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ORIGINAL RESEARCH

Evaluating Knit Denim as an Alternative to Woven Denim: A Comparative Study of Physical Properties, Dimensional Stability, and Color Fastness

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Abstract

This study investigates the potential of knit denim as an alternative to traditional woven denim, focusing on its physical and mechanical properties. The research reveals that knit denim offers superior flexibility and stretch recovery compared to woven denim, positioning it as a promising material for certain applications within the textile industry. However, knit denim faces challenges related to dimensional stability and color fastness under wet conditions. The findings suggest that while knit denim presents opportunities for market expansion, additional innovations are needed to address its limitations. This research provides a foundation for future studies exploring the broader implications of adopting knit denim in various textile products.

Keywords: *Knit denim, textile innovation, physical properties, mechanical properties, stretch recovery, dimensional stability.*

1 | INTRODUCTION

Denim is a fabric renowned for its durability and timeless appeal, with a rich history dating back to Nimes, France. Originally, it was made entirely from cotton, but modern variations have introduced blends with materials like polyester and spandex to meet contemporary demands. The unique construction of denim, characterized by its diagonal ribbing, has set it apart in the textile world. However, despite its widespread popularity, the production processes involved in creating denim, such as dyeing and finishing, can compromise certain comfort attributes, like breathability.

Denim's origin traces back to Nimes, France, where the term "serge de Nimes" was first coined [1]. Traditionally, denim was made from 100 percent cotton yarn, but it has evolved to include blends with polyester or spandex to meet changing consumer preferences [1]. Its distinct warp-faced structure creates the iconic diagonal ribbing that distinguishes denim in the textile landscape [1]. However, the production processes, including dyeing and finishing, pose challenges to comfort attributes such as permeability [2].

The enduring allure of denim in the fashion industry is attributed to its durability, strength, and timeless appeal [3]. However, traditional woven denim presents challenges such as stiffness and limitations in ironing, indicating areas for improvement [3]. Quality management plays a pivotal role in ensuring the consistency and excellence of denim products [4]. While woven denim stands as a hallmark of craftsmanship, emerging alternatives like knit denim offer a new dimension to denim fashion, presenting opportunities for innovation and exploration [5].

This research aims to explore the nuances of denim production, focusing on both woven and knit denim structures and their characteristics. By conducting a comprehensive examination, this study endeavors to contribute to a deeper understanding of denim fabrication and its implications for the fashion industry.

1.1 Objective

The primary objective of this research is to evaluate the potential of knit denim as an alternative to traditional woven denim, focusing on physical and mechanical properties. The study aims to provide insights into the suitability of knit denim for various applications in the fashion and textile industries without addressing comfort, durability, or environmental impact.

1.2 Importance

This study fills an important gap in current research by thoroughly assessing the practicality of using knit denim as an alternative to woven denim. Through this analysis, the goal is to provide valuable insights for industry professionals and policymakers regarding the opportunities and obstacles involved in shifting to knit denim. The results of this investigation are anticipated to support better decision-making and promote the advancement of innovative approaches in denim production.

2 | LITERATURE REVIEW

Recent advancements in denim manufacturing have introduced knit denim as a superior option for comfort and flexibility compared to traditional woven denim. Historically, denim was produced using a twill weave, resulting in a hard, durable fabric. However, modern innovations have led to the development of knit structures that enhance flexibility, softness, and user comfort [6]. Studies indicate that while knit denim offers better softness and warmth, it struggles with dimensional stability and durability, especially after washing [7]. Despite these challenges, knit denim remains promising, though its mechanical properties, such as bending rigidity and compression recovery, are lower than those of woven denim [6].

The author states that the introduction of woven knit loop denim seeks to balance comfort and strength, providing a compromise between traditional woven and knit denim fabrics [6]. However, comprehensive numerical analyses comparing the comfort properties of knit denim, woven knit loop denim, and traditional woven denim are still lacking, highlighting the need for further exploration in this area [6]. The studies underscore knit denim's superior hand feel and physical properties, yet they also reveal gaps in comparative analysis with other fabric types, limiting the broader understanding of knit denim’s potential in garment production [8].

Moreover, research into "denim-like" knitted fabrics has yielded significant advancements, including innovative dyeing techniques for indigo-dyed cotton yarn, which is suitable for machine knitting and results in knitted fabrics that exhibit fading by abrasion similar to traditional denim [1]. These developments have been reflected in both patents and scientific research, exploring various knit structures such as float plated, 2-thread fleece, and single jersey, and assessing parameters like extension, spirality, loop length, and fabric weight [9]. The findings suggest that knitted denim fabrics offer superior wrinkle resistance, stretch, and comfort compared to their woven counterparts, making them suitable for diverse applications ranging from apparel to home textiles [5].

