges faced by the handloom weavers. Moreover, the association between socioeconomic conditions and social well-being was also significant ($F = 10.949$, $p < 0.05$), indicating that better income and monetary situation positively affect the overall well-being of weavers as well. Crisis factors, by contrast, were seen to negatively affect social well-being, further consolidating the perspective that economic hardship is linked to lower scores on the mental and social health axes. To enhance the socio-economic and social welfare of handloom weavers, these results reveal the need for tackling age-related differences and ensuring marital stability and income diversification. The more appropriate response would be through policy interventions that can address these domains of work life directly and through challenges that can be leveraged through the mitigation of elements of crisis in the industry to improve the quality of life of this fragile and precarious workforce.

6. Discussion

The handloom sector, despite its cultural and economic significance, faces challenges such as financial instability, market competition, outdated technology, occupational hazards, and policy inefficiencies. Weavers struggle with low wages, middlemen dependency, and gender disparities, necessitating direct market access and financial inclusion. Competition from mechanized industries and weak marketing strategies hinder growth, emphasizing the need for digital platforms and promotional efforts. The lack of modern weaving techniques reduces productivity, requiring innovation-driven training and technological upgrades. Poor working conditions and health risks call for ergonomic interventions and effective welfare schemes. Although government policies exist, inefficiencies limit their impact, highlighting the need for better administration, cooperative models, and skill development initiatives. A collaborative approach among policymakers, private stakeholders, and artisans is essential for sustaining and revitalizing this traditional craft.

7. Conclusion

The purpose of this study was to critically evaluate the socio-economic conditions, market barriers, technological limitations, and government interventions affecting the handloom weaving industry in Tamil Nadu. The research aimed to identify the key challenges and opportunities for enhancing the sustainability of this culturally significant sector.

The results revealed that handloom weavers in Tamil Nadu continue to face significant socio-economic hardships, including low wages, financial vulnerability, and limited market access. Despite the high level of consumer awareness regarding handloom products, competition from mechanized industries, technological limitations, and poor working conditions further hinder the industry's growth. While government interventions and welfare schemes exist, their impact remains diluted due to administrative inefficiencies and a lack of awareness among weavers.

From these findings, a multifaceted approach is needed to support the handloom sector. This includes improving financial inclusion, enhancing market visibility through digital platforms, introducing technological innovations, and ensuring better working conditions for weavers. Moreover, effective policy interventions and cooperative models are critical in stabilizing the economic conditions of handloom weavers. Addressing these issues will not only improve the livelihoods of weavers but also ensure the continued preservation and growth of the handloom industry for future generations.

References

[1] N. Shama Rao, T. G. A. Simha, K. P. Rao, and G. V. V. Ravi Kumar, "Carbon Composites are Becoming Competitive and Cost Effective," Infosys Ltd., pp. 1–12, 2018

[2] A. R. Bunsell and B. Harris, "Hybrid carbon and glass fibre composites," Composites, vol. 5, no. 4, pp. 157–164, 1974, doi: 10.1016/0010-4361(74)90107-4

[3] A. Muhammad, M. R. Rahman, R. Baini, and M. K. Bin Bakri, Applications of sustainable polymer composites in automobile and aerospace industry. LTD, 2020. doi: 10.1016/B978-0-12-820338-5.00008-4

[4] M. K. Gupta and R. K. Srivastava, "Mechanical Properties of Hybrid Fibers-Reinforced Polymer Composite: A Review," Polym. - Plast. Technol. Eng., vol. 55, no. 6, pp. 626–642, 2016, doi: 10.1080/03602559.2015.1098694

[5] J. Zhang, J. Chen, Z. Li, M. Ji, and T. Sang, "Optimisation design of CFRP passenger car seat backplane based on impact characteristics," Int. J. Crashworthiness, vol. 26, no. 4, pp. 355–367, 2021, doi: 10.1080/13588265.2020.1717919

[6] J. Marzbanrad, M. Alijanpour, and M. S. Kiasat, "Design and analysis of an automotive bumper beam in low-speed frontal crashes," Thin-Walled Struct., vol. 47, no. 8–9, pp. 902–911, 2009, doi: 10.1016/j.tws.2009.02.007

[7] M. Deshmukh and R. K. Sontakke, "www.ijser.in Analysis and Optimization of Engine Mounting Bracket," Int. J. Sci. Eng. Res. ISSN (Online Impact Factor, vol. 3, no. 5, pp. 2347–3878, 2014

[8] M. S. Ummah, No, vol. 11, no. 1. 2019. [Online]. Available: http://scioteca.caf.com/bitstream/handle/123456789/1091/RED2017 Eng8ene.pdf?sequence =12&isAllowed=y%0A http://dx.doi.org/10.1016/j.regsciurbeco.2008.06.005%0Ahttps://www.resear hgate.net/publication/305320484_ SISTEM_PEMBETUNGAN_TERPUSAT_STRATEGI_MELESTARI

[9] F. Khan et al., "Advances of composite materials in automobile applications – A review," J. Eng. Res., no. February, 2024, doi: 10.1016/j.jer.2024.02.017

[10] Q. Fan, H. Duan, and X. Xing, "A review of composite materials for enhancing support, flexibility and strength in exercise," Alexandria Eng. J., vol. 94, no. February, pp. 90–103, 2024, doi: 10.1016/j.aej.2024.03.048

[11] K. G. Prakash, "Characterization and Applications of Natural Fiber Reinforced Polymer Hybrid Composites - A Review," Int. J. Res. Appl. Sci. Eng. Technol., vol. 7, no. 7, pp. 145–156, 2019, doi: 10.22214/ijraset.2019.7022

[12] J. Obradovic, S. Boria, and G. Belingardi, "Lightweight design and crash analysis of composite frontal impact energy absorbing structures," Compos. Struct., vol. 94, no. 2, pp. 423–430, 2012, doi: 10.1016/j.compstruct.2011.08.005

[13] P. Sharma, P. Priyanka, H. S. Mali, and A. Dixit, "Geometric modeling and finite element analysis of kevlar monolithic and carbon-kevlar hybrid woven fabric unit cell," Mater. Today Proc., vol. 26, no. xxxx, pp. 766–774, 2019, doi:10.1016/j.matpr.2020.01.023

[14] H. S. Ashrith, T. P. Jeevan, and J. Xu, "A Review on the Fabrication and Mechanical Characterization of Fibrous Composites for Engineering Applications," J. Compos. Sci., vol. 7, no. 6, 2023, doi: 10.3390/jcs7060252

[15] D. K. Rajak, D. D. Pagar, P. L. Menezes, and E. Linul, "Fiber-reinforced polymer composites: Manufacturing, properties, and applications," Polymers (Basel)., vol. 11, no. 10, 2019, doi: 10.3390/polym11101667

[16] William, "Materials Science and Eng.," Mater. Sci. Eng. A, vol. 42, no. 1, p. 181, 1980 [17] S. Rao, T. G. A. Simha, K. P. Rao, and G. V. V. Ravikumar, "Carbon Composites Are Becoming Competitive And Cost Effective. Infosys Report," Infosys Rep., pp. 2–3, 2015, [Online]. Available: https://www.infosys.com/engineeringservices/white-papers/Documents/carbon-composites-cost-effective.pdf

[18] A. Al-Nini et al., "Flexural behavior of double-skin steel tube beams filled with fiber-reinforced cementitious composite and strengthened with CFRP sheets," Materials (Basel)., vol. 13, no. 14, 2020, doi: 10.3390/ma13143064.

[19] R. Tetlow, "Design With Composites.," p. 125, 1982, doi: 10.1002/9781118097298.weoc067[20] M. A. Bennaceur, Y. M. Xu, and H. Layachi, "Wing Rib Stress Analysis and Design Optimization Using Constrained Natural Element Method," IOP Conf. Ser. Mater. Sci. Eng., vol. 234, no. 1, 2017, doi: 10.1088/1757-899X/234/1/012018

[21] M. Karthikeyan, M. P. Jenarthanan, R. Giridharan, and K. Shunmugesh, "Investigation on Crash Analysis of a Frontal Car Bumper," Trans. Indian Inst. Met., vol. 72, no. 10, pp. 2699–2709, 2019, doi: 10.1007/s12666-019-01741-w

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Treatment of Textile Reactive Orange HE2R Dye by using Biosorbent Azospirillum and Tricoderma

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Abstract:

Adsorption of reactive orange HE2R dye from an aqueous solution by using low cost biofertilizers such as Azospirillum and Trichoderma was studied. The study comprises of assessment of adsorption capacities with respect to adsorbent dosages, dye concentration, pH, contact time, and dye solution temperature. The Langmuir adsorption isotherm effectively associated with the experimental data, and the isotherm parameters, Qmax and R2 was computed. For Azospirillium and Trichoderma, the adsorption capacities were 146.0765199 mg/g and 124.0509789 mg/g respectively.

Keywords: *Adsorption, Azospirillum, Orange HE2R Dye, Batch Adsorption , Trichoderma*

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1. Introduction

Effluent from the textile industry contains a huge quantity of suspended solids, colors, and non-biodegradable compounds. These can affect aquatic habitats like rivers, lakes, and sea if not treated. As some chemicals from effluent are not biodegradable, dyes restrict contact of light to the aquatic environment, which reduces photosynthesis activity in the aquatic atmosphere. Dye concentrations present in the effluent can cause serious diseases like cancer and many more [1]. To protect the ecosystem, effluent from the textile industry must be treated. There are many processes, like coagulation, flocculation, adsorption, and membrane technology. Every process has its own advantages and disadvantages. Some are costly, time-consuming, energy-intensive, and produce secondary waste [2]. During dyeing and washing processes, 50% of dye may be discharged into effluent which typically accounts for a large portion of the color in textile wastewater [3]. Toxic amines are formed in wastewater due to reactive azo bonds. Due to the presence of aromatic structures, dyes are highly resistant to degradation and are present for a long time in wastewater. Most dyes are stable and are not affected by oxidizing chemicals or light. Along with the release of toxic compounds, dyes in water can induce allergic reactions, itching of the skin, nausea, bleeding, and ulcers [4].

From Chitosan, three types of adsorbents were derived and used for the treatment of two dyes, Reactive orange II and reactive Black 5. Three different kinds of chitosan were checked for the removal of dyes without and with treatment. Treatment of FeO nanoparticles in a deep eutectic solvent was done. The removal efficiency after modification was increased for reactive orange by 33% and for reactive black by 17%. Kinetic models were utilized to analyze the process. The Langmuir isotherm showed a fair fit, and the pseudo second order model was suitable for the experimental data. Desorption studies showed use of adsorbent up to 5 cycles [5]. Biofertilizers were also utilized as biosorbents to treat a variety of harmful substances. For the removal of fluoride, Azospirillium biofertilizer was tried. The amount of fluoride eliminated was found to be within permissible limits by batch testing.

