DIMENSIONAL STABILITY, STRENGTH, STRETCH, CREASE RESISTANCE, AND AIR PERMEABILITY OF PURE FLAX SWISS DOUBLE PIQUÉ KNITS

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Received January 18, 2026

This study explores how the average stitch length affects the dimensional, mechanical, and functional properties of pure flax Swiss double piqué fabrics produced on a circular knitting machine. The analysis covers structural features, dimensional changes after washing, strength, stretch, crease resistance, and air permeability. Increasing the average stitch length causes systematic structural changes, notably a decrease in the number of wales, while the number of courses remains relatively stable, resulting in a more open, less dense fabric. Structural loosening reduces the weight and thickness of the knitted fabrics. Dimensional changes are anisotropic, with the largest lengthwise changes occurring after the first wash and consistently greater widthwise changes, emphasizing the importance of initial washing for dimensional stability. Mechanical properties are highly direction-dependent: higher breaking forces and lower breaking elongations are found in the length direction, while widthwise extensibility is greater but with a lower breaking force. Increasing the average stitch length reduces both breaking force and elongation, resulting in a mechanically weaker fabric. Functional performance is also impacted: longer average stitch length with less fabric weight lowers lengthwise crease recovery but enhances air permeability. These findings show that stitch length is a key factor for pure flax Swiss double piqué fabrics, while yarn uniformity and elasticity are crucial for producing high-quality textiles.

Keywords: flax yarn, Swiss double piqué, stretch properties, elasticity, dimensional changes, air permeability

INTRODUCTION

Flax (*Linum usitatissimum* L.) is an annual herbaceous plant that primarily reproduces through self-pollination and represents one of the oldest cultivated crops, with a documented history spanning approximately 6,000–8,000 years. Global flax fiber production reached around 0.3 million tonnes, accounting for 5% of the non-cotton plant-based fiber market in 2024. Linen, the processed form of flax, is predominantly used in the production of home textiles and apparel. 70% of global flax production is in Europe, mainly in France, Belgium, and the Netherlands, with significant contributions from Belarus, Russia, and Ukraine. China is another important producer, having cultivated flax for over 5,000 years, mainly for its seeds and oil, while large-scale fiber production began about 90 years ago.[1]

Flax fibers are highly valued for their intrinsic properties, including high hygroscopicity, good absorbency, effective ultraviolet protection, skin comfort, and high tensile strength, as well as for their eco-friendly characteristics and cultural significance. These attributes extend the applicability of flax beyond apparel to a wide range of technical and industrial uses.[2] Owing to its favorable mechanical properties, flax is increasingly recognized as a sustainable alternative to synthetic fibers in both textiles and composite applications. For instance, the climate impact associated with the production of glass and carbon fiber is up to four and five times higher, respectively, than that of flax fiber, highlighting its environmental advantages.[3]

Flax fibers are also considered promising biodegradable materials for textiles, ropes, and composite reinforcement. Their biodeterioration is relatively rapid and characterized by surface erosion and fiber separation, leading to substantial reductions in tensile strength, although some mechanical functionality may be retained. These characteristics underscore the importance of incorporating end-of-life considerations into the design of flax-based materials.[4]

In textile manufacturing, flax is used both as pure fiber and in blends with various fibers, such as cotton, polyacrylonitrile (PAN), polyamide, viscose, and others. Such yarns are subsequently used to produce woven and knitted fabrics for a wide range of textile and apparel applications. Blending flax with other fibers, typically at approximately 20–30%, has been shown to improve spinnability and facilitate subsequent weaving or knitting processes, while maintaining favorable fabric performance.[5]

The fiber composition of flax-containing yarns is heavily affected by their mechanical properties performance. Pure flax yarn exhibits pronounced sensitivity to preloading, particularly with respect to preload magnitude, leading to noticeable reductions in breaking force and elongation, with elongation changes reaching 10–11%. In contrast, blended flax yarns demonstrate greater structural stability under comparable conditions. Overall, preloading negatively affects the mechanical properties of flax-based yarns, emphasizing the importance of fiber composition and controlled processing conditions to ensure reliable performance during knitting and subsequent textile applications.[6]