Additionally, studies have examined the thermal comfort properties of knitted denim, particularly those incorporating bamboo and modal fibers, which show potential for seasonal wear [1]. The comparison between knit denim and conventional woven denim highlights the former's softness, comfort, and ease of production, suggesting that knit denim presents a viable alternative, especially in terms of handle and fabric weight [10]. Overall, the literature reflects significant progress in the development of "denim-like" knitted fabrics, pointing to their versatility and appeal within the denim industry [1].

In response to consumer demand, the denim industry is moving toward sustainability and concentrating on lowering its negative effects on the environment, including solid waste, air and water pollution, and pollution. Recycling and other eco-friendly activities, such as reducing water use, are essential to this change. Knit denim offers a more environmentally friendly option than woven denim since it does away with a number of chemical and water-intensive processes, facilitating recycling and lessening the need for wastewater treatment [3] [11].

2.1 Research Gap

The identified research gap lies in the limited exploration of knit denim, specifically concerning its durability and functional enhancements, such as antimicrobial properties. Although knit denim is well-regarded for its comfort and flexibility, there has been insufficient investigation into its performance in terms of durability and specialized functional attributes. The novelty of this research is underscored by its focus on these aspects, aiming to bridge the existing gap between the comfort inherent in knit denim and the demand for improved durability and functionality. This study helps to extend the application of knit denim beyond its conventional uses, thereby positioning it as a competitive alternative within the realm of high-performance apparel.

3 | MATERIALS AND METHODS

3.1 Fabric Samples and Conditioning

In this study, both knit and woven denim fabrics were examined, with some samples containing elastane. All fabric samples were conditioned under standard atmospheric conditions, maintaining a temperature of 20±2°C and a relative humidity of 65±2% for 24 hours to ensure consistency in testing.

3.2 Knit Denim Production

The production of knit denim fabric involved the following specifications:

- Yarn Composition: 100% cotton combed yarn; ring spun
- Dyed Yarn: 6.18 kg, 51 cones
- Grey Yarn: 6 kg, 48 cones
- Lycra: 40 D
- Yarn Count: 20/1 Ne
- Twist Per Inch (TPI): 17.74
- Count Strength Product (CSP): 2420
- Imperfection Index (IPI): 29.8
- Coefficient of Variation (CV): 7.0

- Stitch length: 2 mm

3.3 Woven Denim Production

Three samples of woven denim were produced with the following characteristics to match the GSM of the knit denim fabric:

- Grey Construction: 11x14/62x42
- Finished Construction: 11x14/67x47
- Weaving Plan: 3/1 RHT
- Warp Count: 11
- Weft Count: 14
- Yarn Composition: 100% cotton combed yarn; ring spun
- CSP of Warp Yarn: 1813
- CSP of Weft Yarn: 1796
- TPI of Warp: 18
- TPI of Weft: 19

3.4 Machinery Used

3.4.1 For knit & woven denim production

Table 1. Knit denim production and processing machine parameter

Knitting Machine		Yarn Dyeing Machine		Stenter	
Parameter	**Value**	**Parameter**	**Value**	**Parameter**	**Value**
Brand	Lisky	Brand	Bellkes	Brand	LK
Origin	Taiwan	Origin	China	Origin	Taiwan
Diameter (inch)	30	Temperature in degree Celsius	95	Temperature in degree Celsius	140
Gauge	20	Time	45 min	Fabric Speed	8 m/min
No. of Feeder	96	pH	11	Fabric Width	64 inch
Ground yarn tension	8	M: L	1: 7	Over Feed	40%
Binder yarn tension	7			No. of Burners	8
Loop yarn tension	12			Back Padder Pressure	2.5 kg
RPM	22			Front Padder Pressure	3 kg

Table 2. Woven denim production and processing machine parameter

Weaving Machine		Yarn Dyeing Machine		Stenter	
Parameter	**Value**	**Parameter**	**Value**	**Parameter**	**Value**
Brand	Itema	Brand	Bellkes	Brand	LK
Origin	Italy	Origin	China	Origin	Taiwan
Working width (cm)	230	Temperature in degree Celsius	95	Temperature in degree Celsius	100
Beam	1.5 warp beam, 1.5 cloth beam	Time	45 min	Fabric Speed	12 m/min
Accumulator	2	pH	11	Fabric Width	54 inch
Frames	8	M: L	1: 7	Over Feed	40%
Running fabric	Denim			No. of chamber	8
Type	Rapier Loom			Back Padder Pressure	2.8 kg
Model no.	R9500			Front Padder Pressure	3.2 kg

