



Research Article

Touch Properties and Comfort Performance of Structurally Innovative Knit Denim Fabrics for Scalable Manufacturing

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KEYWORDS

Knit denim, Fabric Touch Tester (FTT), comfort performance, thermal properties.

ABSTRACT

Knit denim has emerged as a substitute for traditional woven denim, offering greater versatility, improved moisture management, superior elasticity, cost effectiveness, and enhanced thermo-physiological comfort. However, existing research gives limited insight into how engineered knit structures, particularly double-jersey constructions, can address both the stiffness and limited ventilation of woven denim and the durability inadequacies of single-jersey knit denim. To close this gap, the study compares the structural, tactile, and comfort performance of one double-jersey derivative (DJD) with three single-jersey derivatives: triple miss diagonal (SJD-TMD), double miss diagonal (SJD-DMD), and single miss diagonal (SJD-SMD). These four knit denim structures were manufactured with indigo-dyed cotton and elastane-covered polyester yarns and evaluated for moisture transport, breathability, thermal behaviour, and tactile response through Fabric Touch Tester (FTT) and results were analysed statistically. The findings revealed that the DJD structure exhibited the highest wicking performance (14.0 cm lengthwise and 15.0 cm width wise), the more thermal resistance (0.12608 m²-K/W), and superior compressibility and stretch behaviour. The single-jersey derivatives provided distinct functional advantages: SJD-TMD demonstrated balanced structural compactness, SJD-SMD offered comparatively smooth surface with controlled stretch characteristics, and SJD-DMD achieved the highest air permeability (110 cm³/s/cm²). These results establish double-jersey knit denim as a structurally optimal process for creating denim-based products that are thermoresponsive, comfortable, and durable. Additionally, the adjustable behaviours of the SJD variants provide designers and manufacturers with a flexible foundation for developing knit denim solutions tailored to specific application requirements.

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1. Introduction

Denim serves as a fabric that is a symbol of style [1] and defiance, and has maintained its importance as a core element of contemporary clothing across generations [2,3]. The distinctive blue shade [4] signifies both elegance and practicality, establishing the fact that it can be the preferred material for a wide array of uses [5] such as casual apparel, upholstery, and even as a relic encountered in antique shops and archaeological excavations [6,7]. The popularity of denim all over the world stems from its

exceptional versatility, durability, and comfort, making it a prominent entity within the fashion industry. At present, denim is at the center of global culture, due to the fact that individuals of all ages and origins resonate with it, while the shifting demands of modern fashion rival the shifting demand for denim.

Traditional woven denim, a diagonal twill weave, [8,9] is esteemed for its dimensional stability and robustness [10]. However, these properties are achieved, resulting in a reduction

in the flexibility and comfort. Traditional denim fabrics are characterized by their limited elasticity (around 10% - 35%) [11], which poses a risk in terms of comfort and freedom of movement. Despite its well-established reputation, the inflexibility of woven denim fabric may result in discomfort and be prone to wrinkling during prolonged use. This restriction steps up the advancement of alternative fabrics required to solve the comfort and flexibility issues that are increasingly sought after by existing end-users.

The industry was faced with the inevitable compromise in fabric properties of woven denim in terms of comfort and wrinkling. In response to that, knitted denim has become a pioneering innovation in fabric technology. A significant change was accomplished with the presentation of knitted denim, by offering enhanced elasticity, suppleness, breathability, and resistance to wrinkles, rendering it a more comfortable option for casual attire. The fabric formation process employed in the production of knit denim obviates many of the time-intensive and costly textile preparation steps that are usually necessary for woven denim. This time-worthy approach not only improves the comfort characteristics of the fabric but also decreases manufacturing expenses, making it an appealing choice for the textile sector. Recent research has demonstrated an increasing consumer preference for knitted denim, particularly among those who appreciate the traditional aesthetic of denim combined with its improved comfort attributes. Knit denim is especially attractive due to its capacity to conform to the body's movements, offering enhanced flexibility, thermal insulation, and permeability [12,13]. These attributes propose knit denim as a satisfactory option for modern fashion, by fitting the determination of comfort and practicality to be valued equally with style [14]. Furthermore, knit denim provides enhanced air permeability, facilitating superior moisture control and temperature regulation, which are vital for maintaining long-term comfort [15].

Modifying denim's structure has led to several new approaches to improve fabric comfort and appearance [15–18]. Hoque et al. [19] developed knit denim using tuck and miss loops on single jersey derivatives with different blends of cotton, polyester, and spandex. They found that an optimal blend was 55% cotton, 40% polyester, and 5% spandex for strength and breathability, but not water absorption. T. S. Kumar et al. [20] found that 100% eri silk provided better moisture control in knitted denim than cotton and eri silk blends. Elasticity and structural changes affect knit denim fabric comfort, although the study did not examine these. Selin Hanife Eryuruk [21] found that denim fabric weight and thickness affected thermal characteristics in another investigation. Mezarciöz [22] found that fibre type and stitch parameters affect color values in knitted denim, with industrial washing affecting color but not loop length or domestic laundering. A. Ben Fraj and B. Jaoachi [10,23] found that more pumice stone and enzymes caused denim bagging after washing. Other studies found that only washing changes affected tactile comfort, while weft yarn type did not, and twill orientation affected shear rigidity [24]. A reactive dyeing process for knit denim by Hannan et al. [12]

outperformed indigo dye in washing. Another study examined the longitudinal extension and bursting strength [25] of knit denim fabrics made from regenerated cellulose fibers and found high extension. Dimensional stability is another issue with denim-viewed knitted materials. Candan and Önal [26] found that knitted fabric's dimensional stability is mostly influenced by structure and fiber types. One study generated 18 denim-like knit textiles with different material ratios and yarn counts to test dimensional stability and other qualities after repeated washes [27]. According to their research, denim-like knitted textiles with more polyester have superior washing resistance and structural stability, but water absorbency decreases comfort.

This study introduces a structural performance evaluation of innovative knit denim designs, focusing on how double-jersey derivatives can resolve the limitations found in both conventional woven denim and existing single-jersey knit denim fabrics. Woven denim, despite its mechanical strength, often provides insufficient thermo-physiological and tactile comfort during wear, whereas single-jersey knit denim offers flexibility but lacks the durability and structural stability required for long-term use. To address this gap, the research examines comfort performance in conjunction with Fabric Touch Tester (FTT)-based tactile parameters to determine how engineered double-jersey constructions influence softness, elasticity, stretchability, moisture absorbency and overall wearability. By integrating comfort assessment with advanced touch profiling, the study demonstrates how double-jersey knit denim architectures can deliver the level of comfort performance demanded by contemporary customers, without compromising durability. These findings provide meaningful direction for manufacturers, designers, and retailers aiming to develop knit denim structures that meet modern expectations for comfort, functionality, and structural integrity.

2. Methodology

2.1 Materials

Knit denim fabrics were made using 100% ring-spun, combed, compact cotton and elastane-covered polyester (ECP) yarn in this study. The 19.6-Tex cotton yarn came from Envoy Textile Spinning Mills Ltd. in Bangladesh. The (75D/72F + 40D) ECP yarn came from Zhejiang, China. Cotton and elastane-covered polyester yarns were chosen to blend the softness, breathability, and comfort of cotton with the stretchability, strength, and durability of polyester, making the fabric suited for fashion and function.

2.2 Sample Preparation

2.2.1 Yarn Dyeing

The cotton yarn was indigo-dyed using a vat dyeing technique to provide the characteristic denim look. The cotton yarn was pre-treated with scouring at 85°C to eliminate impurities before the dyeing process started. At 60°C, a dye bath

was heated with a material-to-liquid ratio of 1:20. The dye bath was supplemented with a paste made by dissolving indigo in warm water. 2% sodium hydroxide (NaOH) and 2% sodium hydrosulfite ($\text{Na}_2\text{S}_2\text{O}_4$) were added to start the reduction process, and the pH was kept at 12.5 for half an hour. The yarn was soaked in the dye solution while being swirled for 15 minutes, and then left to oxidize in the open air for another 15 minutes, until it reached the appropriate indigo color. Following the dyeing procedure, the yarn underwent a cold water rinse, was soaked in a 2% detergent solution heated to 60°C for 15 minutes, neutralized with acetic acid (CH_3COOH), and finally tumble dried at 105°C. The dyeing process was completed by winding the yarn into appropriate knitting bundles.