Pure flax yarn is characterized by limited flexibility due to its high torsional stiffness and low elasticity. Consequently, knitted fabrics produced from pure flax yarn exhibit the lowest widthwise elastic contribution and the highest residual deformation, indicating reduced dimensional stability. In contrast, blending flax with cotton or PAN in a 70/30 ratio reduces torsional and tensile stiffness, resulting in yarns with improved flexibility. Fabrics produced from such blended yarns show similar loop geometry, fabric density, and elastic deformation behavior. The enhanced flexibility of flax-based blends contributes to more stable, predictable fabric performance, which is essential for producing comfortable, aesthetically acceptable knitted textiles.[7]

Knitted flax fabrics are particularly suitable for warm-weather clothing due to their breathability, comfort, and aesthetic qualities. Investigations of plain single-jersey flax knitted fabrics indicate that the lower fabric stitch density is associated with increased compressibility and air permeability, but reduced resilience, water retention, and mechanical strength.[8] In general, knitted fabrics produced from blended flax fibers exhibit improved overall performance. While pure flax knitted fabrics provide high tensile strength, bamboo-containing knits offer enhanced antimicrobial properties. Notably, flax/bamboo blended knitted fabrics at a 50/50 ratio achieve a favorable balance between mechanical strength and antibacterial functionality, outperforming fabrics made from either fiber alone.[9]

Flax fibers in knitted fabrics also influence electrical properties. Parameters such as loop length, fabric stitch density, and pilling behavior affect both volume and surface resistivity, which are relevant for functional and technical textile applications.[10] Additionally, flax–synthetic fiber blends, particularly those incorporating polyester or recycled polyester, have been explored to improve the mechanical and comfort-related properties of knitted fabrics. Single-jersey and piqué knitted structures made from flax-containing yarns enhanced dimensional stability, increased bursting strength, and improved air permeability, whereas rib-knit structures are generally less suitable for such blends.[11]

Finishing treatments play an important role in determining the final performance of flax knitted fabric. Enzymatic treatments, such as cellulase application, have been shown to enhance the thermal comfort of 100% linen (flax) fabrics by increasing thermal conductivity and permeability, making them more suitable for summer apparel.[13] In terms of durability, linen fabrics show moderate pilling resistance, which can be enhanced by blending with hemp fibers or by applying enzymatic and conventional finishing processes.[14]

Beyond apparel, knitted flax fabrics can also serve as effective reinforcements in polymer composites. Studies on flax/polyurethane foam composites indicate that incorporating flax knitted fabrics increases tensile strength, particularly in the length direction, although elongation is reduced. Higher fabric density further enhances strength, and finite element simulations confirm the reinforcement effect of flax knitted fabrics with composite structures.[15]

Overall, flax fibers and fabrics offer a unique combination of mechanical performance, sustainability, biodegradability, comfort, and functional properties, making them attractive for both textile and composite applications. A comprehensive understanding of the interactions among fiber composition, fabric structure, processing conditions, and finishing treatments is essential for optimizing the performance of flax-based materials.

It is well established that knitted structures combining single and double stitches significantly influence the structural characteristics and properties of the knitted fabrics. Such configurations enable substantial reductions in fabric stitch density and raw material consumption by partially replacing knit loops with float loops. At the same time, such structures retain the thermal characteristics typical of double-knitted fabrics.[16-19] Analyses of four-row double piqué fabrics indicate that the incorporation of rows of incomplete single stitches reduces widthwise stretch and enhances dimensional stability.[16] Compared with French double piqué, Swiss double piqué fabric exhibits a less pronounced diagonal effect. Key structural characteristics of Swiss double piqué fabric, including dimensional stability after washing, strength, extensibility (stretch), non-creasing properties, and air permeability, depend on the type of flax-containing yarn and the average stitch length. Structural characteristics such as the number of wales and courses per centimeter, fabric stitch density, fabric weight, and tightness are strongly influenced by the average loop length. Fabric weight and thickness are mainly determined by yarn diameter. The most significant dimensional changes occur during the first two washing cycles, whereas non-creasing properties depend predominantly on the inherent properties of the flax yarn rather than on average loop length. Air permeability is affected by the combined influence of average stitch length and fabric stitch density.[16]