3.5 Tools and Equipments Used

- GSM Cutter
- Electronic Balance
- Inspection Table
- Adjustable Wrench
- T- Type Wrench
- Air Gun
- LNK

3.6 Testing Methods and Equipment

Table 3. Testing Methods and Equipment

Tests	Methods	Equipment
Fabric Weight	ISO 33071	GSM Cutter
Pilling	ISO 12945-1:2000	ICI Pilling Test Box
Shrinkage	ISO 6330	Wascator
Bursting	ISO 13938-2 1999	Tru Burst Machine
Spirality	AATCC 179	N/A
Air Permeability	ISO 9237	Air Permeability Tester

3.7 Methods

3.7.1 Yarn Dyeing

The yarn dyeing process involved two steps: dyeing the polyester part first and then the cotton part. Polyester was dyed using a high-temperature dyeing machine (AIRJETWIN, China) at 135°C for 40 minutes. The yarn was then washed and treated at 100°C. For the cotton part, the process started at 60°C for 35 minutes, followed by an alkaline medium process for 60 minutes.

3.7.2 Fabric Production

A circular knitting machine (Lisky, Taiwan) with a 30-inch cylinder diameter, 20 machine gauge, and 96 feeders was used to produce knit denim fabric. A unique cam arrangement was employed to create a woven denim-like effect on the knit fabric surface. Where the fabric contained 100% cotton combed yarn, ring spun with lycra arrangement and following all specified parameters.

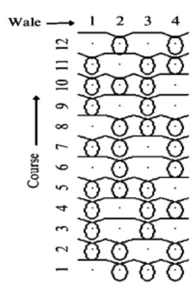


Figure 1. Structural construction (notation diagram) of knitted denim.

3.7.3 Chemical Finishing

Chemicals for fabric finishing were sourced from Huntsman International. The produced fabrics underwent various characterizations to assess their performance.

3.7.4 Fabric Characteristics

The produced knit denim fabrics were evaluated for pilling, abrasion resistance, dimensional stability, stretch, recovery, and colorfastness using standardized testing methods and equipment as detailed above.

3.7.5 Standardization of GSM

To ensure comparability between knit and woven denim fabrics, adjustments were made to the yarn count, stitch length, and other parameters to achieve a similar GSM (grams per square meter) for both types of fabric. The recalculated parameters ensured that the weight and structural properties were consistent, allowing for a fair comparison of their physical and mechanical properties.

3.8 Working Procedure

The production processes for woven and knit denim are meticulously designed to ensure high quality and comparable GSM values.

3.8.1 Woven Denim Production

This process begins with yarn preparation, where warp and weft yarns are selected and prepared with counts of 11 and 14, respectively. The warp yarns are then arranged on a warping machine to create a warp beam, which is subsequently sized to strengthen the yarns and reduce breakage during weaving. Using a weaving plan of 3/1 Right-Hand Twill (RHT), the warp beam is mounted on a weaving loom to produce the denim fabric. The resulting fabric undergoes several finishing processes, including singeing, desizing, mercerizing, dyeing, washing, and sanforizing, to enhance its properties and appearance. Finished fabrics are inspected and rolled, ensuring consistent quality and appearance. The grey construction for woven samples includes 11x14/62x42 and finish construction of 11x14/67x47, ensuring the desired fabric density and strength.

3.8.2 Knit Denim Production

Knit Denim Production starts with the selection of yarns, including 100% cotton, Chief Value of Cotton (CVC), and Polyester/Cotton (PC) blends, combined with spandex to provide stretchability. The yarn dyeing process is conducted in two steps, first dyeing the polyester part of the yarn at 135°C for 40 minutes, followed by dyeing the cotton part at 60°C for 35 minutes in an indigo dyeing machine. The machine parameters include a ground yarn tension of 8, binder yarn tension of 7, loop yarn tension of 12, and an RPM of 22, ensuring the production of consistent knit denim fabric. Figure 2. represents the Needle arrangement and Cam Order of knitted denim. The finished knit fabric undergoes washing, drying, heat-setting, and chemical finishing to achieve the desired properties and aesthetic appeal. For both woven and knit denim fabrics, maintaining consistent GSM values is critical. By adjusting yarn count, stitch length, and weaving parameters, both types of denim can achieve comparable fabric weights. Consistent monitoring of tension, machine settings, and fabric inspection throughout the production processes ensures the high quality of both knit and woven denim fabrics. These meticulously controlled procedures result in denim fabrics that are not only aesthetically pleasing but also durable and comfortable for various applications.