The Langmuir model, which showed a 72.6% fluoride removal efficiency, and best fitted to the kinetic data. Azospirillium biofertilizer showed very good removal efficiency for heavy metals like copper and chromium. Copper and chromium had removal efficiencies of 94% and 70%, respectively. Langmuir capacity of adsorption for copper was found to be 35.71 mg/g, and for chromium, it was 5.58 mg/g. The kinetic data has been established by pseudo second order model [6]. Elimination of pesticides like imidacloprid was also checked using Azospirillium and Rhizobium biofertilizer. The optimized time was 20 minutes for the maximum elimination of imidacloprid. Rhizobium and Azospirillium biofertilizers showed adsorption abilities of 58.8 mg/g and 83.3 mg/g respectively [7]. As a bio adsorbent, Trichoderma was used to eliminate the rhodamine B dye. Through batch experimentation, 76% of the dye was removed. The adsorption experimental data matched Freundlich isotherm. Higher pH values resulted in greater elimination efficiency [8]. For Congo red dye removal, the biofertilizers Rhizobium and Azospirillium were used in an aqueous solution. To optimize the parameters, batchwise experimentation was performed. The adsorption capacity of Rhizobium biofertilizer was 101.01 mg/g, whereas Azospirillium biofertilizer had a capacity of 67.114 mg/g. Experimental data showed favorability to Langmuir isotherm for both biosorbents. No secondary waste formation was observed [9].

Biofertilizers, including Azotobacter and Trichoderma, were used to eliminate the hazardous metanil yellow dye. Batch

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experiments revealed a removal effectiveness of more than 93%. Compared to Trichoderma (30.15 mg/g), Azotobacter had a higher capacity of adsorption, 50.54 mg/g. The suitability of several kinetic models was examined for the experimental data. For both biosorbents, the Langmuir isotherm provided an accurate interpretation [10].

This work deals with the reactive orange HE2R dye treatment using biosorbents like Azospirillium biofertilizer (AZB) and Trichoderma biofertilizers (TB) from an aqueous solution. Trichoderma and Azospirillium are readily available, reasonably priced, and environmentally benign. No one has removed the Reactive Orange HE2R using these materials. Following the adsorption of toxic dye, these compounds have no negative consequences. Following adsorption, the impact of these substances on soil was examined. The item has no evidence of dangerous substances on it. The cost of both biofertilizers is 60 and 80 rupees per kg, respectively. These adsorbents were chosen for more research because they demonstrated no secondary hazardous waste production and could sustain room temperature. Azospirillium and Trichoderma biofertilizers were used in batch experimentations to examine the removal of the reactive orange HE2R dye.

2. Materials and Methods

Reactive orange HE2R dye was purchased from Rushvi Fine Chem Pvt. Ltd. The analytical research grade chemicals were utilized in the batch experimentation. Using double distilled water, a stock solution (100 ppm) of reactive orange HE2R dye was prepared. Azospirillium biofertilizer (AZB) and Trichoderma biofertilizer (TB) were obtained from the Agricultural College located in Pune, Maharashtra. Biofertilizers were applied without any prior pretreatment.

3. Characterization

3.1 Scanning Electron Microscopy (SEM)

Morphology of the material is a very important part of any material used in the chemical processes. Scanning electron microscopy provides information about the surface layer which is helpful in analyzing the mechanism of the process. Scanning electron microscopy was carried out for both the biosorbents. Scanning electron microscopy was carried out by using FEI Nova NanoSEM 450.

3.2 Fourier Transform Infrared Spectroscopy analysis (FTIR)

FTIR spectroscopy mechanism is absorption of infrared light at wavelengths that are unique to them. FTIR is used to identify all types of materials, amount of different material which is represented by the peak and finding out all types of materials in mixture. FTIR spectroscopy of dye samples before and after was analyzed.

4. Experimental

BIO TECHNICS INDIA shaker was used for batch experiments. Standard solution was diluted to the selected concentration and used for parameter optimization study like time (0-120 min), Adsorbent dose (0.1-3.0g), pH (2-12), agitation speed (100-200) and initial concentration (5-25ppm).

UV spectrophotometer (Thermo Scientific GENESYS 10) analysis is carried out to check the unknown concentration of dye at 490 wavelength. The experiment's accuracy and repeatability were confirmed by repeating the sample analysis with an additional +5%.

Equations 1 and 2 were used to calculate the dye removal effectiveness at equilibrium and interval, respectively.

$$Q_e = \frac{(C_0 - C_e)\,V}{M} \qquad 1$$

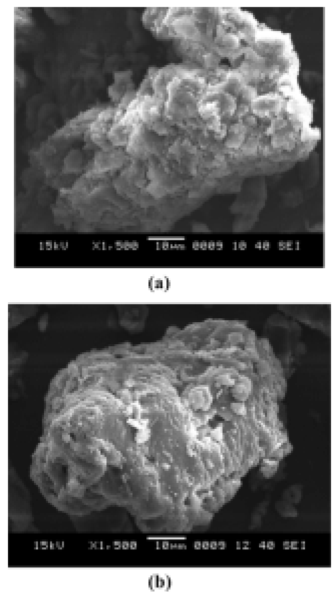
$$Q_t = \frac{(C_0 - C_t)\,V}{M} \qquad 2$$

The initial dye concentration, concentration at specific time, and equilibrium concentration are denoted, respectively, by C0, Ct, and Ce in (mg/l). The adsorption capacity at interval and at equilibrium is represented by Qt and Qein(mg/g). M is the mass of the biosorbent in grams, and V is the volume of the solution in lit.

5. Result and Discussion

5.1 Scanning electron microscopy

Figure 1a and 1b shows the scanning electron microscopy for the AZB and TB respectively. Both biosorbents showed porous structure with layered structure. The porous nature of biosorbents is useful for adsorption of reactive orange He2R dye.



(a)

(b)

Figure 1 - Scanning electron microscopy for a) Azospirillium biofertilizer b) Trichoderma biofertilizers

5.2 Fourier Transform Infrared Spectroscopy analysis (FTIR)

FTIR spectroscopy mechanism is absorption of infrared light at wavelengths that are unique to them. Reactive Orange HE2R dye FTIR spectrum before and after treatment is shown in Figure 2 .

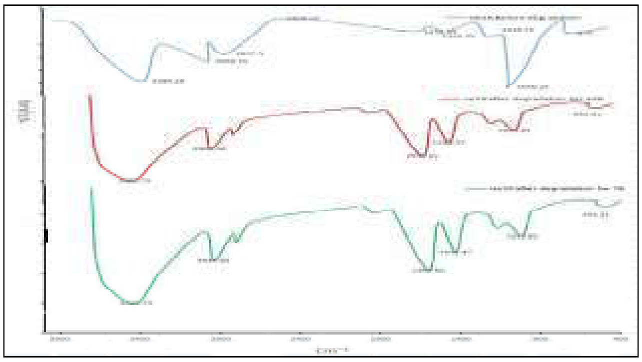


Figure 2 - FTIR analysis of Reactive orange HE2R before and after treatment with AZB and TB

In above fig.2 ,Blue Colour Curve is for Reactive Orange HE2R before degradiation, Red Colour Curve is for Reactive Orange HE2R after degradation by using Azospirrilium Green Colour Curve is for Reactive Orange HE2R after degradation by using Tricoderma.

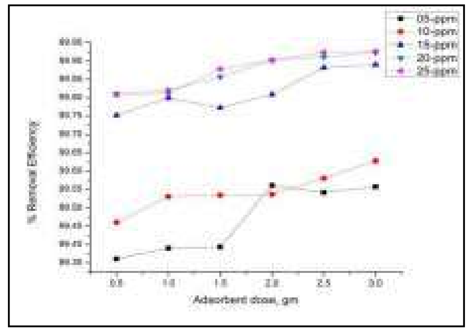
Here, every functional group has its distinctive energy band. The first band was observed at 3364 cm-1which is in the range of 3400 to 3200 cm-1showing N-H stretch bond before and after treatment. The second band was at 2968 cm-1which is correlated with stretching of asymmetric alkanes CH was seen in before treatment and after treatment. At 2837.5 cm-1symmetric stretching of CH was observed. Before treatment, 1056 cm-1was observed which represents C-O stretching and the functional group is primary alcohol which is not seen after treatment. A medium new peak was observed after treatment by AZB and TB at 1598 cm-1which is for N-H bending (1580-1650 cm-1). Two new medium peaks was observed at 1431 cm-1and 1025 cm-1 after treatment which is correlated to O-H bending with carboxylic acid (1395-1440 cm-1), and C-N stretching with amine (1020-1250 cm-1) respectively. Before treatment 670 cm-1(665-730 cm-1) peak was observed linked with C=C bending. All this proposed that the large peak present at 1056 cm-1before treatment was shifted to three medium peaks after treatment which showed the formation of carboxylic acid. This may be due to chemical interaction of dye molecules with the AZB and TB molecules. A small change in the initial transmittance was seen but showed the same functional groups. In the fingerprint region the transmittance was shifted from 670 cm-1to 554 cm-1which is for halo compounds. For both biosorbents a similar pattern was observed.

5.3 Parameter Optimization

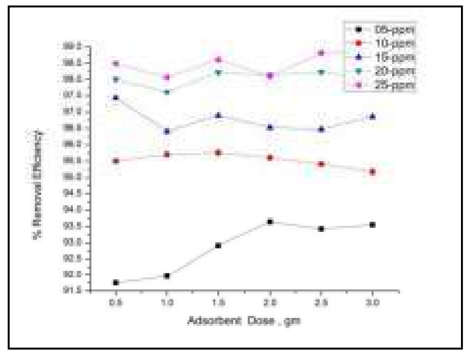
All variables affecting the adsorption process has to be optimized to get the maximum adsorption capacity in the adsorption process. All variable parameters were optimized through batch experimentation.

5.3.1 Optimization of Biosorbent dose

Figures 3(a) and 3(b) display the optimization of dose for both biosorbents. For both biosorbents, a moderate improvement in removal efficiency was seen with an increase in biosorbent loading. The enhanced removal efficiency could be attributed to the biosorbent's more easily accessible active sites [11]. Also noted an identical phenomenon for the dosage of adsorbent for the effluent from textile industry [12]. The optimum parameter for Biosorbent dose are 3 gm for both bioadsorbent.



(a)



(b)

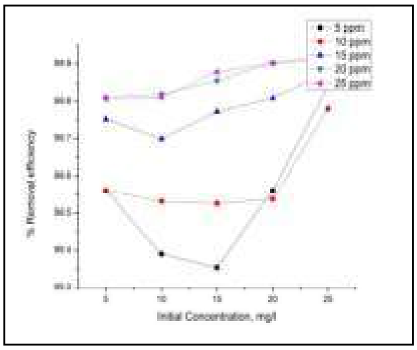
Figure 3 - Optimization of biosorbent dose for a) AZB b) TB

5.3.2 Optimization of initial concentration

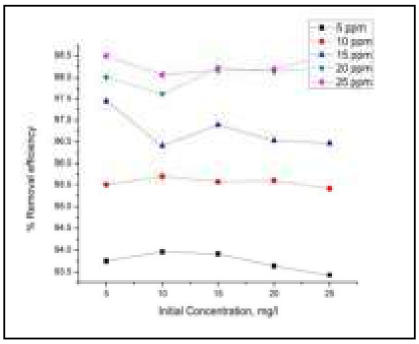
The result of initial concentration on the removal efficiency by AZB and TB is represented in Figure 4(a) and 4(b). For AZB, the efficiency was increased with respect to increased concentration due to increased active sites. TB showed somewhat reduction in removal efficiency, might be due to unavailability of active sites or due to saturation of active sites with respect to time. Initial dye concentration strongly affects the adsorption process. Due to less active site presence maybe there was very small increase in removal efficiency for AZB at increased concentration [13]. For 5 mg/l, 10 mg/l, 15 mg/l, 20 mg/l and 25 mg/l initial concentration of Reactive Orange HE2R, % removal Efficiency by using AZB is 99.80%,99.87%, 99.88%, 99.90% and 99.94% respectively.For 5 mg/l, 10 mg/l, 15 mg/l, 20 mg/l and 25 mg/l initial concentration of Reactive Orange HE2R, % removal Efficiency by using TB is 98.46%, 98.48%, 98.49%, 98.50% and 98.52%respectively.The optimum parameter for initial concentration are 25 mg/l for both bioadsorbent.