Although prior research has examined knitted fabrics incorporating flax, limited focus has been directed towards the knit structures produced through the combination of single- and double-knit stitches on knitting machines, especially when fabricated from pure flax yarn. Consequently, further investigation of these structures is essential to elucidate their processing behavior and performance attributes. The aim of this study is to comprehensively evaluate the performance of pure flax Swiss double piqué knitted fabrics, focusing on dimensional stability, mechanical strength, stretch behavior, crease resistance, and air permeability. By analyzing the effects of knit structure, average loop length, and fabric density, the research seeks to identify relationships among yarn properties, fabric structure, and functional performance. Special attention is given to fabric behavior after washing and under mechanical deformation, providing insights critical for optimizing pure flax knitted fabrics for high-quality, comfortable, and durable knitwear. This study also explores strategies to reduce material consumption through stitch design, while maintaining thermal and mechanical performance, thereby supporting more sustainable and efficient production practices. The results provide practical guidance for selecting stitch length when balancing material efficiency, comfort, dimensional stability, and manufacturability in pure flax knitted fabrics produced on a circular knitting machine.

EXPERIMENTAL

Yarn

In this study, a pure flax 46 tex yarn was selected (Fig. 1). The chosen yarn was produced by a wet spinning system, without any treatment (GOST 10078-85).[20] The key features of the yarn are shown in Table 1.

Knit fabrics

The knitted samples were produced using pure flax yarn on a 10-gauge circular knitting machine. To improve the knitting process, the yarn was waxed before knitting. The machine was configured to operate at a low knitting speed, using only four feeders. The distance between the cylinder and the dial, the yarn tension, and the take-down were kept constant. All stitch cams were replaced simultaneously at the same level in all knitting feeders (for single and double stitches).

For this research, the Swiss double piqué stitch (Fig. 2) was selected. The stitch repeat at the height of the Swiss double piqué stitch consists of four courses: a 2x1 rib stitch knitted in the first and third feeders, and a single float stitch knitted in the second and fourth feeders (Fig. 2b). The Swiss double piqué stitch is a double-faced fabric. The technical face side consists of the knit loops of the 2x1 rib stitch, while the technical back side consists of the knit loops of the 2x1 rib and single float stitches. The knit loops produced on the back needle bed at the first and second feeders are formed by the same set of needles. In contrast, the knit loops formed at the third and fourth feeders are produced by needles that were inactive during the first and second feeders.

Characterisation

Determination of structural characteristics

The structural characteristics of the washed knitted fabrics were evaluated by measuring the number of wales (W, loops/cm) and courses (C, loops/cm) per centimeter in accordance with EN 14971:2006[21] and GOST 8846-87.[22] Measurements were taken over a 10 cm length and recalculated per centimeter, with results averaged from ten different positions on the technical face of each sample. As mentioned above, the technical back of the Swiss double piqué stitch consists of the knit loops of the 2x1 rib and single float stitches, resulting in the irregularity of this side.

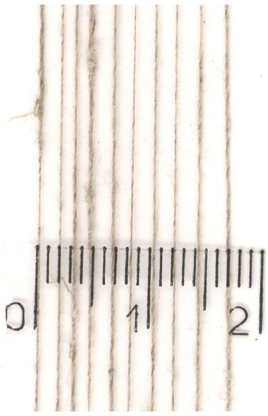


Figure 1: Photo of a pure flax yarn

Table 1
Main characteristics of pure flax yarns[7]