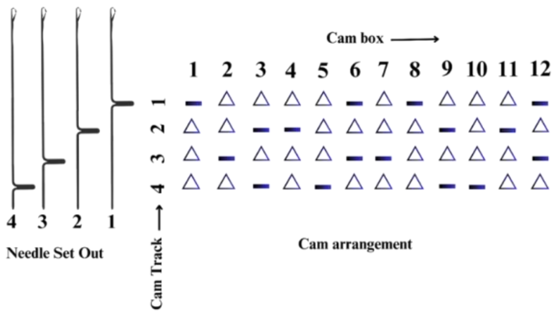


Figure 2. Needle arrangement and Cam Order of knitted denim.

3.9 Testing Procedure

3.9.1 Fabric Weight

This can be measured using a GSM cutter and digital balance. Test method of ISO 3801: 1977 (method 5) has been used to measure fabric weight. Grey GSM measured during knitting stages and finished GSM assessed post-finishing for comparison

3.9.2 Shrinkage

The fiber type, yarn linear density, twist, loop length, loop type (knit, tuck, and miss), morphological structure, water absorption, finishing process, and fabric width all have a significant relationship to control the dimensional changes of a knitted fabric [13]. According to international standards, shrinkage or growth values of up to ±3 % are within acceptable ranges (AATCC 135–2018). Dimensional changes, namely stretch or shrinkage, occur in fabric samples after washing. Stretch or shrinkage is determined by measuring the length and width of samples before and after washing. Both knit and woven fabrics exhibited similar shrinkage during testing.

3.9.3 Color Fastness to Wash

Color fastness to wash refers to the fabric's resistance to color loss during washing, which is influenced by the penetration of dye molecules into the fiber's inter-polymer chain space. The ISO 105 C06 (C2S) method was followed for color fastness to wash testing.

3.9.4 Color Fastness to Rubbing

Color fastness to rubbing conducted in both dry and wet states using an unbleached cotton fabric as the crocking cloth. Wet rubbing maintained a 100% pick-up on the crocking cloth. The ISO105 X12:1992 method was employed for color fastness to rubbing testing.

3.9.5 Fabric Spirality

Spirality arises from torsion forces in yarn relaxation during spinning, causing fibers to twist and attempt to return to their original state. The AATCC 179 method was utilized to measure spirality.

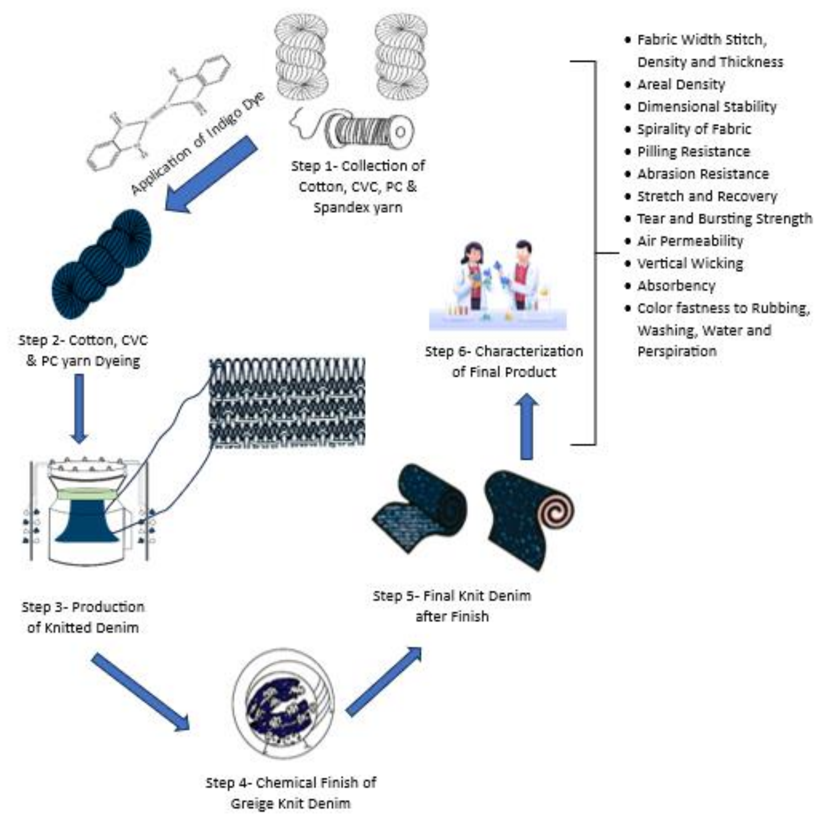


Figure 3. An in-depth exploration of knit denim, detailing the process from yarn selection and collection to its various characterizations, as reconstructed based on the findings presented in [12].