5.3.3 Optimization of contact time

Time is the key variable that best describes the adsorption phenomena. It indicates kinetic parameters of adsorption process. The impact of contact time on removal efficiency by



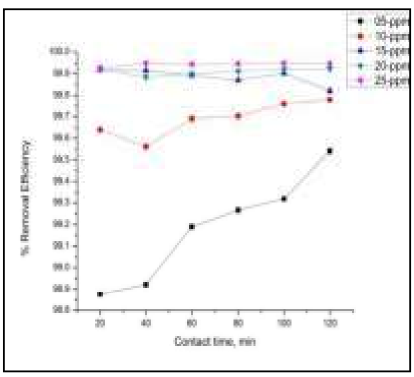
(a)



(b)

Figure 4 - Effect of initial concentration for a) AZB b) TB

using AZB and TB is shown in Figure 5(a) and 5(b). According to the graphical representation, there was a slight increase in removal efficiency over time [14]. There was no enhancement in removal efficiency after 120 minutes; this could be because of saturation of active sites with time [15, 16].



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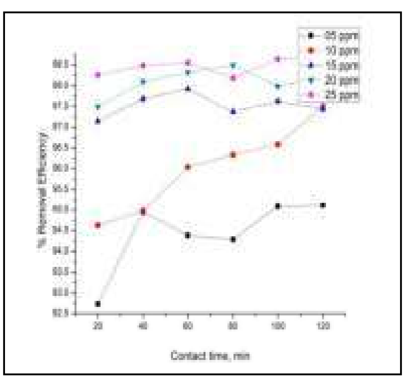
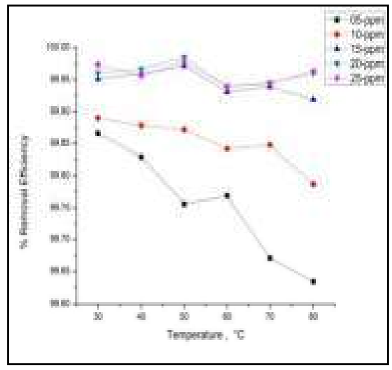


(b)

Figure 5 - Optimization of contact time for a) AZB b) TB

5.3.4 Optimization of temperature

The most significant aspect in the adsorption process is temperature [17]. The temperature influence is shown in figures 6(a) and 6(b) by AZB and TB. The removal effectiveness of both adsorbents reduced as increased in temperature. Reduced removal effectiveness may be caused by the breakage of adsorptive bonds between the adsorbent and adsorbate at high temperatures [18]. A decrease in the electrostatic contact between the molecules of reactive orange HE2R dye and the adsorbent surface resulted in poor removal efficiency. Both biosorbents confirmed maximal removal effectiveness at 300C. The elimination efficiency in the process showed very small variation at higher temperatures.



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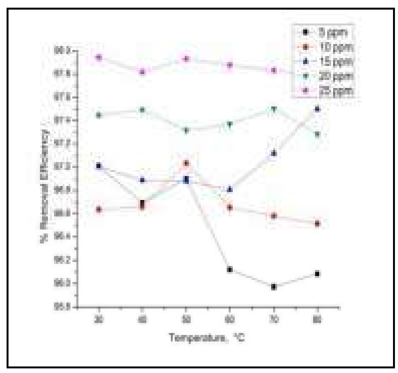


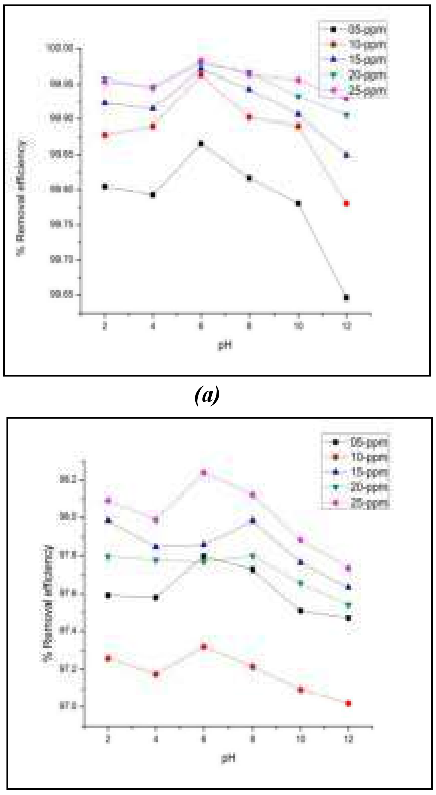
(b)

Figure 6 - Optimization of temperature for a) AZB b) TB

5.3.5 Optimization of pH

A crucial element in the adsorption process is pH since it influences the removal effectiveness. For reactive orange HE2R dye experimentation, pH varied between 2 to 12. The influence of pH on removal efficiency is detailed in figure 7(a) and 7(b). The removal efficiency increased gradually in an acidic medium, reaching its maximum at pH 6.

In the basic medium, the removal efficiency was also above 90% but a small decrease was observed as compared to acidic medium. In acidic and alkaline medium, the removal efficiency was above 90% but maximum removal was obtained near to neutral medium conditions. The pH variation for the textile wastewater was also noted by Sukumar et al., Karegoudar et al., and Chan and Kuo [19, 20].



(a)

(b)

Figure 7 - Optimization of pH for a) AZB b) TB

5.3.6 Optimization of agitation speed

The mass transfer resistance between the solute and bulk solution is impacted by the agitation speed. For both biosorbents, the impact of agitation speed on removal efficiency has been examined at various agitation speeds. Figures 8(a) and 8(b) illustrate the results of the same for AZB and TB. A minute improvement in the removal effectiveness of reactive orange HE2R dye was seen with increased agitation speed for TB. For AZB, a small decrease in removal efficiency was seen with agitation speed. Higher agitation levels may induce a rise in turbulence, which in turn a decrease in resistance between the solute and bulk dye solution was observed [21]. A similar pattern was noted while employing immobilized aquatic weed to remove the yellow metanil dye [22].

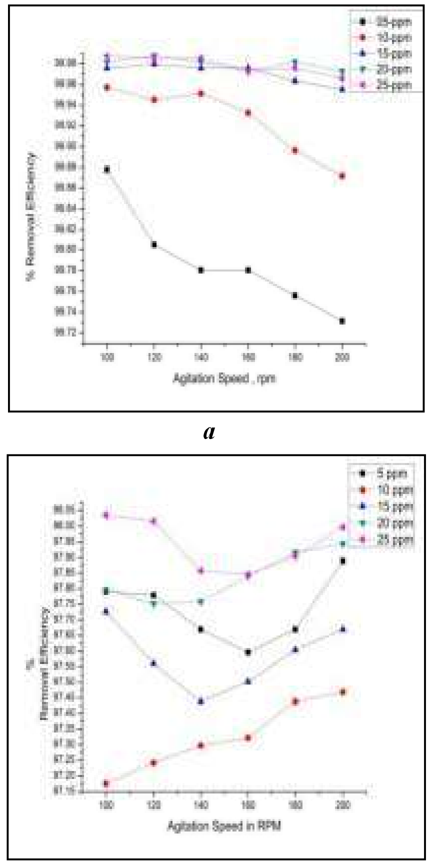
6. Isotherm study

Important interactions between adsorbent molecules and adsorbate molecules are revealed by isotherms [23]. To optimize the utilization of the adsorbent as well as to understand the interaction between the adsorbate and the active adsorption sites, isotherm analysis is essential to the adsorption process [24]. The adsorption process is defined by a multitude of equations. Equation 3 presents the Langmuir isotherm.

$$\frac{C_e}{Q_e} = \frac{1}{k_a Q_m} + \frac{C_e}{Q_m} \qquad 3$$

Ce represents the reactive orange HE2R dye equilibrium concentration in milligrams per lit.

Qm is the amount of dye molecules adsorbed in milligrams per gram at regular intervals.



a

(b)

Figure 8 - Optimization of agitation speed for a) AZB b) TB

Qe is the milligrams per gram amount of dye molecules adsorbed at equilibrium and ka is the Langmuir constant (1/milligrams).

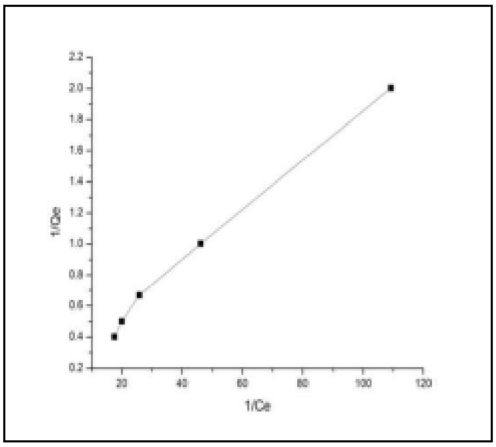
Figures 9(a) and 9(b) illustrate the Langmuir isotherm for AZB and TB. For both biosorbents, the removal of reactive orange HE2R dye was most effectively predicted using the Langmuir isotherm. TB and AZB showed a maximum Langmuir adsorption capacity of 146.0765199 mg/g and 124.0509789 mg/g respectively. The linear plot correlation (R2) of 0.9935 and 0.9962 for AZB and TB, respectively, showed that the Langmuir isotherm was perfect for the adsorption process. The sorption was decreased once interactive sorption had saturated every active site on the monolayer. The crucial factor that determines whether the adsorption method is feasible is the separation factor. Equation 4 presents the expression for the separation factor.

$$R_L = \frac{1}{1 + k_a C_0}$$

The Langmuir constant is ka, the separation factor is RL, and the initial concentration is C0. Favorability is determined by, when RL equals 1, the method is considered linear. It is an unfavorable method if RL is bigger than 1. Method is favorable if RL is larger than 0 and less than 1. It is a reversible method if RL equals 0.

For the removal of reactive orange HE2R dye the RL values for AZB and TB were 0.002 and 0.003 respectively. The process favorability was reflected by these values.

Freundlich and Langmuir isotherms were observed for treatment of reactive orange HE2R dye. Experimental data shown in table 1 explains that the Langmuir isotherm matches most closely the equilibrium data for two biosorbents.