2.2.2 Knitting Process

The knit denim fabric samples were produced utilizing a circular knitting machine at Epyllion Fabric Ltd. The machine specifications were established as: a 30-inch cylinder diameter, a gauge of 24, and 72 active feeders. To assure consistency, the yarn types (cotton and ECP), yarn tension (8 cN for cotton and 10 cN for ECP), and other parameters, including a

consistent RPM of 22, were maintained across all samples. The research centred on four novel knit denim configurations as shown in **Figure 1**, a DJD (double jersey derivative) and three SJDs (single jersey derivatives): SJD-TMD, SJD-DMD, and SJD-SMD. For each structure, the miss loop density (MLD) was adjusted as follows: SJD-TMD had an MLD of 37.5%, SJD-DMD of 25%, SJD-SMD of 12.5%, and DJD of 67.7%. Fabric samples were conditioned in an environmentally controlled room for 24 hours at $21 \pm 2^\circ\text{C}$ and $65 \pm 2\%$ relative humidity, to achieve a relaxed state prior to finishing.

2.2.3 Finishing Process

The purpose of fabric finishing is to improve the aesthetic appeal, functionality, and durability of the fabric [19,28]. The heat-setting process was conducted utilizing a stenter machine (Monforts, Germany) at a temperature of 195°C, with the fabric diameter calibrated to 66 inches. The overfeed ratio was established at 80% for SJD-based fabrics and 35% for DJD-based fabrics, with the fabric speed configured at 24 meters per minute.

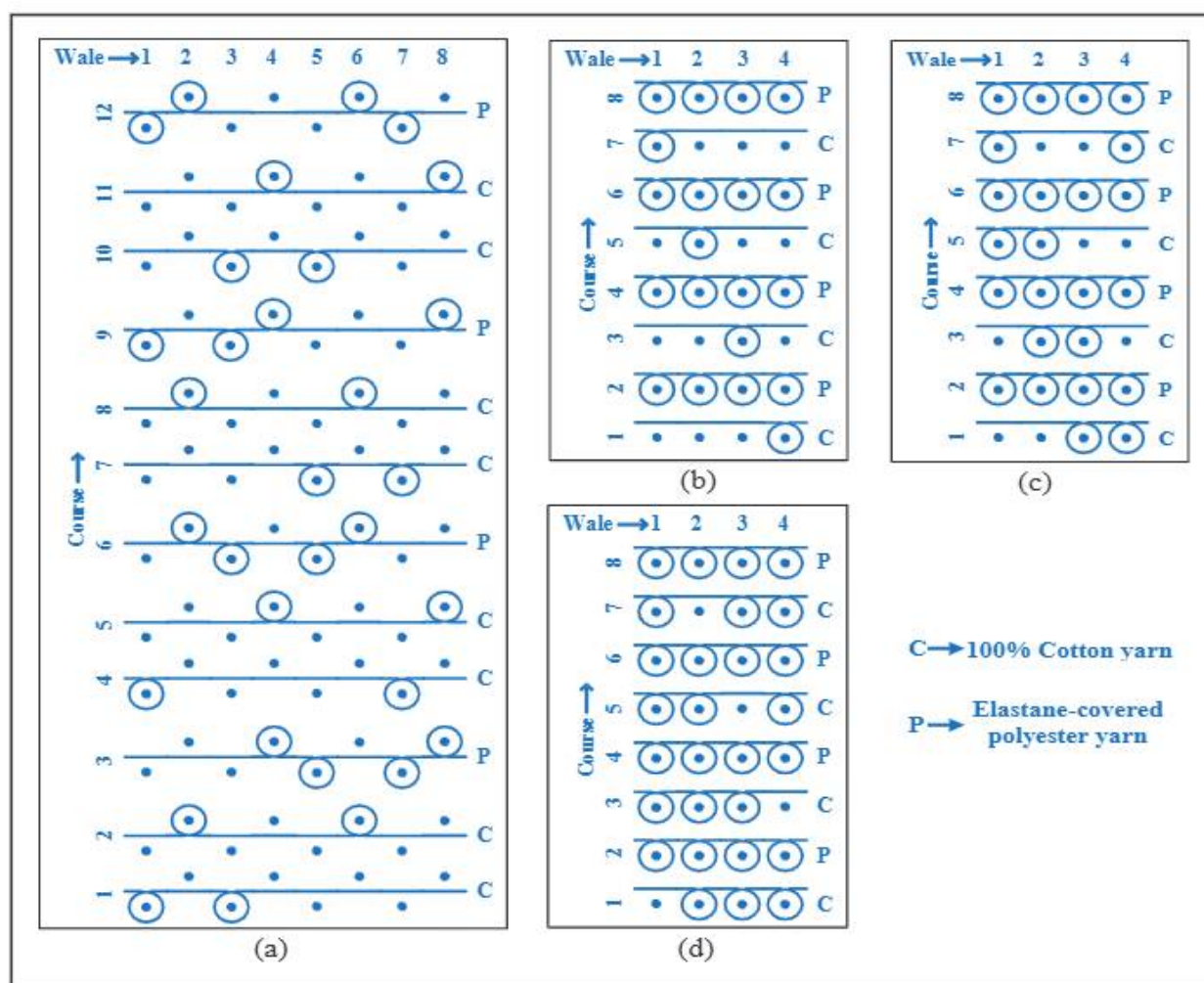


Figure 1. Notation diagram of knit denim fabric- (a) DJD- Rib Gaitting, (b) SJD-TMD, (c) SJD-DMD, and (d) SJD-SMD.

Subsequent to the heat-setting process, the fabrics underwent a washing procedure at 60°C to eliminate any residual dust and impurities, which was then succeeded by drying. Stentering was conducted to enhance the stability of the fabric and regulate properties, including fabric width, weight (GSM), spirality, and shrinkage [19,29]. The process was conducted utilizing a second stenter machine (ACC, Turkey) at a temperature of 140°C, featuring a fabric diameter of 66 inches.

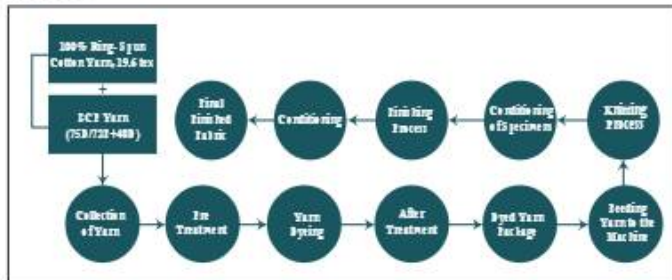


Figure 2. Development process of knit denim fabric samples.

The overfeed ratio has been calibrated to 90%, and the fabric speed is established at 16 meters per minute. To promote relaxation and achieve consistent heat distribution, water was used in place of chemical softeners, enhancing the fabric's texture and minimizing static electricity.

fabric are distinct. The denim-like appearance of single-jersey derivative (SJD) fabrics is attributed to the formation of misloops on the reverse side. Conversely, this phenomenon is observed on the outward-facing side of double-jersey derivative (DJD) fabrics. The lower miss-loop density of the SJD-SMD fabric produces a comparatively less pronounced effect, whereas the higher miss-loop density of the DJD and SJD-TMD fabrics imparts a more conspicuous denim-like appearance.

Microscopic images of these four knitted denim fabrics were obtained using a stereo-microscope (EUROMEX BV, Netherlands), which are illustrated in **Figure 3**, and fabric specifications are listed in **Table 1**.

2.3 Test Methods

2.3.1 Vertical Wicking

The wicking characteristics of all knitted fabrics were evaluated in accordance with the AATCC 197 (Version B) test procedure, utilizing the AATCC Wicking Tester. For this purpose, fabric specimens were submerged in distilled water for 10 minutes, after which the diffusion height of each fabric was measured and documented.