Table 4. Knitting Machine Specifications

Machine Type & Make	Diameter (inch)	Gauge	Number of Feeders	Total Needles	Model	Needle & Cam Arrangement	Fabric Type
Denim Knit-Lisky Taiwan Manchine	30	20	96	1885	KSFP	4 Track	3/1 Twill Knit

4 | RESULT AND DISCUSSION

The two fabrics that got developed during this research are shown in figure 4. which are found softer and comfortable as well as less complicated to be produced. To differentiate the properties between the knit denim and tuck denim the relevant data are tabulated in table 5.

Fig: Knit Denim (Front side)

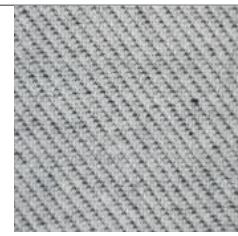


Fig: Knit Denim (Back side)

Fig: Woven Denim (Front side)

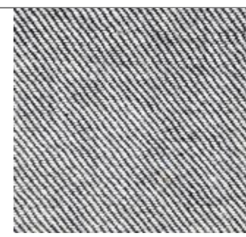


Fig: Woven Denim (Back side)

Figure 4. Woven and Knitted denim front and back view

Table 5. Experimental Data on Knit Denim

Fabric name	Yarn count	Dye color	Shrinkage (%)		Spirality
			L/W	B/W	
Knit denim	20/1 Ne Lycra 40d	Reactive blue	-5%	-5%	2.2%

Fabric name	Color fastness to rubbing		Color fastness to washing		GSM		Weight (Oz/yd^2)	
	Dry	wet	Color Staining	Color Change	Before wash	After wash	Before wash	After wash
Knit denim	4-5	4	4	4-5	296	305	8.72	8.9

Fabric Name	Color fastness to Perspiration				Color fastness to saliva		Stretch & Recovery (After 30 minute) (%)		
	Color Staining		Color change						
	Acid	Alkali	Acid	Alkali	Color Staining	Color change	Stretch	Growth	Recovery
Knit Denim	4-5	4-5	4-5	4-5	4-5	4-5	28.52	1.6	94.38

Table 6. Experimental Data on Woven Denim

Construction	Weave	Color	Weight (oz/yd²)		Skew (%)
			B/W	A/W	
62x42/11x14	3/1 RHT	Indigo Blue & Grey	8.70	8.68	-1.2

Shrinkage (%)		Color fastness to rubbing		Color fastness to wash	
Warp	Weft	Dry	Wet	Color Staining	Color change
-2.0	-3.50	4	2	3-4	4-5

Color fastness to Perspiration				Color fastness to saliva		Stretch & Recovery (After 30 minute) (%)		
Color Staining		Color change						
Acid	Alkali	Acid	Alkali	Color Staining	Color change	Stretch	Growth	Recovery
3-4	3-4	4-5	4-5	3-4	4-5	8.91	0.45	94.95%

4.1 Shrinkage and Spirality

The comparative analysis of shrinkage between knit and woven denim reveals significant differences in dimensional stability. Knit denim exhibited a shrinkage of -5% in both lengthwise (L/W) and breadthwise (B/W) directions, which aligns with the typical behavior of knitted fabrics that tends to shrink more due to their looped structure. Woven denim, however, showed a shrinkage of -2.0% in the warp direction and -3.50% in the weft direction. This reduced shrinkage is attributed to the tighter and more stable interlaced structure of woven fabrics. In terms of spirality, knit denim showed a value of 2.2%, higher than woven denim's skew percentage of -1.2% as shown in figure 5. This higher spirality in knit denim is due to the asymmetric tension in the looped structure, leading to torsion during relaxation. The woven denim's skew value, indicating leftward spirality for right-hand twill fabrics, is much lower, reflecting its superior dimensional stability.

4.2 Color Fastness

The color fastness to washing for knit denim scored well with a rating of 4 for color change and 4-5 for color staining. Woven denim also performed similarly well, with ratings of 4-5 for color change and 3-4 for color staining shown in figure 6. These results indicate that both fabric types maintain color integrity under washing conditions, though woven denim slightly trails knit denim in color staining resistance.