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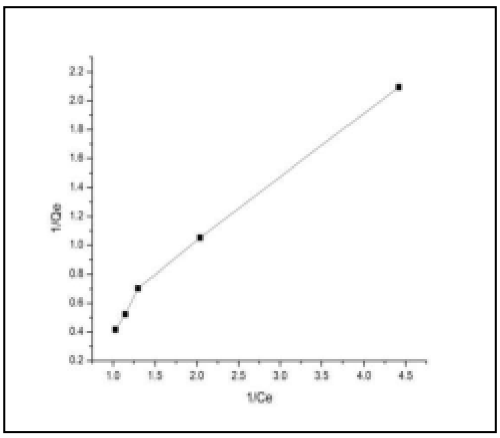


(b)

Figure 9 - Langmuir isotherm for a) AZB b) TB

Table 1: Isotherm constant

Isotherm study	Adsorption Capacity, mg/g		R^2	
	AZB	TB	AZB	TB
Langmuir isotherm	146.0765199 mg/g and	124.0509789 mg/g	0.9935	0.9962

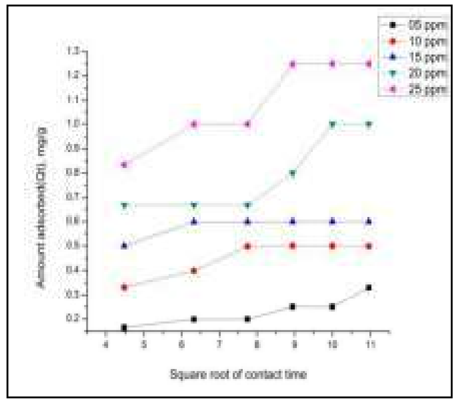
7. Kinetic models

7.1 Intraparticle model

Morris and Weber developed an intraparticle diffusion theory [26]. Equation 5 presents the intraparticle theory developed in mathematical form.

$$Q_t = k_p t^{0.5} + C \qquad 5$$

Where,
Kp, Qt, t and C is rate constant for intraparticle diffusion, dye adsorbed, time and thickness of boundary layer respectively. The model considers intraparticle diffusion and minor film diffusion resistance as rate-determining variables. Figures 10(a) and 10(b) demonstrate a graph of QtVs t0.5 for AZB and TB. Linear form of plot indicated that the intraparticle diffusion was controlled by the boundary layer minute resistance and velocity. The properties of the intraparticle diffusion model are represented by the rate parameter kp. The factor, kp determines the sorption phenomenon between dye molecules and biosorbent [27]. Similar work was reported for intraparticle diffusion [28].



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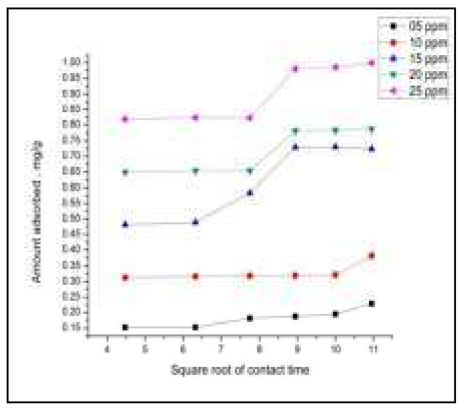

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Figure 10 - Intraparticle diffusion model for a) AZB b) TB

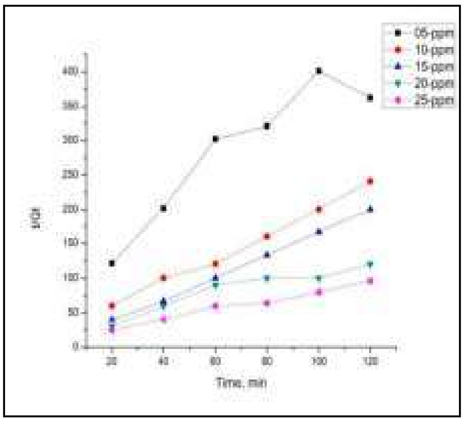
7.2 Pseudo second order

The pseudo second order model states that molecules are removed by physiochemical interactions at the surface, and the adsorbate concentration has no impact on the adsorption rate [27]. Mathematical form of pseudo second order model is presented by equation 6

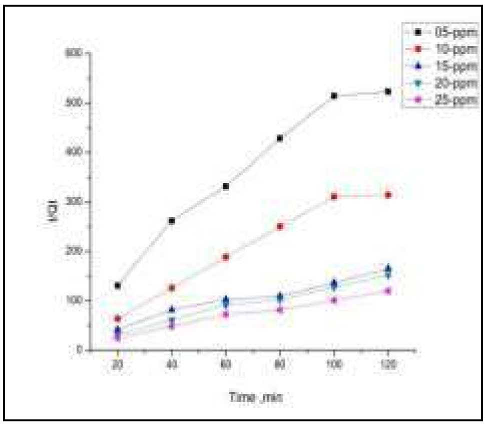
$$\frac{t}{Q_t} = \frac{1}{k_2 {Q_e}^2} + \frac{1}{Q_e} t \qquad 6$$

Where, Qt, t and k2 are dye adsorbed, time and pseudo second order rate constant respectively.

According to the correlation and linearity coefficients, the pseudo second order model was suitable. It is evident from figures 11(a) and 11(b) that, the interaction between the sorbate and biosorbent is important [29].



(a)



(b)

Figure 11 - Pseudo second order model for a) AZB b) TB

8. Comparative study

From Table 3, we come to know that Azospirillum and Trichoderma has high adsorption capacity and also maximum % removal efficiency as compared to other.

9. Reusability

Due to ecological constraints, adsorbent reusability is essential. Thus, for both biosorbents, the reusability work was conducted at 25-ppm concentration of reactive orange HE2R dye, as illustrated in Figure 14. In the seventh cycle, AZB exhibited decreased efficiency, while Trichoderma showed decreased removal effectiveness in the fifth cycle.

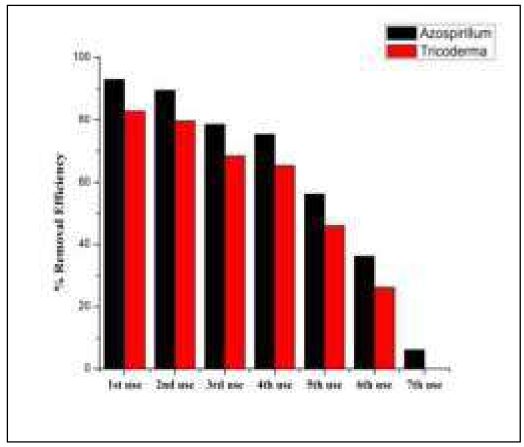


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Figure 14 - Reusability study for AZB and TB

10. Conclusion

Reactive Orange HE2R dye was removed using biosorbents like Trichoderma and Azospirillium biofertilizer. Batch experiments conducted under ideal conditions, Azospirillum showed more removal efficiency and reusability than Trichoderma.

The Langmuir isotherm and pseudo second order model was suitable.Five cycles of reusability testing of the adsorbent demonstrated that AZB and TB are economical to use on a large scale for maximum % removal of textile dye. All things considered, AZB and TB are good option for treating textile

Figure 3: Specimens of developed composites for moisture, absorption and linear swelling test

Sr. No.	Biosorbent	Material Removed	%Removal Efficiency	q_{max}	References
1	Azospirillum	fluoride	Cu 94% Cr 70%,	Cu 35.71mg/gm, Cr 5.58 mg/g.	[07]
2	Azospirillum Rhizobium	imidacloprid		AZB-58.8 mg/gm RZB-83.3 mg/gm,	[08]
3	Trichoderma	rhodamine B	76%		[09]
4	Rhizobium Azospirillum	Congo red dye		RZB 101.01 mg/gm, AZB 67.114 mg/gm	[10]
5	Azotobacter Trichoderma	metanil yellow	93%.	Azotobacter 50.54 mg/gm, TZB 30.15 mg/gm	[11]
6	Activated Sludge	reactive orange HE2R dye	98 %	-----	[30]
7	Azospirillum Trichoderma	reactive orange HE2R dye	99.94% 98.52%	AZB 146.076 mg/gm, TZB124.0509mg/gm	**This Study**

waste because of its environmental friendliness, potential for a high percentage removal, availability, and reusability.The optimum parameter for adsorbent dosages are 3gm , dye concentration25mg/l, pH-7, contact time-120 min, and dye solution temperature-30oC.Here, Maximum % removal Efficiency for Azospirollum is 99.94% and Tricoderma is 98.52%.It will assist in crop development that doesn't harm the environment and remove hazardous elements from effluent. There was no evidence of these biofertilizers having a negative impact on the environment.

11. Funding

No funds, grants, or other support was received.

12. Acknowledgments

We are grateful to PVPIT College, Budhgaon District. Sangli, for offering us the laboratory facility required to conduct the experiment.

13. Conflicts of Interest

The authors declare no conflict of interest.

References

[1] F M D Chequer, T M Lizier, R de Felicio, M V B Zanoni, H M Debonsi, N P Lopes, D P de Oliveira (2015) The azo dye Disperse Red 13 and its oxidation and reduction products showed mutagenic potential. Toxicology in Vitro, ,29,7,1906-1915 http://dx.doi.org/10.1016/j.tiv.2015.08.001

[2] Fahed Javed ,Fahad Rehman , Asad Ullah Khan,Tahir Fazal,Ainy Hafeez, Naim Rashid (2022) Real textile industrial wastewater treatment and biodiesel production using microalgae, Biomass and Bioenergy,165, 106559 https://doi.org/10.1016/j.biombioe.2022.106559

[3] Venceslau M. Correia ,Tom Stephenson & Simon J. Judd(1994) Characterisation of textile wastewater a review, Environmental Technology,25,15,917-929, https://doi.org/10.1080/09593339409385500

[4] I. Bisschops, H. Spanjers (2003) Literature review on textile wastewater characterization, Environmental Technology, 24,11,1399-1411, https://doi.org/10.1080/09593330309385684

[5] Martinez-Rico ,Blanco L, Dominguez A, Gonzalez B(2023) Removal of Azo Dyes Orange II and Reactive Black 5 from Aqueous Solutions by Adsorption on Chitosan Beads Modified with Choline Chloride: Urea Deep Eutectic Solvent and FeO, Separations,10:426, https://doi.org/10.3390/separations10080426

[6] M Basar and H Silah(2020) Adsorption of reactive Orange 16 by Amberlyst A21: Isotherm and kinetic investigations, Turkish Journal of Analytical Chemistry,2 1 22-28

[7] Kulkarni K, Dhulipudi S, Chendake Y, Kulkarni A, Subrahmanyam C V(2022) Adsorptive removal of copper and chromium ion by using azospirillum biofertilizer as low-cost biosorbent in aqueous medium,Water Air and Soil Pollution, 233-245,10.3390/microorganisms12030508

[8] Kulkarni K, Chawan A, Kulkarni A, Gharat S.(2022)Bioremediation of imidacloprid using azospirillum biofertilizer and Rhizobium biofertilizer, Korean Journal of Chemical Engineering,39:2702–2712,https://doi.org/10.1007/s11814-022-1149-5

[9] Kulkarni K., Kulkarni A, Bodare P (2019) Removal of rhodamine-B dye from aqueous solution using biofertilizer containing trichodermaviride as low cost adsorbent, Asian Journal of Chemistry, 31:2291–2297. https://doi.org/10.14233/ajchem.2019.22160