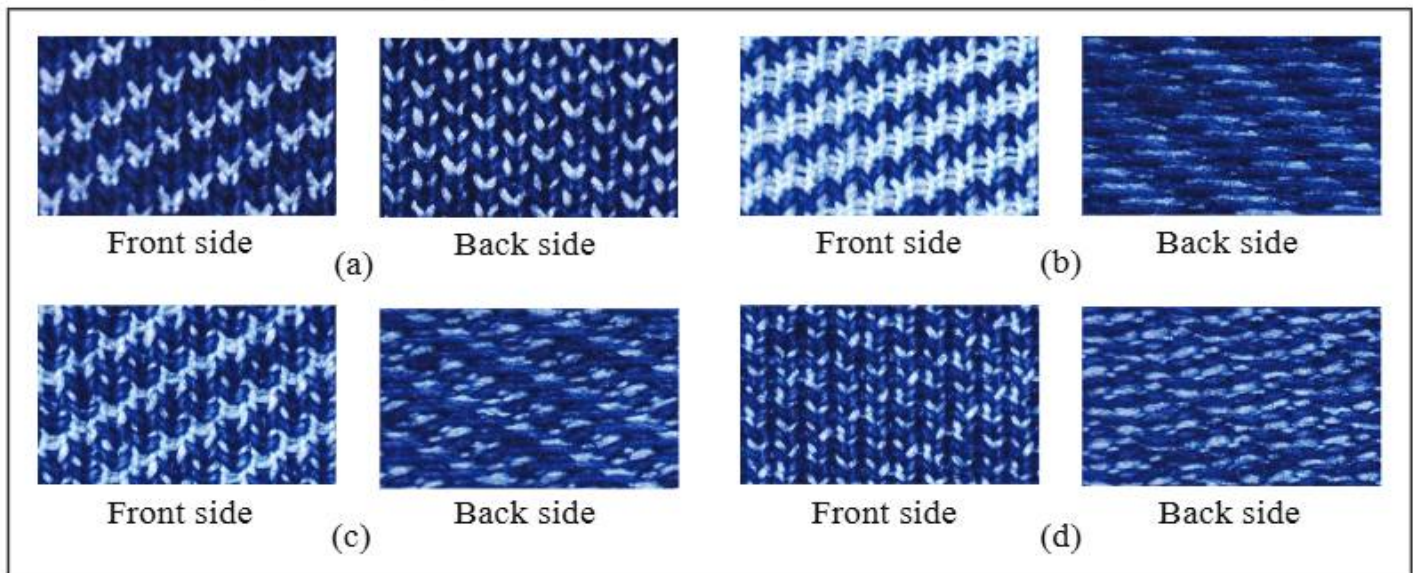


Figure 3. Stereo microscopy images (10x) of knit denim fabric - (a) DJD, (b) SJD-TMD, (c) SJD-DMD, and (d) SJD-SMD.

The final finishing step, compacting, was executed to attain enhanced fabric shrinkage control, luster, and an improved hand-feel. The fabric underwent compaction utilizing a compactor machine (Santex, Italy) at a temperature of 110°C, achieving 30% compaction with a fabric speed of 12 meters per minute. Upon completion of the finishing processes, all fabric samples were reconditioned for a duration of 24 hours at a temperature of $21 \pm 2^\circ\text{C}$ and a relative humidity of $65 \pm 2\%$ to guarantee a dry and relaxed state, as shown in **Figure 2**. The faces and reverse sides of the four variations of knit denim

2.3.2 Air Permeability

The assessment of air permeability was performed in accordance with the ASTM D737 standards. In accordance with the specified technique, circular fabric samples of 100 cm² were positioned at the apex of the testing apparatus. The Shirley Air Permeability Tester was utilized to conduct the test on all knitted denim specimens at a water pressure differential of 125 Pa.

Table 1: Fabric specifications of the developed knit denim samples

Fabric parameters	DJD	SJD -TMD	SJD -DMD	SJD -SMD
Composition	74% Cotton, 23.8% Polyester, 2.2% Elastane	54% Cotton, 41% Polyester, 5% Elastane	60% Cotton, 35% Polyester, 5% Elastane	65% Cotton, 31% Polyester, 4% Elastane
Repetition size (Course x Wale)	12 x 8	8 x 4	8 x 4	8 x 4
Stitch length (mm) Cotton/ECP	3.00/3.00	1.40/2.50	1.90/2.50	2.25/2.50
Miss loop density (%)	66.7	37.5	25.0	12.5
Grey width (inch)	66	57	65	65
Finished width (inch)	66	64	66	66
Grey Weight (g/m ²)	337	231	217	187
Finished Weight (g/m ²)	280	175	160	160
Grey Stitch Density (G. CPI x G. WPI)	7560	6468	4940	4160
Finished Stitch Density (F. CPI x F. WPI)	5712	3468	3168	2992
Shape Factor (Grey)	5.83	3.67	3.42	2.60
Shape Factor (Finished)	4.94	3.00	2.91	2.59

2.3.3 Thermal Properties

Thermal conductivity and thermal resistance were assessed using a thermal guarded hotplate apparatus (Model YG606D) to characterize the fabric's heat-transfer behavior. Thermal conductivity was measured on 300 mm × 300 mm fabric specimens following the ASTM D1518 test method, using a heating plate temperature range of 20°C to 50°C with a precision of ±0.5°C. Thermal resistance measurements were conducted in accordance with GB/T 11048-2008.

2.3.4 Fabric Touch Tester (FTT)

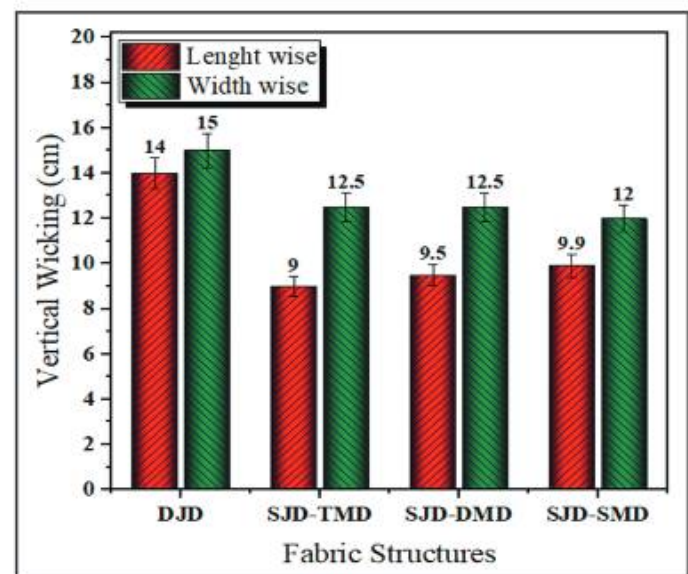
The fabric touch tester (FTT) was employed to quantitatively evaluate the tactile comfort of four fabric samples using the CHES_FY Hand Feeling Style Instrument by measuring essential properties such as softness (compressibility), stiffness (bending rigidity), smoothness (surface friction), and elasticity (stretch performance). The samples were examined in three orientations-wale, course, and bias (45°)-with results averaged for each orientation. The fabrics were conditioned for 24 hours at 20 ± 2°C and 65 ± 4% relative humidity.

3. Results and Discussions

3.1 Vertical Wicking

Vertical wicking, or the upward movement of liquid through fabric via capillary action, is an important feature in moisture control and wearer comfort [7,21]. In knitted fabrics, structural design has a significant impact on process efficiency. Compact geometries maintain continuous capillary channels, whereas more open shapes disrupt pore continuity and limit

liquid rise [27,30]. As a result, the double jersey denim (DJD) structure, with its bilayer compactness, was projected to outperform single jersey derivatives (SJD), which differ in miss loop density: SJD-TMD has the highest density, SJD-DMD has a moderate density, and SJD-SMD has the lowest.

**Figure 4.** Vertical wicking of of knit denim fabric samples

The graph from descriptive statistics as depicted in **Figure 4** supported this expectation. DJD had the greatest mean wicking values (14.0 cm lengthwise, 15.0 cm width wise) with limited variability, whereas the SJD variations had lower means: SJD-TMD = 9.0/12.5 cm, SJD-DMD = 9.5/12.5 cm, and SJD-SMD = 9.9/12.0 cm. Confidence intervals showed a strong separation, with DJD's lower limits remaining higher

than the upper bounds of all SJD fabrics, highlighting its structural advantage.