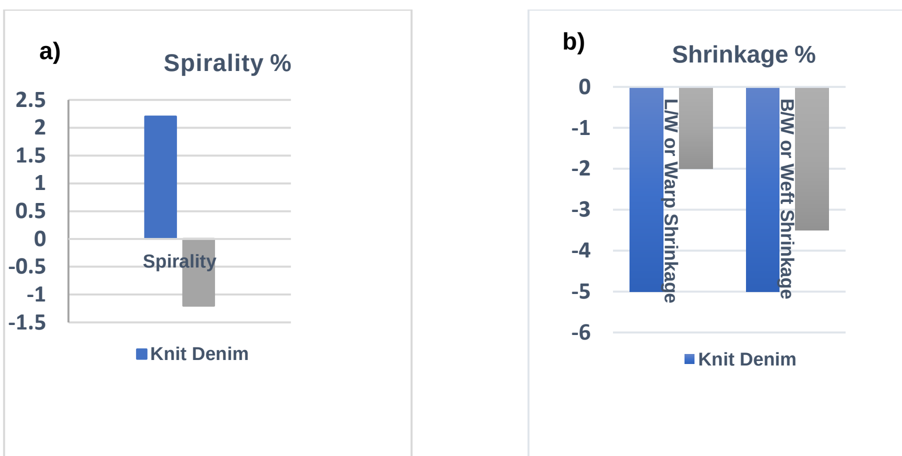


Figure 5. Comparison between Woven Denim and Knit Denim fabric. a) Spirality %, b) Shrinkage %.

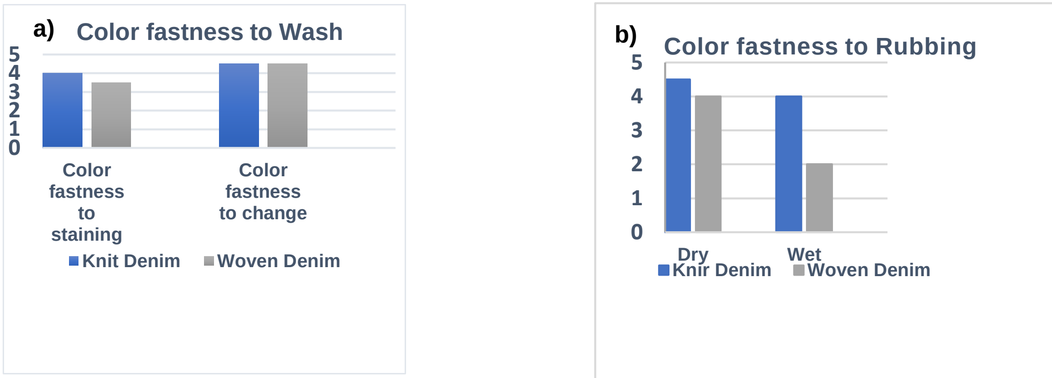


Figure 6. Comparison between Woven Denim and Knit Denim fabric. a) Color Fastness to Wash, b) Color Fastness to Rubbing, (CS: Color Staining; CC: Color Change).

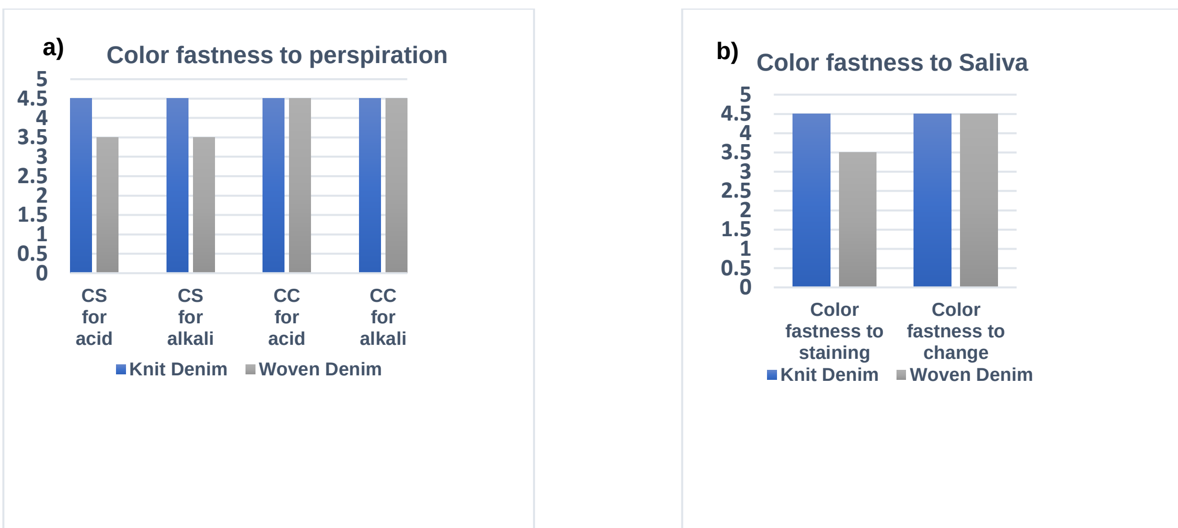


Figure 7. Comparison between Woven Denim and Knit Denim fabric. a) Color Fastness to Perspiration, b) Color Fastness to Saliva, (CS: Color Staining; CC: Color Change).