[10] Kulkarni K, Kurhade S, Chendake Y, Kulkarni A.(2023) Utilization of Low Cost Biofertilizers for Adsorptive Removal of Congo red Dye, Bulletin of Environmental Contamination and Toxicology , 111, 33. https://doi.org/10.1007/s00128-023-03784-8

[11] Kulkarni K., Manujendra Kumar Prajapati, Kulkarni Anand, SatputeSatchidanand, (2023)Bioremediation of hazardous Metanil yellow dye by using Trichoderma and Azotobacter biofertilizers ,Acta Ecologica Sinica , doi = {10.1016/j.chnaes.2023.11.007

[12] Mensah K, Mahmoud H, Fujii M et al. (2022)Dye removal using novel adsorbents synthesized from plastic waste and eggshell: mechanism, isotherms, kinetics, thermodynamics, regeneration, and water matrices. Biomass Conversion and Biorefinery,14 12945-12960, https://doi.org/10.1007/s13399-022-03304-4

[13] Eletta O A, Mustapha SI, Ajayi OA, Ahmed AT(2018) Optimization of dye removal from textile wastewater using activated carbon from sawdust, Nigerian journal of technological development,7 15(1) 26-32, 10.4314/njtd.v15i1.5

[14] Ali Maleki, Masita Mohammad, Zeynab Emdadi, Nilofar Asim, Mojtaba Azizi, Javad Safaei(2020) Adsorbent materials based on a geopolymer paste for dye removal from aqueous solutions,Arabian Journal of Chemistry,13(1)3017-3025, https://doi.org/10.1016/j.arabjc.2018.08.011

[15] Abdulsalam K A, Giwa A R A, Adelowo J M(2020) ptimization studies for decolourization of textile wastewater using a sawdust-based adsorbent., Chemical Data Collections, 27:100400. http://dx.doi.org/10.1016/j.cdc.2020.100400

[16] Parimelazhagan V, Yashwath P, Dharun AP, Carpenter J (2022) Optimization, isotherm, kinetic and thermodynamic investigation: Rapid removal of toxicremazol brilliant blue-r dye from aqueous solutions using juglansnigra shell biomass activated carbon as potential adsorbent, International Journal of Molecular Sciences,23:12484. https://doi.org/10.3390/ijms232012484

[17] Memon G Z, Bhanger M I, Akhtar M, Talpur F N, Memon J R. (2008)Adsorption of methyl parathion pesticide from water using watermelon peels as a low cost adsorbent, Chemical Engineering Journal, 138:616-621. https://doi.org/10.1016/j.cej.2007.09.027

[18] Sandesh Y. Sawant, Radheshyam R. Pawar, S. Senthilkumar, Rajesh S. Somani, Moo Hwan Cho, Hari C. Bajaj (2018) Pilot-scale produced super activated carbon with a nanoporous texture as an excellent adsorbent for the efficient removal of metanil yellow, Powder Technology,333:243-251,https://doi.org/10.1016/j.powtec.2018.04.024

[19] O Anjaneya, S YogeshSouche, M Santoshkumar, T B Karegoudar(2011) Decolorization of sulfonatedazo dye Metanil Yellow by newly isolated bacterial strains: Bacillus sp. strain AK1 and Lysinibacillus sp. strain AK2, Journal of Hazardous Materials,190(1–3)351-358, https://doi.org/10.1016/j.jhazmat.2011.03.044

[20] M Sukumar, A Sivasamy, G Swaminathan(2007) Decolorization of textile dye effluent by genetically improved bacterial strains, Applied Biochemistry and Biotechnology,136:53–61, https://doi.org/10.1007/bf02685938

[21] J Chan, T Kuo (2000) Kinetics of bacterial decolorization of azo dye with Escherichia coli NO3, Bioresource Technology,75:107–111, https://doi.org/10.1016/S0960-8524[00]00049-3

[22] Mourabet M, Rhilassi A, El, Boujaady H.El, Bennani-Ziatni M, Hamri R E l, Taitai A.(2015)Removal of fluoride from aqueous solution by adsorption on hydroxyapatite (HAp) using response surface methodology, Journal of Saudi Chemical Society,19:603-615, http://dx.doi.org/10.1016/j.jscs.2012.03.003

[23] Sivashankar R, Sivasubramanian V, Sathya AB, Pallipad S (2013) Biosorption of hazardous azo dye metanil yellow using immobilized aquatic weed , In Proceedings of the International Conference on Future Trends in Structural, Civil, Environmental and Mechanical Engineering–FTCEM ,153-157, ISSN 2475-2711

[24] Tarhan, T, Tural, B, Boga K et al.(2019) Adsorptive performance of magnetic nano-biosorbent for binary dyes and investigation of comparative biosorption., SN Applied Sciences,1,8, https://doi.org/10.1007/s42452-018-0011-1

[25] Zhang Y, Yu F, Cheng W, Wang J, Ma J. (2017) Adsorption equilibrium and kinetics of the removal of ammoniacal nitrogen by zeolite X/activated carbon composite synthesized from elutrilithe. , Journal of Chemistry, 9:1936829, http://dx.doi.org/10.1155/2017/1936829

[26] Wang H, Zhou A, Peng F, Yu H, Yang J.(2007) Mechanism study on adsorption of acidified multi-walled carbon nanotubes to Pb (II) , Journal of Colloid and Interface Science,316:277–283, https://doi.org/10.1016/j.jcis.2007.07.075

[27] Nagappan, Saravanan and Jeon, Yubin and Park, Sung Soo and Ha, Chang-Sik(2019)Hexadecyl trimethyl ammonium Bromide Surfactant-Supported Silica Material for the Effective Adsorption of Metanil Yellow Dye, ACS Omega,4(5)8548–8558, https://doi.org/10.1021/acsomega.9b00533

[28] Kelvin Y, Mutiu A, Patrick S, Jean M, Michael D (2022) Diffusion mechanism and effect of mass transfer limitation during the adsorption of CO2 by polyaspartamide in a packed-bed unit, International Journal of Sustainable Engineering,13:54–67, https://doi.org/10.1080/19397038.2019.1592261

[29] Ho Y S, Mckay G.(1999) Pseudo-second order model for sorption processes, Process Biochemistry,34:541-465, https://doi.org/10.1016/S0032-9592[98]00112-5

[30] Pratibha S. Patil (2016) Activated Sludge: Decolorization and Degradation of Textile Dye Reactive Orange HE2R, International Journal of Science and Research (IJSR), 5(4)251-256, http://dx.doi.org/10.1016/S0043-1354(00)00200-1

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Driving Excellence in Cellulose Yarn Production: V. Thangavel & Sons Success with LMW's Smart Machinery

Innovation and Sustainability at the Core: The Success Story of **V. Thangavel & Sons Pvt. Ltd. (VTS)**

Karthikeyan Thangavel, Whole Time Director, V. Thangavel & Sons Pvt. Ltd.

V. Thangavel & Sons Pvt. Ltd. (VTS), a third-generation family-run enterprise, has built a strong legacy rooted in trust and reliability. Over the years, the company has achieved significant milestones in modernization and innovation by adopting LMW's advanced smart machinery for cellulose yarn production. With cutting-edge automation and digitalization, the company has enhanced productivity, improved quality standards, and excelled in producing superior high-strength yarns.

Founded with a visionary entrepreneurial spirit, VTS began its journey producing household textiles such as dhotis, lungis, and towels as FOX Brand Fabrics. Under the stewardship of three generations, the company has transitioned into a leading name in premium yarn manufacturing FOX Brand Yarns.
This remarkable evolution was bolstered by their collaboration with LMW, whose state-of-the-art machinery and dedicated support played a crucial role in driving productivity and quality improvements.

With its legacy of trustworthiness, the company has established an impeccable reputation among textile players in Tamil Nadu. The adoption of LMW's smart machinery has not only enabled them to remain at the forefront of the industry but also reinforced their commitment to innovation and sustainability, setting new benchmarks in the textile sector.

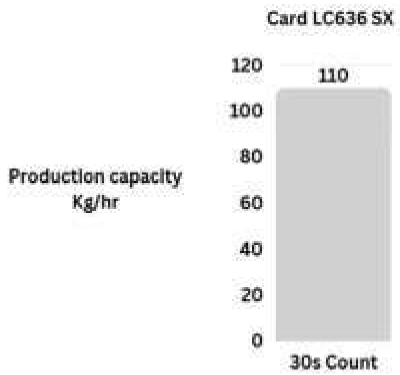
"LMW has played a pivotal role in our growth journey. Their support team visits our factory every three days, ensuring seamless operations. Their state-of-the-art machinery, coupled with 24/7 support for both our floor-level staff and management, truly distinguishes them. We are grateful to have such a reliable and innovative partner," said Mr. Karthikeyan Thangavel, Whole Time Director of V. Thangavel & Sons Pvt. Ltd. (VTS).

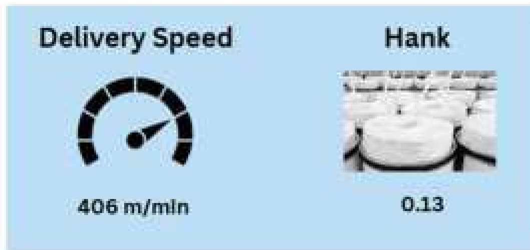
Driving Technological Excellence in Cellulose Yarn Production
V. Thangavel & Sons has long been a leader in the textile industry, with a firm commitment to excellence in cellulose yarn production. With a daily output of 25 tons of 100% cellulosic yarn, the company specialises in Viscose, Micro Viscose, Bamboo, Eucalyptus, Sustainable Viscose Fibres like Liva Eco, Eco Vero, FSC, Modified Viscose like Modal, Micro Modal, Lyocell like Tencel Standard, LF, A100 & Excel, Recycled Cellulose like Liva Reviva, Circulose & Refibra and many more. Their dedication to eco-friendly materials is matched by an unwavering focus on quality and efficiency, ensuring that every product meets the highest industry standards.

At the heart of their success is a blend of innovative technology and meticulous processes that prioritize consistency and minimize imperfections. The integration of LMW's Smart machinery, including the Card LC636 SX with CDS attachment, has played a pivotal role in enhancing both productivity and yarn quality. This cutting-edge equipment allows VTS to consistently deliver premium yarns, reinforcing their position as a trusted name in the global textile market. They give all kinds of yarns like Ring, Ring Compact, Siro Compact, TFO, Slubs, High Twist and Airjet Yarns.

Designer Aarti Vijay Gupta shared her vision for the collection, "Traditional artists are often overshadowed in the global fashion conversation, and so bringing their work to an international stage is incredibly special to me. With this collection, I wanted to reframe the narrative around Indian art by using the old to create something new. Working with Liva Reviva, a sustainable fabric, provided the perfect canvas to honour these traditions while embracing innovation. This is the future of fashion where heritage and sustainability come together with purpose."

Liva's collaboration with Aarti Vijay Gupta aligns with its mission to drive change in the fashion industry through conscious design and advanced fabrics that minimize waste. By supporting designers in merging artistry with sustainability, Liva continues to shape a future where fashion is both meaningful and responsible.