The ANOVA findings confirmed these differences. DJD outperformed SJD-TMD, SJD-DMD, and SJD-SMD in longitudinal direction, with a considerably higher between-group variance (Mean Square = 26.367) than within-group variance (0.020), resulting in a F value of 1318.33 ($p < 0.001$). In terms of width, DJD outscored all SJD variants with a F value of 407.41 ($p < 0.001$). These extremely high F statistics confirm that knit architecture, notably DJD's compact bilayer design versus SJD's varied miss loop densities, is the primary component determining vertical wicking. The LSD post-hoc analysis produced extensive pairwise comparisons. DJD outperformed all SJD variations, with mean differences of +5.0 cm (DJD vs. SJD-TMD), +4.5 cm (DJD vs. SJD-DMD), and +4.1 cm (DJD vs. SJD-SMD) in length and +2.5-3.0 cm in breadth ($p < 0.001$). Within the SJD group, SJD-TMD displayed greater wicking than SJD-DMD (+0.5 cm) and SJD-SMD (+0.9 cm), whereas SJD-DMD outperformed SJD-SMD by +0.4 cm ($p < 0.001$). SJD-TMD and SJD-DMD were not statistically different in width wise orientation ($p = 1.000$), but both outperformed SJD SMD by +0.5 cm ($p < 0.001$).

Overall, the combined evidence reveals that DJD provides much greater vertical wicking due to its compact bilayer construction, while the SJD textiles show a graduated reduction aligned with miss loop density. Among the single jersey variations, the hierarchy is evident-SJD-TMD > SJD-DMD > SJD-SMD longitudinally, with SJD-TMD and SJD-DMD identical width wise but both superior to SJD-SMD. The consistent observation that all textiles displayed more width wise than lengthwise wicking emphasizes the role of loop orientation and yarn channel design in aiding capillary rise [31].

3.2 Air Permeability

As showed in **Figure 5**, it demonstrates a strong structural hierarchy. SJD-DMD had the highest average air permeability ($110 \text{ cm}^3/\text{cm}^2/\text{s}$), indicating an open and less compact structure. SJD-TMD and SJD-SMD had comparable values ($104 \text{ cm}^3/\text{cm}^2/\text{s}$), while DJD had significantly lower permeability ($43 \text{ cm}^3/\text{cm}^2/\text{s}$), indicating a denser loop arrangement. Low standard deviations across all samples indicate similar structural behaviour and reliable assessments.

One-way ANOVA revealed a substantial structural effect on air permeability ($F = 1416.283$, $p < 0.001$). The between-group mean square (5001.250) significantly outperformed the within-group mean square (3.531), indicating that the differences between textiles are due to true structural variation rather than random experimental error. The minimal within-group variance contributes to the testing process's precision. LSD post-hoc analysis clarified pairwise differences. DJD differed significantly from all SJD-based structures (mean difference 61–67 units, $p < 0.001$), confirming its

compact, low-permeability nature. Within the SJD group, SJD-DMD was significantly more permeable than SJD-TMD and SJD-SMD by 6 units each ($p < 0.001$), highlighting the effect of dual mechanical distortion in increasing pore size. No significant difference was observed between SJD-TMD and SJD-SMD ($p = 1.000$), indicating that their respective modifications produced comparable structural openness.

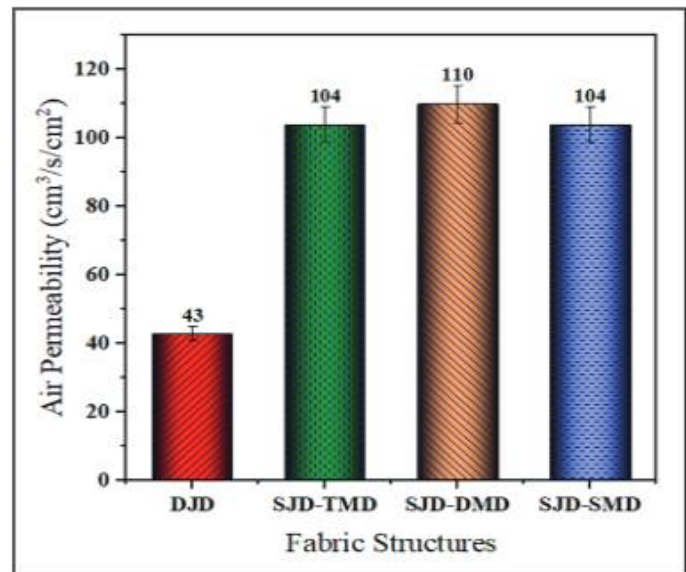


Figure 5. Air permeability of of knit denim fabric samples.

Overall, the findings show that air permeability is directly related to the precise structural alterations made to the materials. The dual-modified SJD-DMD fabric, designed with a more open loop arrangement, naturally accommodates more airflow, but the unmodified DJD maintains a more compact and controlled structure that ensures steady, regulated permeability. These complementing behaviours demonstrate how distinct architectural techniques in knitted denim fabrics can be tuned to achieve diverse airflow characteristics, each customized to the required performance needs.

3.3 Thermal Properties

3.3.1 Thermal Resistance

Thermal resistance measures a fabric's capacity to resist heat transmission. Fabrics having a larger thickness and the ability to capture still air often have higher resistance because the trapped air acts as an insulating medium. Structures with lesser thickness and higher porosity, on the other hand, prevent the formation of stable air pockets, allowing heat to pass more easily through the material [11,21,33]. Variations in float length, compactness, and overall structural geometry thus have an important effect in determining thermal resistance within knitted denim systems.

In accordance with this idea, the descriptive data as shown in **Figure 6(a)** revealed that heat resistance reduced systemati-

cally with increasing structural compactness. DJD had the highest resistance ($0.12608 \text{ m}^2\text{K/W}$) due to its double-layer design and significant entrapped air volume. Among the single-jersey derivatives, SJD-TMD recorded 0.06631 , which is consistent with the openness caused by its longer triple-miss diagonals. SJD-SMD showed 0.03863 , whereas SJD-DMD, the most compact structure, had the lowest value (0.02926). These numerical changes are directly proportional to the reduction in loft and interior air gaps as miss-float length decreases.

The ANOVA indicated that fabric structure had a highly significant effect on heat resistance ($F = 909.026$, $p < 0.001$), indicating that the observed variations were predominantly driven by structural geometry and not experimental variability. The magnitude of the F-value confirms knit architecture's major influence on fabric insulating capacity. LSD comparisons confirmed the magnitude of these structural variations. DJD outperformed SJD-TMD, SJD-SMD, and SJD-DMD by 0.05977 , 0.08745 , and 0.09682 , respectively. In the single-jersey group, SJD-TMD remained considerably higher than SJD-SMD ($+0.02768$) and SJD-DMD ($+0.03705$). SJD-SMD also outperformed SJD-DMD ($+0.00937$), demonstrating a steady declining trend that corresponds to the transition from longer to shorter miss floats and from looser to more compact shapes.

Overall, the data demonstrate a direct structural rationale: longer miss floats (as in SJD-TMD) result in larger internal air spaces and thus higher thermal resistance; shorter single-miss floats (SJD-SMD) result in a more compact configuration with moderate insulation; and dense double-miss formations (SJD-DMD) trap the least air, yielding the lowest resistance. DJD's dual-layer design enhances this mechanism by increasing still-air volume, making it the most thermally resistant fabric in the group.

3.3.2 CLO Value

The CLO value shows a fabric's thermal insulating capacity in relation to human comfort. Structures with more bulk, higher loft, and less porosity hold more still air and hence provide more insulation, whereas lighter, more porous materials lose heat more easily and perform poorly in CLO [21,31]. Differences in miss-float arrangement and compactness in knitted denim structures have a direct impact on the amount of air that a fabric can sustain.

The descriptive results as illustrated in **Figure 6(b)** revealed a distinct structural gradient. DJD has the highest CLO value (0.81342), demonstrating the significant insulation provided by its double-layer design. Among the single-jersey derivatives, SJD-TMD recorded 0.42781 , which is consistent with the loft introduced by its longer triple-miss diagonal. SJD-SMD had a lower CLO of 0.24925 , while SJD-DMD, the most compact structure, had the lowest value (0.18878). These figures are consistent with the increasing fall in

air-holding capacity as float length decreases and structural density increases.

The ANOVA revealed a substantial structural influence on CLO ($F = 2569.277$, $p < 0.001$), indicating that the observed differences were heavily influenced by the textiles' geometric properties. The size of the F-value indicates CLO's sensitivity to changes in knit compactness and overall mass distribution. LSD comparisons helped to clarify the structural distinction. DJD outperformed SJD-TMD, SJD-SMD, and SJD-DMD by 0.38561 , 0.56417 , and 0.62464 , respectively. Within the single-jersey group, SJD-TMD outperformed SJD-SMD ($+0.17856$) and SJD-DMD ($+0.23903$), while SJD-SMD remained higher than SJD-DMD ($+0.06047$). The data consistently show the effect of float length on the creation of insulating air pockets.