Characteristics of the yarn	Value
Materials of yarn, %	100% flax
Nominal linear density T_n, tex	46
Experimental linear density T_e, tex	50.9±0.5
Twist T, turns/m	246.3±28.9
Torsional stiffness C_t	0.88±0.11
Breaking force P, cN	880±221
Tenacity P_u, cN/tex	17.12
Breaking elongation E, %	2.05±0.35
Tensile stiffness C_b	3.660
Spinning system	wet

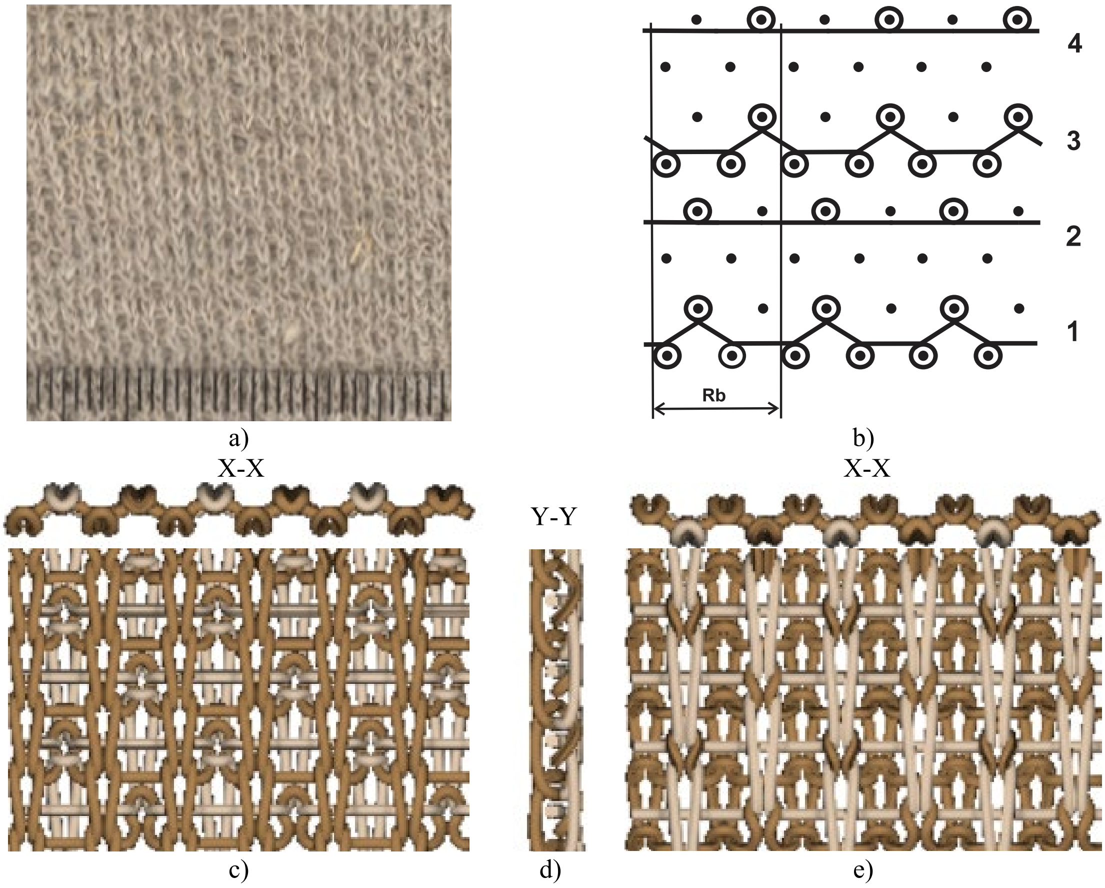


Figure 2: Swiss double piqué knitted fabric: a) photo of the technical face side, b) graphical representation, c) visualization of the technical face side with X-X cross-section, d) Y-Y cross-section, e) visualization of the technical back side with X-X cross-section

Stitch lengths of the single float stitch (l_1, mm) and 2×1 rib stitch (l_2, mm) were measured following GOST 8846-87.[22] Measurements for each stitch (single float and 2x1 rib) were taken from both feeders (the 1st and 3rd for a 2x1 rib stitch, and the 2nd and 4th for single float stitches) and then averaged per stitch. The average values represent the average of twenty measurements for each stitch type.