Strategic Collaboration with LMW: A Path to Excellence

LMW has played a crucial role in the growth story of V. Thangavel & Sons by equipping their facility with our cutting-edge machinery.

Today, they are equipped with Smart Machinery of LMW which are Card with CDS attachment, Draw Frames with Autoleveller and Non Autoleveller, and SPINPACT with SIRO Compact attachment. These machines have delivered unparalleled performance, enabling the company to achieve remarkable efficiency and quality.

V. Thangavel & Sons Pvt. Ltd.	
Department	**Model**
LMW Blowroom	LA21
LMW Card	LC363
	LC636 S
	LC636 SX
LMW Draw Frame (Breaker)	LD2
	LDB3
LMW Draw Frame (Finisher)	LDF3
	LDF3 S
LMW Speed Frame	LF 4200/A
	LF 4280/A
LMW Ring Frame	LRJ 9/AXL
	LRJ 9/SXL

Mr. Karthikeyan Thangavel shared his thoughts, stating, "LMW's training programs are truly remarkable, benefiting not just executives but the entire industry. I dream of an LMW School of Excellence to educate and empower entrepreneurs with knowledge on machinery, yarn, and fabric applications."

Expanding Horizons: Market Reach and Future Plans

V. Thangavel & Sons serves a wide array of domestic markets, supplying high-quality yarn to major textile hubs such as Surat, Mumbai, Erode, Salem, Tirupur, Palladam, Somanur, Coimbatore, Madurai, Ludhiana, Delhi and Kolkata. Looking ahead, the company has ambitious plans to broaden its footprint by extending its reach to new regions, including Uttar Pradesh, with a particular focus on areas like Panipat and Varanasi.

Figure 8 - Optimization of agitation speed for a) AZB b) TB

Future Goals: Innovation and Expansion

V. Thangavel & Sons has set ambitious future goals, including the blending of Poly cellulose and Cotton cellulose yarns to create innovative products. The company is also planning significant investments in weaving and knitting facilities to further enhance value addition. As part of its growth strategy, V. Thangavel & Sons aims to double its spinning capacity and install 100 looms, positioning itself for long-term diversification and market leadership.

Commitment to Sustainability and Innovation

Sustainability is at the heart of V. Thangavel & Sons' operations as a 100% cellulosic yarn producer. By utilizing eco-friendly fibers and incorporating LMW's energy-efficient machinery, the company reduces its environmental footprint while upholding high-quality standards. Additionally, V. Thangavel & Sons primarily sources its energy from renewable sources, reinforcing its commitment to both sustainability and innovation.

Scan here to visit website:

AHMEDABAD UNIT

21st October 2024

The Textile Association (India) Ahmedabad Unit organized a technical seminar on "Sustainable Textile Production" on 21st October 2024 at meeting room of the Association. The key speaker Dr. Seshadri Ramkumar, Prof. Nonwovens & Advance Materials Laboratory, Textile Tech University, Texas, USA delivered a speech on Role of Natural Fibre in Textile Sustainability. He expressed in his speech that Natural fibres are considered as potential replacement for man-made fibres. Cotton can find new opportunities in the nonwovens sector as the cost will be competitive with bioplastics and also these fibers are important for technical textiles production. The seminar was very much informative to the audience.

21st October 2024

High Commissioner for Gujarat & Rajasthan and some of the office bearers of our association on 15th January 2025 at Office meeting room. President Shri H. S. Patel warm welcomed Mr. Stephen and two other colleagues Ms. Amee & Richa. The one hour meeting was over in a very enthusiastic way. Maybe very soon a British trade delegation will be visiting to Ahmedabad. Discussion was also about textile trade relations between two countries.

28th January 2025

The Textile Association (India) Ahmedabad Unit & SIDBI jointly organized a seminar on "ESG related Compliance for Competitiveness & Business Continuity for MSMEs". Ms. Sivaranjani Subramanian, Chief Operation Officer and Mr. Prahlad Tewari, Vice President of Environmental Management Centre Pvt Ltd delivered the speech on the subject matter. During the deliberations speaker focused on integrating ESG into their core strategies. MSMEs can drive long-term growth, attract investments, and contribute to a more sustainable and inclusive global economy. The discussions during the seminar were highly informative for the audience.

20th February 2025

Dr. Ashwin Thakkar, Chairman of TAI-Ahmedabad Unit attended a meeting organized by Hon. CM Shri Bhupendrabhai Patel regarding issues pertaining to industries, at CM office Gandhinagar Gujarat.

25th March 2025

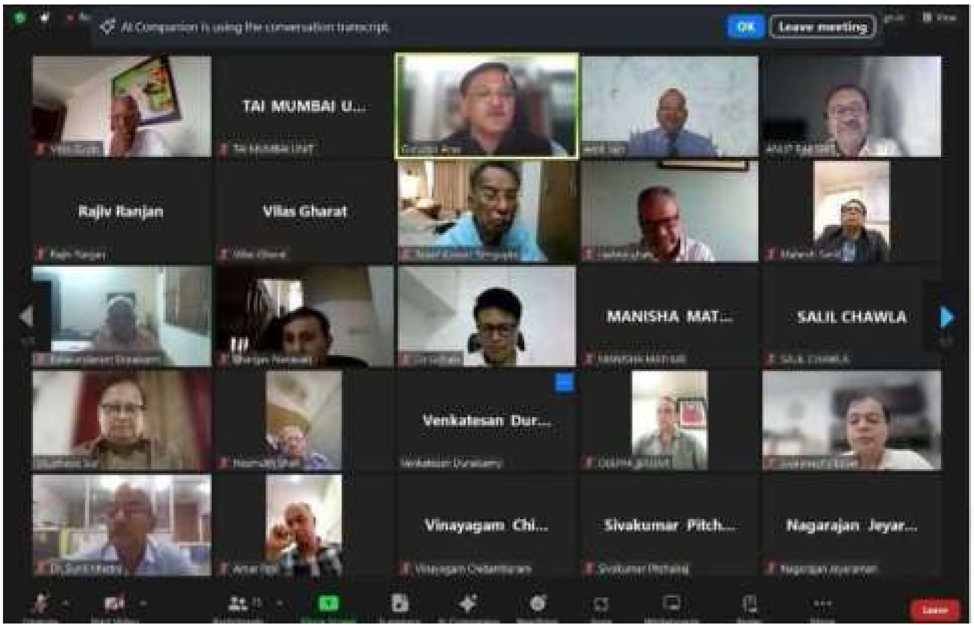
The Textile Association (India) Ahmedabad Unit organized a technical seminar on "Textile Business: Post Budget & Gujarat Textile Policy". Ms. Hetal H. Shah- H Square Advisors, Ahmedabad and Mr. Akhilesh Kumar, Zonal Head, Union Bank of India, Gujarat were the speakers of the said seminar. The seminar was attended by our members as well as some other association leaders.

MUMBAI UNIT

A Webinar on India's Textile Mahakumbh Bharat Tex 2025 Highlights, Trends and Innovations – A Grand Success

The Textile Association (India) - Mumbai Unit, conducted a very interesting and informative Webinar on 05-03-2025 as a follow-up of the recently conducted Bharat Tex 2025 at Bharat Mandapam, New Delhi. This was a grand mega show of the textile industry, showcasing the latest developments, trends and innovations to the world. This webinar was specially organized for those who could not visit this show and those who could not complete the mega exhibition.
I had the privilege of moderating this webinar held on 5th March 2025. The knowledgeable panelists with deep domain knowledge in textile verticals, were carefully selected for this important webinar.

Following were the subject experts who shared their experiences at Bharat Tex on different textile value chain verticals.



- Mr. Amey Padma
- Mr. Amit Jain
- Prof (Dr.) Sameer Sood
- Dr. Anup Rakshit

All the speakers wonderfully covered their observations and innovations noticed during the exhibition as well as during the knowledge sessions.

The following points were the main highlights of their talks.

- Innovations in fibres and blends including Bioengineered fibres
- Promotion of Inonconventional fibres like Hemp, Bamboo, Linen and their blends
- Development of new fabrics
- New developments in home textiles area
- Sustainable product development
- Promotion of Khadi as the most sustainable fabric
- Sustainability and Circularity push
- New varieties of garments with photo chromatic properties
- Digital Platforms helping manufacturers
- New product developments in Technical Textiles

After the individual presentations covering the entire value chain, there was a Q&A session. Some of the participants asked very interesting questions which were answered by the speakers.

Three cheers to the TAI, Mumbai unit team for successfully organizing this unique webinar which immensely helped those who missed the Bharat Tex 2025 mega show.

There was an overwhelming response from the attendees with more than 200 people attending through the webinar link and live YouTube show.

Those who want to watch the webinar can use the following link.
https://lnkd.in/dKg57-Gc

TAI Post Event Report – Seminar at Surat

South Gujarat Unit

The Textile Association (India) – South Gujarat Unit organized a Seminar on "Opportunities in Export for MMF Products" on Tuesday, 22/04/2025 at the Baghban Kratos Club - New Gaurav Path Road, Pal, Surat.

Dr. Gurudas Aras - Independent Director & Strategic Advisor - addressed the topic of Export Opportunities in MMF Products. He enlightened the delegates with his vast knowledge and showed the exact picture of various opportunities in many segments of MMF products which could be explored and get benefit from the same.

Mr. Ashish Gujarati - Member of Textile Advisory Committee (Ministry of Textiles) - gave insight of various Government Schemes to promote Export in MMF Products.

Mr. Kailash Hakim - President of Federation of Surat Textile Traders Association - presented a Trader's Viewpoint on MMF product Export possibilities. He also talked about the lack of education among Surat traders and requested TAI to arrange more programs like this to develop enlightenment among the traders.

TAI National President Mr. T. L. Patel and Hon General Secretary Mr. Mahendrabhai G. Patel attended the meeting as Chief Guest and Guest of Honour respectively.

130 delegates attended the meeting and after the end of Seminar all dispersed for the networking dinner.

FORM IV (See Rule 8)

Statement about Ownership and other Particulars about Newspaper

JOURNAL OF THE TEXTILE ASSOCIATION

1. Place of Publication	: The Textile Association (India), Central Office 702, Santosh Apartment, 7th Floor, 72-A, Dr. M. B. Raut Road, Shivaji Park, Dadar (W), Mumbai – 400 028 MS
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6. Name and address of individuals who own the newspaper and partners holding more than 1% of the total capital	: The Textile Association (India), Central Office 702, Santosh Apartments, 7th Floor, 72-A, Dr. M. B. Raut Road, Shivaji Park, Dadar (W), Mumbai – 400 028 MS

I, J. B. Soma, hereby declare that the particulars given are true to the best of my knowledge and belief.

Mumbai
1st APRIL 2025

(Sd/-)
J. B. SOMA
Hon. Asso. Editor & Publisher

Liva Unveils 'Unified Contrasts' Collection at Fashion Week with Showstopper Anupriya Goenka

Navyasa by Liva Unveils 'Unified Contrasts' Collection at Fashion Week with Showstopper Anupriya Goenka.