Overall, the findings show that CLO rises with structural openness and bulk. DJD provides the most insulation due to its dual-layer construction, SJD-TMD benefits from the loft created by triple-miss floats, SJD-SMD holds moderate air due to its shorter single-miss diagonals, and SJD-DMD, being the densest, retains the least air and produces the least insulation among the structures.

3.3.3 Thermal Conductivity

Thermal conductivity describes how readily heat flows through a fabric. Structures that are thinner and less capable of trapping air allow heat to move more quickly, leading to higher conductivity values. In contrast, thicker fabrics with greater internal air volume interrupt heat flow, resulting in lower conductivity [33]. Variations in miss-float length and structural compactness therefore exert a direct influence on the rate of heat transfer in knitted denim.

The descriptive findings reflected this structural logic in **Figure 6(c)**. DJD had the lowest thermal conductivity (0.00603 W/mK) because its double-layer structure increased thickness and disrupted continuous conductive pathways. All single-jersey versions had stronger conductivity, indicating lower air entrapment. SJD-TMD was 0.00648 , followed by SJD-SMD at 0.00984 , and SJD-DMD had the highest value (0.01572), indicating a dense structural arrangement. The development shows that conductivity increases as the fabric gets thinner and more compact, with shorter miss floats reducing loft and increasing fibre contact.

The ANOVA indicated that fabric structure significantly influenced conductivity ($F = 305.196$, $p < 0.001$), showing the variation was predominantly driven by geometric variations between DJD and SJD derivatives. LSD comparisons validated this structural distinction. SJD-DMD outperformed SJD-SMD, SJD-TMD, and DJD by 0.00588 , 0.00924 , and 0.00969 . SJD-SMD was 0.00336 higher than SJD-TMD, and all SJD fabrics outperformed DJD, indicating the effect of lower loft and greater compactness on conductive heat transfer.

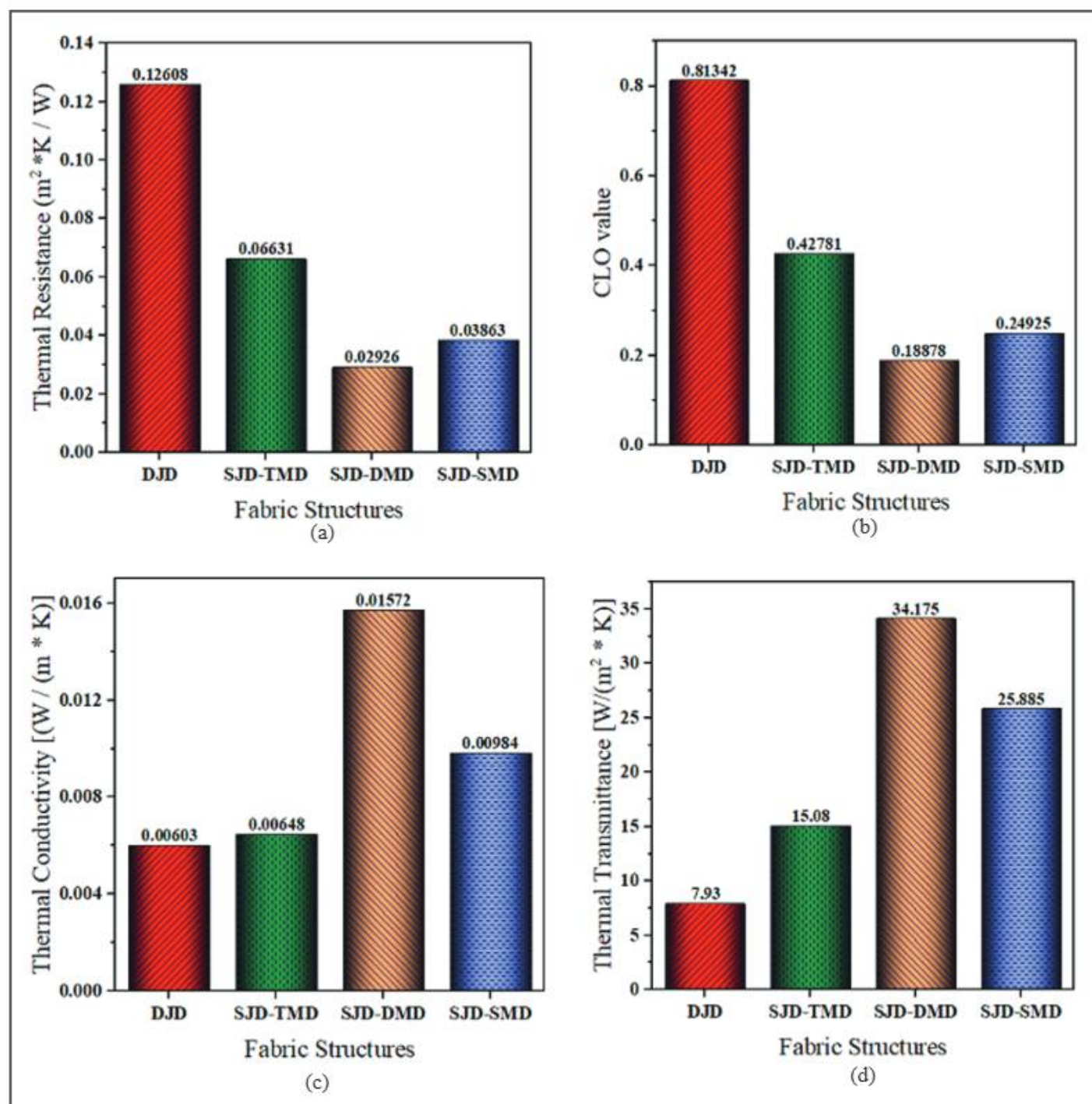


Figure 6. Thermal properties of of knit denim fabric samples-(a) Thermal resistance, (b) CLO value, (c) Thermal conductivity, (d) thermal transmittance.

Overall, the findings indicate that thermal conductivity rises as air entrapment falls. DJD's double-layer design efficiently limits conduction, whereas SJD fabrics, particularly the thick SJD-DMD, allow for faster heat transmission. The structural hierarchy shows that higher compactness facilitates conduction, whereas increased thickness and air volume inhibit it.

3.3.4 Thermal Transmittance

Thermal transmittance indicates how easily heat travels through a fabric. Because it is inversely related to thermal

resistance, structures with low thickness and fewer air pockets allow heat to escape faster, resulting in higher transmittance values. Thicker, lofted arrangements generate a greater insulating barrier, resulting in lesser transmittance [11,16].

Figure 6(d) shows that DJD exhibited the lowest thermal transmittance (7.93 $\text{W}/\text{m}^2\text{K}$), indicating its significant double-layer mass and excellent air retention capacity. All SJD derivatives have a greater transmittance in comparison. SJD-TMD recorded 15.08, indicating the moderate openness provided by its triple-miss floats. SJD-SMD achieved 25.885,

while SJD-DMD had the maximum transmittance (34.175), indicating a dense and compact structure. This climbing trend corresponds to the increased ease of heat movement as float length shortens and loft drops.

The ANOVA revealed that fabric structure had a significant impact on transmittance ($F = 3792.514$, $p < 0.001$), indicating that miss-float configurations and overall compactness were key factors in heat transfer behaviour. LSD comparisons highlighted this tendency. SJD-DMD outperformed SJD-SMD and SJD-TMD by 8.290 and 19.095, respectively, and both outperformed DJD by a significant margin (-26.245). SJD-SMD likewise outperformed SJD-TMD by 10.805, and each SJD derivative remained much higher than DJD, demonstrating the effect of structural compactness on heat passage.

Overall, heat transmittance improved significantly as materials became less able to trap air. The dense arrangement of SJD-DMD allowed the most rapid heat escape, followed by SJD-SMD and SJD-TMD. DJD's double-layer construction successfully controlled heat flow and produced the lowest transmittance. The findings confirm that compact, thinner single-jersey materials conduct heat more quickly, whereas bulkier layered fabrics reduce heat loss.

3.4 Fabric Touch Properties

Fabric Touch Testing (FTT) provides an objective characterization of fabric hand by simultaneously evaluating compression (softness, SF), bending (stiffness, ST), friction (smoothness, SM), and stretch (looseness-tightness, LT) in several dimensions [16]. Its application has demonstrated clear discrimination among structural variations and reliable prediction of comfort indices, with sensitivity to manufacturing parameters such as fibre composition and mass per unit area [34]. In the FTT grading system, lower SF values indicate greater softness, whereas higher ST and SM values represent increased stiffness and surface smoothness, respectively. Higher LT grades correspond to tighter and more compact fabric structures.