Fabric weight or mass per unit area (W_s, g/m²) was determined according to EN 12127:1997[23] as the mean of five specimens (200 cm² each).

Fabric thickness (t, mm) was measured in accordance with ISO 5084:1996[24] using a Thickness Gauge SM-124 at a pressure of 2.5 N/cm² (25 kPa), as the mean of ten measurements per sample.

Based on the received measurements, the following characteristics were calculated:

- fabric stitch density (S, loops/cm²): $S = W \cdot C$ (1)
- average stitch length (l_a, mm): $l_a = \frac{l_1 \cdot n_1 + l_2 \cdot n_2}{n_1 + n_2}$ (2)

where l_l – the loop length for single float stitch, mm; l_2 – the loop length for 2x1 rib, mm; n_l and n_2 represent the number of loops in unit repeat in % for single float stitch and 2x1 rib, respectively (in this case, n_l = 25%, n_2 = 75%).

Determination of dimensional change after washing

After knitting, the fabrics were relaxed for several days under standard atmospheric conditions according to ISO 139:2005[25] to eliminate knitting-induced stresses. The samples were then washed in a fully automatic household washing machine using a cotton program at 30 °C with 3 g/L of a wetting agent. After each wash, the fabrics were laid flat with minimal tension and conditioned under standard atmospheric conditions for at least 24 hours. Four washing relaxation cycles were applied in accordance with ISO 6330:2021[26] and ISO 5077:2007.[27]

The lengthwise (DC_l, %) and widthwise (DC_w, %) dimensional change, expressed as shrinkage (−) or extension (+), was calculated using the formula:

$$Dimensional\ change = \frac{final\ measurement - original\ measurement}{original\ measurement} \cdot 100 \quad (3)$$

where "original measurement" refers to measurements taken before the first washing.

The presented results are the mean of five measurements per sample in both directions.

Based on experimental data on the dimensional changes after washing, the theoretical dimensional change (DC_t, %) during washing cycles was calculated,[19] using the following formula:

$$DC_t = \frac{k}{a + b \cdot k} \quad (4)$$

where k is the number of washing cycles; a and b are the constants. The potential total change in dimensions as k→∞ approaches infinity will be $1/b = DC_p$.

Determination of strength properties

The strength properties were determined across the breaking force (F, N) and breaking elongation (Ɛ, %) of knitted fabrics, which were determined after washing using ISO 13934-1:2013.[28] The results were obtained as the mean of five measurements for each direction (length and width).

To determine the relationship between the strength of knitted fabrics and the yarn used, the breaking force element (F_e, N/el) of the knit structure is computed for each direction – length and width – using the following method equations:

$$F_{e\,l} = k_l \cdot \frac{F_l}{W}, \quad (5)$$

$$F_{e\,w} = k_w \cdot \frac{F_w}{C} \quad (6)$$

where k_l, k_w – the ratio of the length of the section used in determining the density to the width of the test strip (in this case, k_l = 1/5; k_w = 1/5); F_l, F_w – the breaking force of the knit fabric lengthwise and widthwise, respectively, N; W – the number of wales per centimeter, loops/cm; C – the number of courses per centimeter, loops/cm.

Determination of stretch characteristics

The stretch properties of the knitted samples were measured using the established standard GOST 8847-85[29] after undergoing washing. To conduct this research, a "rack" relaxometer was used, implementing a well-defined "loading-unloading-rest" cycle as described in papers.[18,19]

The fabric specimens underwent a 60-minute loading phase under a constant load of 5% of their breaking force. Afterward, they rested for 120 minutes, as presented in Figure 3. This cycle enabled accurate analysis and measurement of the stretch behavior of knitted fabrics under controlled conditions.