Navyasa by Liva, from Birla Cellulose, unveiled their stunning Spring Summer '25 collection Unified Contrasts at a Fashion Week. Designed for the modern woman, this highly anticipated collection offers a mesmerizing blend of ethereal prints and chic silhouettes that weave a vibrant and colorful story. Navyasa continues to stand as a beacon of self-expression and creativity, empowering women to embrace their true selves through fluid, breathable fabrics.

Navyasa by Liva Unveils 'Unified Contrasts' Collection at Fashion Week with Showstopper Anupriya Goenka

Navyasa by Liva Unveils 'Unified Contrasts' Collection at Fashion Week with Showstopper Anupriya Goenka

This collection brings together a diverse range of designs to suit every mood and moment. Sarees crafted from Liva Linen Excel fabric offer light, fluid silhouettes with soft pastel backgrounds and striking bold puzzle-inspired motifs—perfect for the Indian summer. Timeless monochrome print sarees, made from lightweight and lustrous Liva Satin, showcase unique contemporary prints, making them an elegant choice for evening wear. These sarees are light, vibrant, and a great accompaniment to an effortlessly chic, confident look. For everyday grace, the Liva Kota Doria Collection features regal hues with bold floral prints on airy Kota Doria fabric—ideal for both casual outings and office wear, while adding a touch of luxe to your everyday style.

The showstopper, actress Anupriya Goenka adorned a beautiful free-flowing saree in soft pastel hues and striking bold motifs, looking surreal as she glided on the runway.

Designer Aarti Vijay Gupta shared her vision for the collection, "Traditional artists are often overshadowed in the global fashion conversation, and so bringing their work to an international stage is incredibly special to me. With this collection, I wanted to reframe the narrative around Indian art by using the old to create something new. Working with Liva Reviva, a sustainable fabric, provided the perfect canvas to honour these traditions while embracing innovation. This is the future of fashion where heritage and sustainability come together with purpose."

Liva's collaboration with Aarti Vijay Gupta aligns with its mission to drive change in the fashion industry through conscious design and advanced fabrics that minimize waste. By supporting designers in merging artistry with sustainability, Liva continues to shape a future where fashion is both meaningful and responsible.

Anupriya Goenka expressed her excitement, saying, "Walking for Navyasa by Liva was an absolute joy. I loved how the saree looked and felt, it was amazingly light and flowy, yet so luxurious. This collection is perfect for women who want effortless elegance in their everyday wardrobe."

Commenting on the showcase, Mr. Manmohan Singh, Group Executive President and Chief Marketing Officer of Birla Cellulose, said, "With this collection, we look forward to fulfilling the aspiration of modern women who want high-fashion outfits that are easy to wear and move in. The entire collection is sustainable, of natural origin & skin friendly."

The showcase at the Fashion Week was a testament to Navyasa by Liva's commitment to quality fashion attires. By blending innovation, sustainability, and timeless aesthetics, the brand continues to set new trends while celebrating the essence of contemporary femininity.

Hanover Gears Up to Welcome ITMA Participants after Three Decades

Official travel agent appointed to manage accommodation

The city of Hanover is eagerly waiting to welcome participants of the world's largest textile and garment technology exhibition - ITMA 2027. The exhibition will be held from 16 to 22 September 2027. It is expected to gross 200,000 square metres, occupying 13 exhibition halls at the Messegelaende Hannover.

Held once every four years since 1951, ITMA was last staged in the German city in 1991. The bid for ITMA 2027 was submitted by the venue owner Deutsche Messe in close cooperation with the capital of Lower Saxony and the office of the Lord Mayor.

Belit Onay, Mayor and CEO of the City of Hanover enthused, “We are elated to have successfully bid for ITMA 2027. A bustling hub for trade fairs and congresses, the city looks forward to welcome ITMA back to Hanover after more than 30 years.

“We will spare no effort to ensure the hosting of an excellent ITMA. Hanover is a green and efficient city with a relaxed atmosphere. As a major trade fair city, Hanover is organised, and easy to navigate, making it a stress-free destination for visitors. Its blend of history and modernity makes it a hidden gem for those seeking a well-balanced urban experience.”

Interesting accommodation options

Hanover is no stranger to hosting mega trade shows. Supporting this established trade fairs destination is an ample and diverse range of accommodation options, including hotels, guesthouses, inns and private apartments. Each of these options caters to different needs and offers a unique experience.

Currently, the city of Hanover offers over 18,000 hotel beds, ranging from budget to premium options. In the surrounding districts and metropolitan region, an additional 54,000 beds are available. According to Deutsche Messe, the exhibition venue operator, around 4,000 private accommodations can also be found throughout the city, nearby areas, and the broader metropolitan region.

“The majority of the accommodation allow you to get to the fairground within 30 to 90 minutes. In addition, we have a campground opposite the exhibition venue that is open to participants who bring their motorhomes and caravans. ITMA 2027 participants can expect to have more options when another 700 rooms are made available in the city centre next year,” said Dr. Jochen Koeckler, chairman of Deutsche Messe's Board.

To further assist ITMA participants, the organiser ITMA Services has appointed accommodation specialist bnetwork to provide hotel and vacation apartment booking services. Backed by nearly two decades of experience, the destination management company has handled two past ITMA exhibitions in Barcelona and is attuned to the needs of participants.

A dedicated website is being set up for ITMA participants to book their accommodation. Meanwhile, to enquire about accommodation or to book rooms, please contact itmahotels@bnetwork.com

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Rieter On-site Preventive Repair Enhances Autoconer Efficiency by 10%

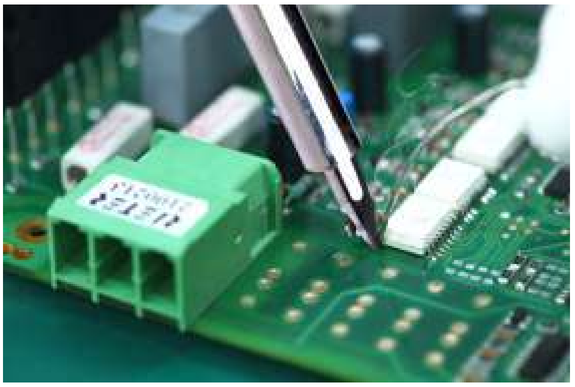
Rieter's on-site preventive repair service at Sudhan Spinning Mills, India, has enhanced the efficiency of Autoconer 338 winding machines by 10%, leading to increased productivity. This service reduces downtime, prevents component failures and ensures peak performance with minimal operational disruptions and logistical challenges.

The winding machine Autoconer 338 has been a cornerstone for many spinning mills over the past two decades. Over time, these machines require comprehensive repair and maintenance of critical electronic control units in the winding section to sustain optimal performance.

Economical repair service solution for Sudhan Spinning Mills

Rieter's on-site preventive repair (Fig. 1) is carried out at the mill and provides original, high-quality repair components at a competitive price. The Autoconer 338 on-site repair package includes motherboards (Fig. 2), operating units, propack anti-patterning system, conveyor drive systems, power supplies and doffing control boards. These elements ensure consistent performance and increased lifetime for aging machines.

The preventive repair also reduces idle drums and downtime due to unexpected component failures, making it a smart



On-site preventive repairs are carried out by Rieter repair service engineers

The Autoconer 338 winding unit motherboard helps achieve higher machine efficiency

investment for customers aiming to enhance the performance of their machines. Leading spinning mills like Sudhan Spinning Mills Pvt Ltd. in India have already implemented this solution, achieving a 10% increase in efficiency (Fig. 3). Issues like red lights and programming faults have decreased significantly, further boosting productivity and machine longevity.

“We have completed on-site preventive repairs for our 13 Autoconer 338 winding machines. The machine efficiency has improved resulting in increased productivity as expected. Thanks to Rieter for extending the machine's lifetime,” says S Jayaraja Perumal, Chief General Manager, Sudhan Spinning Mills Pvt Ltd., India.

The advantages of on-site repairs

On-site preventive repairs are an economical solution for customers, as they save time and cost associated with transportation while reducing production loss. Rieter repair service engineers perform the repairs, bringing the necessary know-how, special tools and equipment to each site. The use of state-of-the-art equipment with original repair components extends the lifetime of the machine. Additionally, during the on-site repair work Rieter repair service engineers identify and address operational issues. They also provide essential training to operators to ensure maximum utilization of the machine.

For further information, please contact:

Rieter AG Relindis Wieser
Head Group Communication & Marketing
T +41 52 208 70 45
media@rieter.com www.rieter.com

Post Doctorate PhD & Honorary Doctorate Awardees XXII Convocation Function at Bel-la Monde Hotels, New Delhi

Dr. Gurudas V. Aras receiving the Award

Dr. Gurudas V. Aras is a distinguished leader in the Indian Textile and textile machinery industry with over 45 years of experience including 15 years in board positions. A gold medalist and Mumbai University topper in Textile Engineering, he also holds a Master's degree in Textile Engineering and a Post-graduation in Marketing Management. Dr. Aras is a Ministry of Corporate Affairs-certified Independent Director and a CRISIL-certified ESG Risk analyst. In 2018 he received the 'Service Gold Medal' the highest honor from The Textile Association (India). He has played pivotal role in bringing European textile machinery companies to India through joint ventures and collaboration. Dr. Aras has actively contributed to CII, FICCI, and the Indo-Vietnamese Chamber of Commerce.

Currently he serves as an Independent Director on the Board of six large companies and is a Strategic Advisor to four global firms. He is also a Board of Studies and Advisory Group Member at VJTI, Mumbai, shaping the future of Textile Engineering education.

Birla Cellulose Showcases Sustainable Elegance with Livaeco Collection at Jaipur Times Fashion Week

Birla Cellulose, from the house of Aditya Birla Group, made a striking statement at Jaipur Times Fashion Week with an exclusive showcase featuring its latest collection crafted using Livaeco, the eco-enhanced variant of its fabric. Created in collaboration with esteemed partner brands like Indoera, Juniper, and Holly Hock, the collection is a testament to sustainable fashion that blends style, comfort, and eco-consciousness.

The much-anticipated fashion event witnessed the elegance and charisma of Tejasswi Prakash, who graced the runway as the showstopper for Livaeco. Known for her impeccable style and strong advocacy for responsible fashion, Tejasswi was styled in a specially curated ensemble by the brand, embodying the essence of fluid fashion with sustainability at its core.

Livaeco's latest collection was a seamless fusion of tradition and modernity, offering ensembles that were not just high on fashion but also had a lower environmental impact. The brand's commitment to sustainability was reflected in its responsibly sourced fibers, which contributed to reduced water consumption and a smaller carbon footprint, making each garment an eco-friendly choice.

Speaking about the collection and her association with Livaeco, Tejasswi Prakash shared, "Fashion is an expression of who we are, and it is inspiring to see brands like Birla Cellulose making sustainability an integral part of style. The collection beautifully merges elegance with a responsible approach, and I am thrilled to walk the ramp in an ensemble that speaks of eco-conscious fashion choices."

Birla Cellulose' collaboration with Indoera, Juniper, and Holly Hock brought together diverse design aesthetics under a shared vision of sustainability. From flowing silhouettes to intricate handcrafted details, the collection highlighted how fashion can be both luxurious and environmentally responsible.