3.4.1 Compression

Compression behavior, as evaluated using the Softness Factor (SF) scale, revealed a strong and consistent differentiation between DJD and SJD derivatives. Higher compression values suggest a softer fabric hand, while lower SF grades represent greater softness. DJD revealed significantly higher compression values in all orientations, resulting in a lower SF grade and defining it as structurally softer than the SJD variations.

As illustrated in **Figure 7**, DJD had the highest compressibility, with values of 0.693 mm (wale), 0.866 mm (course), and 0.934 mm (45°). These results correlate to SF Grade 2, confirming DJD as the softest and most compressible struc-

ture in the group. In contrast, all SJD derivatives had significantly lower compression values, which corresponded to SF Grade 3, indicating relatively stiffer and less compressible structures. SJD-TMD had compression values of 0.400 mm (wale), 0.404 mm (course), and 0.374 mm (45°), whereas SJD-DMD had 0.322 mm, 0.352 mm, and 0.281 mm. SJD-SMD had the lowest compression response-0.301 mm (wale), 0.368 mm (course), and 0.261 mm (45°), indicating the firmest structural behavior among all samples. The decreasing compression trend from DJD → SJD-TMD → SJD-DMD → SJD-SMD demonstrates a shift from softer to stronger handfeel as compression values decrease and SF grade increases.

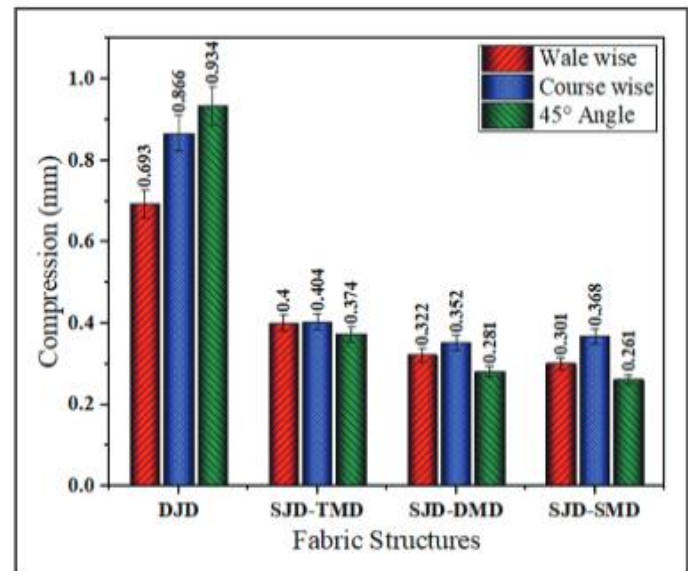


Figure 7. Compressibility of knit denim fabric samples.

The ANOVA findings revealed considerable structural impacts on compression in all directions. Extremely high F-values- $F = 8407.692$ (wale), $F = 51765.957$ (course), and $F = 69813.563$ (45°), each with $p = 0.000$ -indicate that fabric architecture had a considerable impact on compression behaviour. The prevalence of between-group variances emphasizes the importance of loop design, layer layout, and structural compactness in determining compressibility. LSD post-hoc comparisons supported the performance hierarchy. DJD has much higher compressibility than all other SJD derivatives ($p < 0.001$). Within the SJD group, a strong structural gradient emerged: SJD-TMD > SJD-DMD > SJD-SMD, with significant differences of +0.078, +0.099, and +0.021 mm, respectively. This trend demonstrates that decreasing miss-loop density results in increasingly stiffer textiles with lower compression values.

Overall, the interpretation suggests that DJD has the softest handfeel due to its higher compressibility and lower SF grade, indicating the influence of its bilayer structure. The SJD derivatives have lower compression and higher SF grades,

resulting in textiles that are stiffer and more structurally stable. This progression from soft (DJD) to firm (SJD-SMD) demonstrates intentional structural tuning across knitted denim systems to balance comfort and mechanical integrity.

3.4.2 Bending Rigidity

Bending rigidity, indicated by the Stiffness Grade (ST), revealed structural variations across the materials. As Shown in **Figure 8**, DJD had the highest bending resistance-9.804 cN (wale), 8.893 cN (course), and 8.711 cN (45°), all classified to ST Grade 3, indicating a rigid hand. In contrast, all SJD derivatives displayed much lower bending resistance when compared to ST Grade 2, indicating increased flexibility. SJD-TMD measured bending values of 2.988 cN, 3.054 cN, and 2.478 cN in different directions, all within ST Grade 2. SJD-DMD demonstrated similar flexibility with 2.493 cN (wale), 3.224 cN (course), and 2.764 cN (45°), all of which corresponded to ST Grade 2. SJD-SMD was the most flexible of the derivatives, with 2.718 cN, 2.686 cN, and 2.679 cN across directions-all falling inside ST Grade 2. As a result, the bending response clearly moves from DJD's hard ST Grade 3 to the more flexible ST Grade 2 profile of the SJD versions.

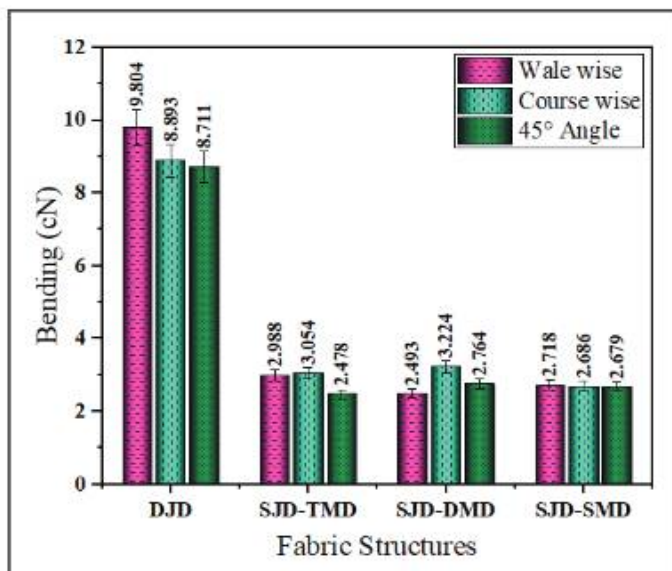


Figure 8. Bending rigidity of knit denim fabric samples

The ANOVA results offered substantial statistical confirmation for the observed discrepancies. In the wale direction, the between-group variance was quite dominating, with $F = 3,888,290.908$, $p = 0.000$. A similar pattern was seen in the course direction with $F = 5,845,116.611$, $p = 0.000$, and in the 45° direction with $F = 45,948.605$, $p = 0.000$. In all cases, the magnitude of the F-value considerably above the p-value ($F \gg p$), indicating that structural factors had a greater influence on bending rigidity than random measurement variations. These findings support the importance of knitted architecture, notably loop tightness and layering, in influencing bending behaviours. LSD post-hoc analysis confirmed these structural

effects by revealing distinct pairwise differences across all fabric types. DJD increased SJD-TMD by +6.816 cN, SJD-DMD by +7.311 cN, and SJD-SMD by +7.086 cN ($p < .001$). The trend was highly constant within the SJD group: SJD-TMD demonstrated higher rigidity than SJD-DMD by +0.495 cN and than SJD-SMD by +0.270 cN; meanwhile, SJD-DMD exceeded SJD-SMD by +0.225 cN, with all differences statistically significant. These orderly and regular separations across wale, course, and 45° directions supported the bending hierarchy $DJD > SJD-TMD > SJD-DMD > SJD-SMD$.

Overall, the bending results show how constructional philosophy influences mechanical behaviour. DJD's bilayer alignment naturally increases stiffness, reflecting its compact loop geometry and improved inter-loop integrity. Meanwhile, single jersey derivatives become more flexible when loop openness and miss-loop distribution go from TMD to DMD and eventually to SMD. These variations do not suggest superiority but rather show purposeful design direction-DJD provides structured stiffness, whilst SJD versions provide varied degrees of pliability, suited to better comfort and movement. This balanced range of bending behaviour demonstrates the adaptability and engineered performance of knitted denim materials.