For evaluating the stretch properties of the knitted fabrics, the following types of deformation were calculated:

Total deformation (E, %): $E = \frac{L_1 - L_0}{L_0} \cdot 100$ (7)

Elastic deformation (E_1, %): $E_1 = \frac{L_1 - L_2}{L_0} \cdot 100$ (8)

Delayed elasticity (E_2, %): $E_2 = \frac{L_2 - L_3}{L_0} \cdot 100$ (9)

Residual deformation (E_3, %): $E_3 = \frac{L_3 - L_0}{L_0} \cdot 100$ (10)

where L_0 – the specimen length between grips before testing, mm (L_0 = 100 mm); L_1 – the specimen length between grips under loading for 60 min, mm; L_2 – the specimen length between grips after unloading, mm; L_3 – the specimen length between grips after 120 min resting, mm.

To evaluate fabric elasticity, the contributions of each deformation component were calculated as E_1/E, E_2/E, and E_3/E.

Five measurements were taken in length and width to obtain accurate fabric dimensions, and the mean values were reported.

Determination of non-creasing properties

Materials' non-creasing properties are described by the non-creasing coefficient, which quantitatively measures how the linear dimensions of the knitted fabric respond after removal of the deforming load and a subsequent rest period. The non-creasing characteristics of knitted fabrics were assessed following DSTU 2994-95.[30] The non-creasing properties were measured according to the methodology described in the paper.[16]

The non-creasing properties coefficient (CR, %) in both directions (length CR_l and width CR_w) is calculated according to the equation:

$$CR = \frac{100}{h_0 \cdot n} \cdot \sum_{i=1}^{n} h_i, \quad (11)$$

Five measurements were recorded for both fabric directions.

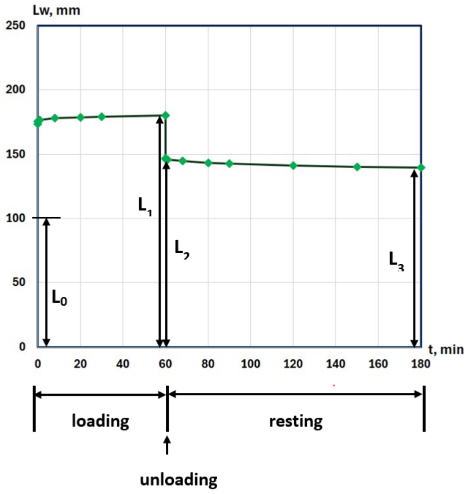


Figure 3: Widthwise dimensional changes of specimens during the "loading-unloading-resting" cycle for knitted fabric variant 1

Determination of air permeability

The air permeability (AP, mm/s) of the knitted fabrics was evaluated to assess their comfort properties, according to ISO 9237:1995.[31] Air permeability tests were carried out on the Tester III device in the laboratory of the Institute of Natural Fibers (Poland) at a pressure drop of 100 Pa with the test surface area of 20 cm^2. The results presented represent the mean of five fabric measurements.

RESULTS AND DISCUSSION

Structural characteristics

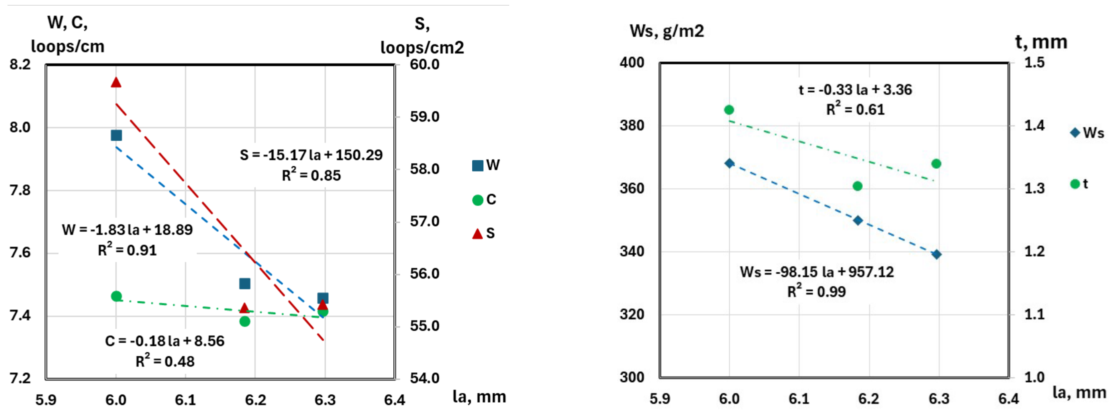
The structural characteristics of the investigated pure flax knitted fabrics are shown in Table 2. Based on the results obtained, the relationships between the number of wales (W), the number of courses (C) per centimeter, fabric stitch density (S), weight (W_s), thickness (t), and average stitch length (l_a) are illustrated in Figure 4a and 4b, respectively.