Commenting on the showcase, Mr. Manmohan Singh, Group Executive President and Chief Marketing Officer of Birla Cellulose said, "At Birla Cellulose, sustainability is not just a commitment—it's an ongoing journey. While LIVA itself is an inherently sustainable fabric, Livaeco takes it a step further with responsibly sourced raw materials from certified forests, minimal water consumption, and low greenhouse gas emissions. Its unique traceability solution ensures complete source credibility, empowering consumers to make informed, eco-friendly fashion choices. In Jaipur Times Fashion Week, we proudly present the Livaeco based collection in collaboration with our three esteemed partners—Juniper, Indoera, and Holly Hock—who have crafted an exquisite range that seamlessly blends sustainability with high fashion, perfect for the modern woman who values both style and a greener future".

Jaipur Times Fashion Week continued to be a premier platform for celebrating innovation in fashion, and Livaeco's showcase set new benchmarks in sustainable couture. The event brought together designers, fashion enthusiasts, and industry leaders, all converging to witness the transformative power of responsible fashion.

As Livaeco by Birla Cellulose took centre stage at Jaipur Times Fashion Week, it reinforced its commitment to a greener tomorrow—one stylish step at a time.

Birla Cellulose Showcases Sustainable Elegance with Livaeco Collection at Jaipur Times Fashion Week

Birla Cellulose Showcases Sustainable Elegance with Livaeco Collection at Jaipur Times Fashion Week

The Textile Association (India) – Central Office

(Registered under the Society's Registration Act XXI of 1860 and under Bombay Public Trust Act XXIX of 1950)
702, Santosh Apartment, 7th floor, 72-A Dr. M. B. Raut Road, Dadar (W), Shivaji Park, Mumbai – 400 028
Tel.: 022-3554 8619 , E-mail: taicnt@gmail.com
(Subject to Mumbai Jurisdiction)

RESULTS FOR ATA PART I - PASSED/ATAHE CANDIDATES DECEMBER, 2024

Centre / Result	PASS	ATAHE
Ahmadabad	2024/01, 2024/02	_
Bhilwara	NIL	_
Coimbatore	NIL	_
Delhi	2024/10, 2024/11	_
Ichalkaranji	2024/20, 2024/22	_
Mumbai	2024/29, 2024/30, 2024/31	_

Total	Registered	Appeared	Passed	ATAHE	PASS %
	10	10	09	NIL	90%

RESULTS FOR ATA PART II- DECEMBER, 2024

Centre / Result	PASS	ATAHE
Ahmadabad	2024/501, 2024/502, 2024/503, 2024/504	_
Bhilwara	2024/510	_
Coimbatore	2024/520	_
Delhi	2024/530, 2024/531	_
Ichalkaranji	2024/540, 2024/541	2024/542
Mumbai	2024/550	_

Total	Registered	Appeared	Results	ATAHE	Passed %
	12	12	11	01	91%-

ATA Part II Result is with -hold for want of submission of Industrial Report.

RESULTS OF ATA PART III - PASSED CANDIDATES DECEMBER, 2024

Centre	Yarn Manufacture	Fabric Manufacture	Textile Wet Processing	Knitting & Garment Manufacture
Ahmedabad	2024/602	2024/701, 2024/702	_	_
Bhilwara	2024/610, 2024/611, 2024/612	-	-	-
Delhi	-	2024/710, 2024/711, 2024/712, 2024/713	-	-
Ichalkaranji	_	2024/720	2024/801	_

ATA Part III Result will be declared after submission of Industrial Report.

Candidate	Yarn Manufacture	Fabric Manufacture	Textile Wet Processing	Knitting & Garment Mfg.	Total
Registered	05	07	01	NIL	13
Appeared	05	07	01	NIL	13
Results	04	07	01	NIL-	13

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Schedule of A.T.A. Part - I, II & III December, 2025

ATA Part - I	Time 10.00 a.m. to 1.00 p.m.	ATA Part - II	Time: 2.00 p.m. to 5.00 p.m.
Date	Subjects	Date	Subjects
20-12-2024	Basic Engineering Sciences	20-12-2024	Principles of Yarn Manufacture
21-12-2024	General Engineering	21-12-2024	Principles of Fabric Manufacture
22-12-2024	Textile Fibres	22-12-2024	Principles of Textile Wet Processing
23-12-2024	Elements of Textile Technology	23-12-2024	Principles of Textile Testing and Statistics
24-12-2024	Elements of Comp. and its Applications	24-12-2024	Industrial Organization and Management

ATA Part - III - Time: 10.00 a.m. to 1.00 p.m.

Compulsory Subjects

20-12-2024	Elements of Technical Textiles
21-12-2024	Man-Made Fibre Technology

Optional Subjects

Date	Yarn Manufacture Group	Fabric Manufacture Group	Textile Wet Processing Group	Knitting & Garment Manufacture Group
22-12-2024	Process Control in Yarn Mfg.	Process Control in Fabric Mfg.	Wet Processing-I	Knitting Technology
23-12-2024	Modern Yarn Manufacture	Modern Fabric Manufacture	Wet Processing-II	Garment Technology

1. Last Date for receiving applications at unit **25th July 2025.**
2. Last Date for receiving all the applications with late fee at unit **25th August 2025.**
3. Last Date for receiving applications at the central office **25th September 2025.**

Sd/-
Dr. G. S. Nadiger
Chairman, P. A. C.

Sd/-
Mahendrabhai G. Patel
Hon. Gen. Secretary

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RESULTS FOR GMTA SECTION A/B/C PASSED CANDIDATES DECEMBER, 2024

Centre	Section A	Section B	Section C
Ahmadabad	2024/AHA/01, 2024/AHA/02	2024/AHB/01, 2024/AHB/02	NIL
Delhi	NIL	NIL	NIL
Ichalkaranji	2024/ICA/10, 2023/iCA/02	2024/ICB/10, 2024/ICB/11	2024/ICC/01, 2024/ICC/02, 2024/ICC/03, 2024/ICC/04, 2024/ICC/05
Mumbai	2024/MUB/20, 2024/MUB/21	2024/MUB/21	2024/MUC/10, 2024/MUC/11, 2024/MUC/12

Candidates	Section - A	Section -B	Section -C	TOTAL
Registered	05	06	08	19
Appeared	05	06	08	19
Result	05	05	08	18

Pass 95.00 %

RESULTS FOR GMTA SECTION D & E PASSED CANDIDATES DECEMBER, 2024

Centre	Section D			
	Yarn Manufacture	Fabric Manufacture	Textile Wet Processing	Apparel Manufacture
Ahmadabad	NIL	NIL	NIL	NIL
Delhi	NIL	NIL	NIL	NIL
Ichalkaranji	NIL	2024/ICD/01/FM, 2024/ICD/02/FM	2024/ICD/01/WP, 2024/ICD/02/WP, 2024/ICD/03/WP, 2024/ICD/04/WP	2024/ICD/01/AM
Mumbai	NIL	2024/MUD/10/FM	2024/MUD/10/WP, 2024/MUD/11/WP	NIL

Candidates	Section - D				
	Yarn Manufacture	Fabric Manufacture	Text. Wet Processing	Apparel Manufacture	Total
Registered	NIL	03	06	01	10
Appeared	NIL	03	06	01	10
Passed	NIL	03	06	01	10

Pass 100.00%

Candidates	Section - E			
Ahmadabad	2024/AHE/01, 2024/AHE/02, 2024/AHE/03			
Delhi	NIL			
Ichalkaranji	2024/ICE/10, 2024/ICE/11, 2024/ICE/12, 2024/ICE/13, 2024/ICE/14, 2024/ICE/15, 2024/ICE/16, 2024/ICE/17, 2024/ICE/18, 2024/ICE/19,			

Candidates	Section - E			
Registered	13			
Appeared	13			
Results	13			

Sd/-
Dr. G. S. Nadiger
Chairman, P. A. C.

Sd/-
Mahendrabhai G. Patel
Hon. Gen. Secretary

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Schedule of G.M.T.A. Examination December 202 5

Section A Date	Time 10.00 a.m. to 1.00 p.m. Subject No. & Title	Section B Date	Time: 2.00 p.m. to 5.00 p.m. Subject No. & Title
20-12-2024	A-1 Engineering Physics	20-12-2024	B-1 Yarn Manufacture
21-12-2024	A-2 Engineering Chemistry	21-12-2024	B-2 Fabric Manufacture
22-12-2024	A-3 Engineering Mathematics	22-12-2024	B-3 Textile Wet Processing
23-12-2024	A-4 General Engineering	23-12-2024	B-4 Apparel manufacture
24-12-2024	A-5 Professional Orientation	24-12-2024	B-5 Textile Testing

Section C Date	Time 10.00 a.m. to 1.00 p.m. Subject No. & Title
20-12-2024	C-1 Textile Fibre Science
21-12-2024	C-2 Polymer Technology
22-12-2024	C-3 Textile Engineering Mechanics
23-12-2024	C-4 Applied Statistics
24-12-2024	C-5 Data Management and Information System

Date	Section D - Time: 2.00 p.m. to 5.00 p.m.			
	Yarn Manufacture	Fabric Manufacture	Text. Wet Processing	Apparel Manufacture
20-12-2024	Short Staple Yarn Mfg.	Advanced Fab. Manufacture	Wet Proc-Pre Treat. & Bleaching	Apparel Technology
21-12-2024	Long Stap & other Yarn Mfg.	Knitting Technology	Wet Proc.-Dyeing	Supply Chain Mange in Apparel Mfg.
22-12-2024	Engg Design & Yarn Structure	Engg. Design of Fab. Structure	Wet Proc-Printing & Finishing	Apparel Merchandising
23-12-2024	Process & Quality Management & Yarn Mfg.	Process Control & Qual. Mrkt in Fab. Mfg.	Analytical Chem. In Textiles	Garment Proce. Tech.
24-12-2024	Man-made Fibre Technology	Fabric Structure & Design	Processing & Quality Manage In Wet Proce.	Process Control & Quality Manage in Apparel Mfg.

Optional Papers

5-12-2024	Specialty & High Performance Yarns(s)	Non-Woven Technology	Colour Tehory & Col. Matching	Social & Trade Compliances
26-12-2024	Silk Reeling & Throwing Technology	Technical Textiles	Effluent Treat & Eco Friendly Proce.	Garment Acces. & Fashion Forecasting
27-12-2024	Quality & Envir. System in Yarn Mfg.	Quality & Environment Systems In Fab. Mfg.	Quality & Environ System in Wet Proc.	Visual Merchandising

Section E	Time 10.00 a.m. to 1.00 p.m.
Date	Subject No & Title
23-12-2024	E-1 Industrial Engg. & Mill Management
24-12-2024	E-2 Energy Environment & Efficiency in Textiles

Optional Papers

25-12-2024	EOD-1 International Trade Management
26-12-2024	EOD-2 Control Systems in Textile Machines
27-12-2024	EOD-3 Entrepreneurship Development

1. Last Date for receiving applications at unit **25th July 2025.**
2. Last Date for receiving all the applications with late fee at unit **25th August 2025.**
3. Last Date for receiving applications at the central office **25th September 2025.**

Sd/-	Sd/-
Dr. G. S. Nadiger	**Mahendrabhai G. Patel**
Chairman, P. A. C.	Hon. Gen. Secretary

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SUBJECT INDEX

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