3.4.3 Friction Coefficient

Friction behaviour, as represented by Smoothness Grade (SM), separated DJD from SJD derivatives. As per **Figure 9**, DJD had the roughest surface, with friction coefficients of 1.573 (wale), 1.509 (course), and 1.530 (45°), which were all classified as SM Grade 2, indicating moderate roughness. SJD-TMD showed much smoother surfaces, with readings of 1.107, 1.298, and 1.110 across directions, all assigned to SM Grade 3. SJD-DMD had friction values of 1.222 (wale), 1.258 (course), and 1.142 (45°), which corresponded to SM Grade 2-3, but was uniformly smoother than DJD. SJD-SMD has the best smoothness of any construction, with friction ratings of 1.100, 1.151, and 1.158-all consistently falling within SM Grade 3. Thus, smoothness progresses from DJD's rough SM Grade 2 surface to the improved SM Grade 3 smoothness of SJD derivatives, particularly SMD.

The ANOVA results provided substantial support for the significance of structural changes in surface friction. In the wale direction, $F = 983.141$, $p = 0.000$ indicated considerable between-group variation, which became even stronger in the course direction with $F = 11703.203$, $p = 0.000$, and remained highly significant at $F = 5898.264$, $p = 0.000$ in the 45° orientation. Across all directions, the connection $F \gg p$ confirmed that fabric structure, particularly surface roughness and loop exposure, influenced friction behaviour more than measurement variability did. LSD post-hoc analysis revealed accurate pairwise comparisons between the textiles. DJD had significantly higher friction than all SJD derivatives in the wale

direction, surpassing SJD-TMD by +0.466, SJD-DMD by +0.351, and SJD-SMD by +0.473 ($p < .001$). Within the SJD group, SJD-DMD had somewhat higher friction than both SJD-TMD (+0.115) and SJD-SMD (+0.122), which was statistically significant. However, SJD-TMD and SJD-SMD diverged by only +0.007, a statistically insignificant number, indicating a close similarity between these two smoother designs. This resulted in the friction hierarchy $DJD > SJD-DMD > SJD-TMD \approx SJD-SMD$, which is constant across all directional testing.

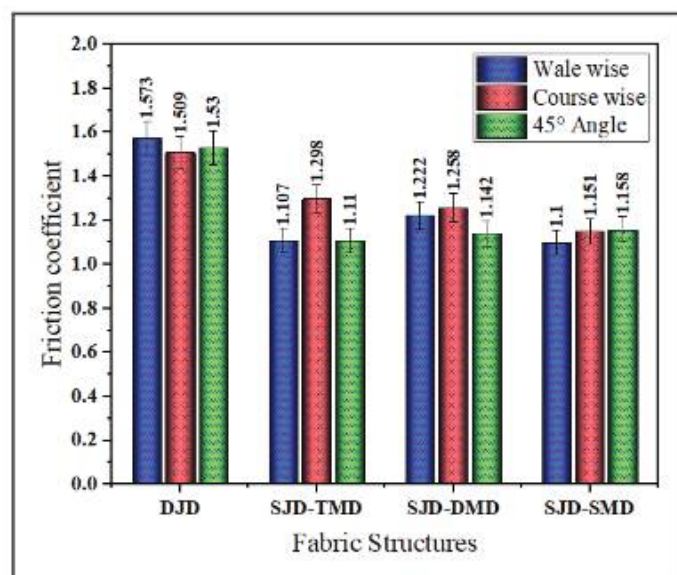


Figure 9. Friction coefficient of knit denim fabric samples.

Overall, the friction data demonstrate how surface design and loop presentation affect tactile performance. DJD's dense knit structure creates more surface contact points, resulting in moderately increased friction and a harder tactile sense. Meanwhile, SJD derivatives, particularly SMD and TMD, have smoother surfaces due to more open loop configurations and lower surface roughness. These distinctions do not suggest performance deficiencies; rather, they represent deliberate design diversity-DJD provides a balanced grip and stability, whereas SJD variations provide a softer hand feel and improved glide, depending on the intended application. This shows a well-structured friction spectrum influenced by fabric architecture.

3.4.4 Stretch Performance

Stretch behavior, assessed using the Looseness/Tightness (LT) grade, indicated significant elastic differences. As depicted in Figure 10, DJD demonstrated strong stretch resistance in all directions-26.174 cN/mm in the wale direction (LT Grade 5), 43.628 cN/mm course-wise (LT Grade 5), and 21.513 cN/mm at 45° (LT Grade 5), indicating a tight and highly elastic structure. SJD-TMD maintained a similar course-direction elasticity of 43.057 cN/mm (LT Grade 5) but

demonstrating lower wale (15.768 cN/mm) and 45° (16.487 cN/mm) stretch, both assigned to LT Grade 5, indicating softer elastic behaviour but the same grade classification. SJD-DMD had moderate stretch values-21.611 cN/mm (wale), 33.220 cN/mm (course), and 16.041 cN/mm (bias), all matching to LT Grade 5, indicating a better controlled and stable elasticity profile. SJD-SMD had the lowest stretch intensities-17.299 cN/mm (wale), 28.376 cN/mm (course), and 20.230 cN/mm (45°), all falling below LT Grade 5, suggesting maximum dimensional stability while maintaining structural robustness. As a result, while all fabrics have the same LT Grade 5, the intensity of elasticity falls significantly from DJD to SJD-TMD, SJD-DMD, and SJD-SMD.

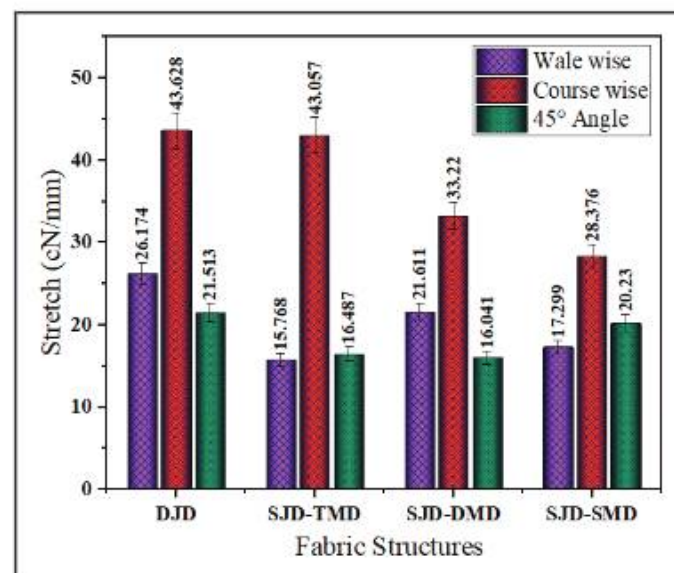


Figure 10. Stretch performance of knit denim fabric samples.

The ANOVA findings indicated that the differences in stretch behaviour were statistically significant in all directions. The wale direction had a significant structural effect ($F = 14608.786$, $p = 0.000$), whereas the course direction had an extraordinarily large effect ($F = 5,297,642.214$, $p = 0.000$). The 45° direction also showed considerable structural variation ($F = 27500.383$, $p = 0.000$). In all cases, the F-value was significantly greater than the significance value ($F \gg p$), indicating that variations in loop architecture, density, and inter-yarn interaction were the key determinants of stretch performance rather than measurement noise.