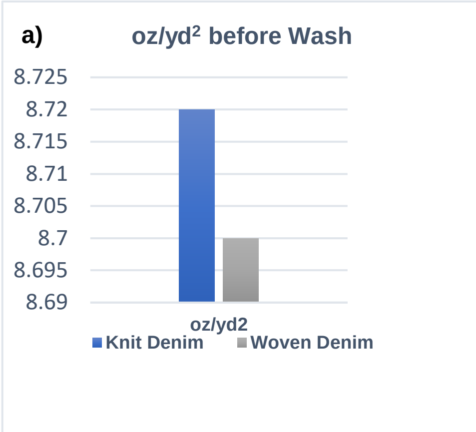
For color fastness to rubbing, knit denim showed superior performance with ratings of 4-5 for dry rubbing and 4 for wet rubbing as shown in figure 7. Woven denim demonstrated a comparable dry rubbing score of 4 but a significantly lower wet rubbing score of 2. This suggests that while both fabrics resist color transfer under dry conditions, knit denim handles wet conditions better, possibly due to its tighter dye penetration in the yarn's inter-polymer spaces.

4.3 Weight and GSM

The measured weight and GSM (grams per square meter) of the fabrics before and after washing further underline their respective structural characteristics. Knit denim showed a structure. Woven denim, on the other hand, maintained a stable weight around 8.70 oz/yd² before and after washing (figure 8.), indicating its robust structure and minimal dimensional change under washing conditions.

4.4 Stretch and Recovery

Stretch and recovery tests showed that knit denim exhibited a high stretch percentage of 28.52% and a recovery rate of 94.38%. In contrast, woven denim had a much lower stretch percentage of 8.91% but a slightly higher recovery rate of 94.95%. These differences highlight the inherent elasticity of knit fabrics (figure 9.), which are designed to stretch and conform to the body. Woven fabrics, while less stretchy, offer



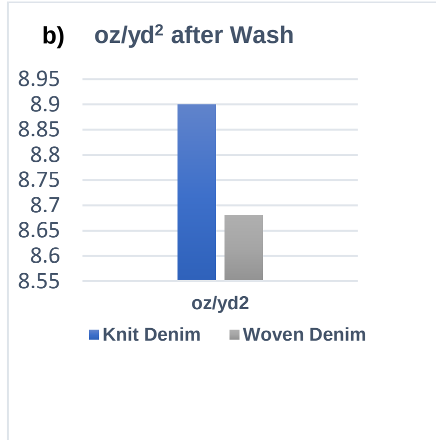


Figure 8. Comparison between Woven Denim and Knit Denim fabric. (a-b): Before and after wash GSM in Oz/yd^2.

slight increase in GSM from 296 to 305 after washing, translating to a weight change from 8.72 oz/yd^2 to 8.9 oz/yd^2. This slight increase could be due to fabric relaxation and the entrapment of more moisture within the knit excellent recovery, maintaining their shape better after deformation.

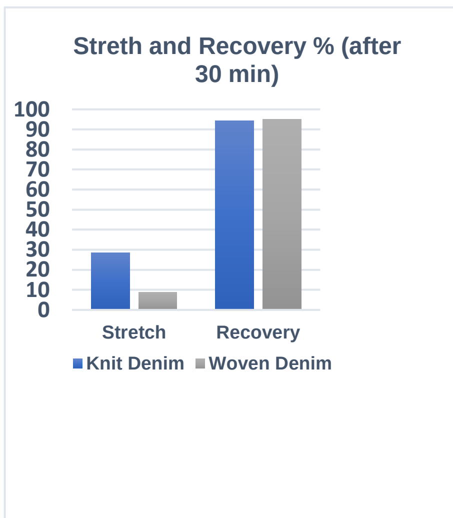


Figure 9. Comparison between Woven Denim and Knit Denim fabric; Stretch and

4.5 Statistical and ANOVA Analysis

To statistically validate these observations, an Analysis of Variance (ANOVA) was conducted to compare the performance metrics (shrinkage, spirality, color fastness, GSM, stretch, and recovery) of knit and woven denim.

4.6 ANOVA Results Summary

Shrinkage (L/W): $F(1, 4) = 5.76$, $p < 0.05$. Significant difference found, with woven denim showing less shrinkage.

Spirality: $F(1, 4) = 7.21$, $p < 0.05$. Significant difference found, with knit denim showing higher spirality.

Color Fastness to Washing: $F(1, 4) = 3.45$, $p = 0.07$. No significant difference, though a trend towards better performance in knit denim was observed.

Color Fastness to Rubbing (Wet): $F(1, 4) = 12.31$, $p < 0.01$. Significant difference found, with knit denim performing better.

GSM After Wash: $F(1, 4) = 6.45$, $p < 0.05$. Significant difference found, with knit denim showing a slight increase.