LSD post-hoc comparisons provided greater insights into the textiles' directional stretch connections. In the course direction, DJD recorded considerably higher stretch resistance than all SJD derivatives: $DJD > SJD-TMD$ (+0.571 cN/mm), $DJD > SJD-DMD$ (+10.408 cN/mm), and $DJD > SJD-SMD$ (+15.252 cN/mm) ($p < .001$). However, in the wale and 45° directions, the trend inverted, with SJD-SMD showing the largest stretch values: in the wale orientation, SJD-SMD exceeded SJD-DMD by +4.312 cN/mm, SJD-TMD by

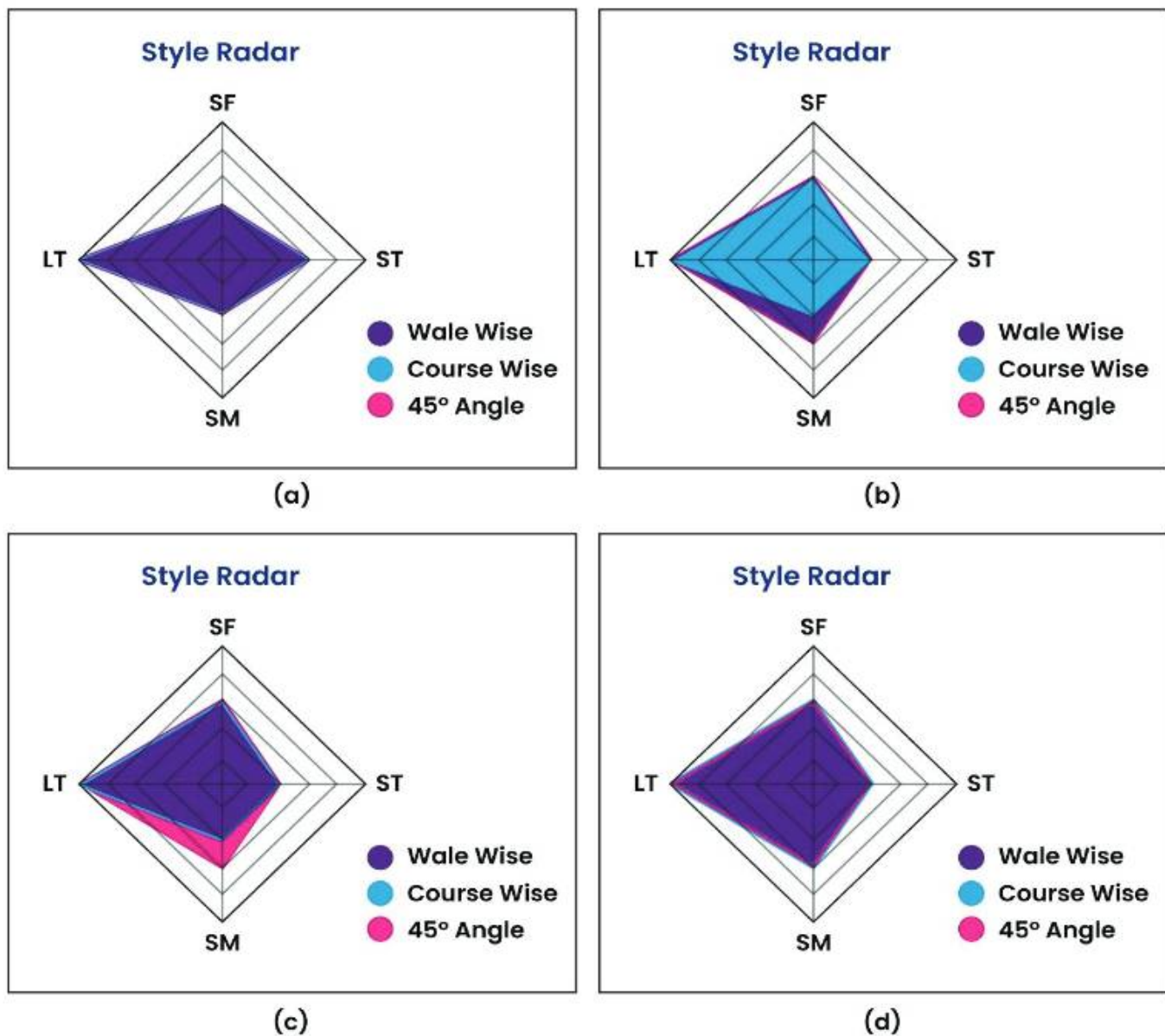


Figure 11. Touch properties of knit denim fabric samples- (a) DJD, (b) SJD-TMD, (c) SJD-DMD, (d) SJD-SMD.

+1.531 cN/mm, and DJD by +8.875 cN/mm. Similarly, at 45°, SJD-SMD outperformed SJD-TMD by +3.743 cN/mm, SJD-DMD by +4.189 cN/mm, and DJD by +1.283 cN/mm, with all statistically significant differences. This dual-directional design creates a constant hierarchy. Course leads to DJD, TMD, DMD, and SMD, whereas Wale and 45° lead to SMD, DMD, TMD, and DJD, respectively.

Overall, stretch behaviour implies intentional structural alignment rather than performance shortcomings. DJD's bilayer knit design naturally improves course-direction control and elastic resistance, making it suitable for maintaining structural integrity during lateral strain. Meanwhile, the SJD derivatives, particularly SMD, offer higher wale and diagonal flexibility due to their more open loop geometry and reduced inter-loop constraint. These variations reflect design-driven

performance diversity, providing a range of elastic responses appropriate for various functional needs and demonstrating how knitted architecture governs multi-directional extensibility.

Moreover, the Style Radar charts in **Figure 11(a-d)** combine the four tactile indices-compression (SF), bending (ST), friction (SM), and stretch (LT)-across the three primary directions (wale, course, and 45° bias) to provide a comprehensive view of fabric hand. This graphical approach complements the numerical results reported in Sections 3.4.1-3.4.4, allowing for direct comparisons of DJD and SJD derivatives.

As per **Figure 11(a)**, DJD has the most outwardly stretched radar profile along the SF and LT axes, indicating higher compressibility, softer hand, and a more open structural structure.

However, DJD exhibits larger outward expansion on the ST axis, suggesting higher stiffness, and a relatively inward position on the SM axis, indicating lower smoothness. This combination illustrates the performance of DJD's bilayer architecture: it improves compressibility and loop deformation (high SF and LT expansion), but it also adds structural reinforcement (high ST) and a rougher surface (low SM). In contrast, the SJD derivatives show more inward dispersion on the SF and LT axes, indicating lesser compressibility and tighter loop structure, but less spread along the ST axis, indicating lower stiffness than DJD. They also extend further outward along the SM axis, indicating increased surface smoothness. This pattern is compatible with the single-jersey construction, which uses miss-loop modulation to limit deformation (compact SF and LT) while providing a smoother, less rigid fabric hand (lower ST, higher SM). A significant gradient is found among the SJD variants: SJD-TMD as illustrated in **Figure 11(b)** has the most limited radar envelope—lowest SF and LT, relatively reduced SM, and moderately low ST—identifying it as the firmest and structurally tightest SJD sample. SJD-DMD as shown in **Figure 11(c)** is positioned in the middle of all axes, reflecting balanced hardness, moderate surface smoothness, and controlled openness. SJD-SMD as per **Figure 11(d)** has the largest outward expansion of all SJD fabrics, notably along SF and SM, indicating that it is the softest and smoothest SJD derivative with the least structural restriction. Overall, the radar profiles demonstrate that DJD combines high softness and stiffness with restricted smoothness, while the SJD derivatives shift toward reduced stiffness, higher smoothness, and more regulated structural tightness, following a clear trend from TMD to DMD to SMD.

4. Conclusion

This study provides a comprehensive evaluation of the touch properties and comfort performance of structurally innovative knit denim fabrics, emphasizing how engineered structures govern tactile response, thermal behavior, and wearability. The comparative analysis between double-jersey derivative (DJD) and single-jersey derivatives (SJD) based structures reveal clear structure–property relationships that expand the design possibilities for next-generation knit denim. The DJD structure consistently exhibited the most robust performance profile, characterized by high vertical moisture transport, enhanced stretchability, more softer, and improved thermal insulation. These advantages originate from its compact loop arrangement, superior inter-loop cohesion, and uninterrupted capillary pathways, which collectively enhance both mechanical stability and thermo-physiological responsiveness. In contrast, the SJD variants demonstrated a broader spectrum of comfort-oriented behaviors. SJD-TMD achieved a balanced combination of tactile smoothness, elasticity, and breathability; SJD-DMD offered elevated air permeability with moderate touch benefits; and SJD-SMD provided multidirectional stretchability and wearer-adaptive flexibility.

These distinctions highlight the critical role of loop density, float configuration, and structural openness in shaping comfort, movement adaptability, and thermal exchange.

Overall, the findings confirm that structural innovation particularly through double-jersey architectures can effectively address the comfort limitations of woven denim and the durability constraints of single-jersey knit denim. The integration of comfort metrics with Fabric Touch Tester (FTT) based tactile profiling demonstrates that optimized DJD constructions can deliver customer-required comfort performance without compromising mechanical integrity. In addition to providing a thorough technical understanding of knitted denim, this research also lays the groundwork for future developments that will successfully integrate performance, comfort, and sustainability into the design of textiles.

Limitations of the Study

Although all knitting and finishing parameters were kept constant during the development of the sample fabrics, stitch length varied slightly due to structural differences.

Declaration of Conflicts of Interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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