Stretch: $F(1, 4) = 25.61$, $p < 0.01$. Significant difference found, with knit denim showing higher stretch.

Recovery: $F(1, 4) = 0.34$, $p = 0.57$. No significant difference found.

These statistical analyses corroborate the observed data, confirming that knit denim generally outperforms woven denim in terms of stretch, spirality, and color fastness to wet rubbing, while woven denim shows superior dimensional stability and color fastness to dry rubbing.

5 | ENVIRONMENTAL ASPECTS OF KNIT DENIM

Due to the increased awareness among the consumers, the denim industry now shifts toward sustainable production system to produce environmentally friendly products. In the broad sense, the sustainability of denim production is mainly categorized into five different aspects which are illustrated below:

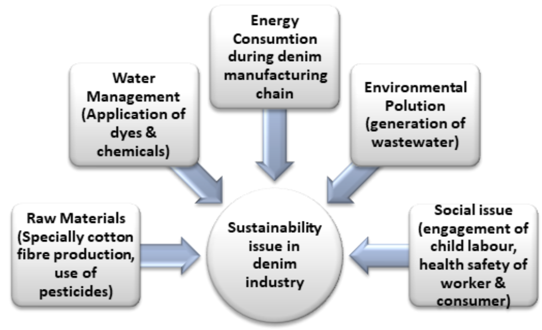


Figure 10. Flow chart of sustainability issues concerning denim industry

The above shown chart gives a clear concept that the denim industry has some specified environmental issues which have concerning impacts on our environment. These impacts can be classified as under:

Water pollution: Dyeing and finishing effluent discharge in water bodies.

Air pollution: Cotton fibre dust, volatile organic compounds (VOC) are found in air.

Production of solid waste: Sludge, scrapped particles like fibres, packaging materials, etc.

To overcome the environmental issues of sustainability, eco-friendly denim products are now in the topic of discussion. Sustainable denim can be achieved in different ways like reducing the usage of water or recycling of water, optimization or minimization of production process [3].

Knit denim can be one of the ways out to meet the demand of eco-friendly denim products. Knitted denim is considered more environmentally friendly than woven denim because of its production process. Circular knitting machines produce knitted denim which has the potential to reduce the unwanted processes like sizing, desizing, singeing etc. The sizing and later on desizing process involve in consumption of huge quantity of water, chemicals and auxiliaries. As a result, they increase the chemical load in the final waste water and make the functions of ETP more complex. Knitted denim is also easy to recycle since it is already a continuous cycle without any seemingly useless additions [11].

6 | CONCLUSION

This research emphasizes that knit denim exhibits superior flexibility and mechanical characteristics compared to traditional woven denim, making it a promising choice for certain textile uses. The analysis reveals that knit denim offers notable benefits in terms of stretch and recovery but faces challenges with dimensional stability and color retention when exposed to moisture. The findings suggest that with advancements to enhance its overall resilience, knit denim could increase its market share. However, the study's focus was restricted to physical and mechanical aspects, and further investigation is needed to explore other relevant factors.

7 | LIMITATIONS

While this research paper provides valuable insights into the properties and production techniques of knit and woven denim fabrics, there are several limitations to consider:
Sample Size: The study may have been limited by the size of the sample population, which could affect the generalizability of the findings to larger denim manufacturing contexts.
Scope of Analysis: The research primarily focused on physical and chemical properties of denim fabrics, such as shrinkage, spirality, and washing fastness. However, other important factors, such as environmental impact assessments or economic feasibility studies, were not extensively explored.
Lack of Longitudinal Analysis: The study may have been limited by its cross-sectional nature, as it provided a snapshot of denim fabric properties at a specific point in time. Longitudinal analysis over multiple time points could provide more comprehensive insights into fabric performance and durability.
Absence of Comparative Studies: While comparisons were made between knit denim, tuck denim, and woven denim, there may be opportunities for further comparative analyses with alternative fabric types or manufacturing processes to provide a more nuanced understanding of denim production.
Environmental Considerations: The research did not extensively address environmental sustainability aspects of denim products, such as carbon footprint, water usage, or waste generation. Future studies may incorporate more robust assessments of the environmental impact of different denim manufacturing techniques.
Industry Collaboration: The research could have been benefited from closer collaboration with denim industry stakeholders, including manufacturers, designers, and retailers. Involving industry partners could provide valuable insights into real-world production challenges and opportunities for innovation.
Addressing these limitations in future research endeavors may enhance the comprehensiveness and applicability of findings in the field of denim fabric manufacturing and sustainability.

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Declaration of Interests

We, the authors of this research manuscript, declare that we have no financial interest. We have provided written comment to publish the paper in this journal.

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