As shown in Figure 4, the relationships between structural characteristics and average stitch length are linear trends, as reported earlier.[16] By increasing the average stitch length (l_a) from 6.00 mm to 6.30 mm (5.0 %), the knitted fabrics exhibit systematic structural changes toward a looser construction.

Increasing the average stitch length (l_a) reduces the number of wales per centimeter (W) from 7.98 to 7.46 loops/cm – a reduction of about 6.5%. This shows that higher stitch lengths significantly lower the number of wales due to larger loop sizes. In contrast, the number of courses per centimeter (C) remains mostly unchanged, decreasing only from 7.46 to 7.42 loops/cm, representing a roughly 0.5% change.

Table 2
Experimental values of structural characteristics of pure flax knitted fabrics

Structural characteristics		Variant of samples		
		1	2	3
Number of wales	W, loops/cm	7.98±0.87	7.51±0.19	7.46±0.24
Number of courses	C, loops/cm	7.46±0.83	7.39±0.71	7.42±0.62
Fabric stitch density	S, loops/cm^2	59.67±10.20	55.36±4.55	55.43±6.06
Stitch length in:				
- a single stitch	l_1, mm	6.70±0.05	6.78±0.03	7.06±0.04
- double stitch (2x1 rib)	l_2, mm	5.77±0.05	5.98±0.04	6.04±0.06
- average	l_a, mm	6.00±0.04	6.18±0.03	6.30±0.05
Weight	W_s, g/m^2	368.28±7.97	350.02±8.57	339.22±9.86
Thickness	t, mm	1.43±0.17	1.30±0.16	1.34±0.15



a) b)

Figure 4: Relations between structural characteristics and average stitch length (l_a) of knitted fabrics: a) number of wales (W) and courses (C) per centimeter, as fabric stitch density (S); b) weight (W_s) and thickness (t)

This demonstrates that the number of courses is less affected by changes in the average stitch length under the given knitting conditions. The trends in the relationships between the number of wales (W), the number of courses (C), and the average stitch length (l_a) are reflected in the fabric stitch density (S), as shown in Figure 4a. Fabric stitch density (S) decreases from 59.67 to 55.43 loops/cm², resulting in an overall drop of about 7.1%. This decrease reflects the combined effects of fewer wales (W) and slight changes in the number of courses (C), confirming the formation of a more open fabric structure as stitch length increases.

A clear decreasing trend is observed for fabric weight (W_s), which drops from 368.28 g/m² to 339.22 g/m², corresponding to a reduction of about 7.9% (Fig. 4b). This behavior is attributed to the redistribution of yarn over a larger fabric area as the average stitch length (l_a) increases, leading to a lower fabric density (S).

Fabric thickness (t) decreases from 1.43 mm to 1.34 mm, representing an overall reduction of approximately 6.3% (Fig. 4b). Although thickness initially decreases with increasing the average stitch length (l_a), a slight increase at the highest average stitch length suggests structural rearrangement of loops and increased yarn mobility in the thickness direction.

The percentage changes of the structural characteristics confirm that increasing the average stitch length (l_a) has a pronounced effect on the number of wales per centimeter (W), fabric stitch density (S), and fabric weight (W_s), while the number of courses (C) remains largely unaffected. Average stitch length (l_a), therefore, acts as a dominant structural parameter controlling fabric compactness and mass-related properties in pure flax knitted fabrics.

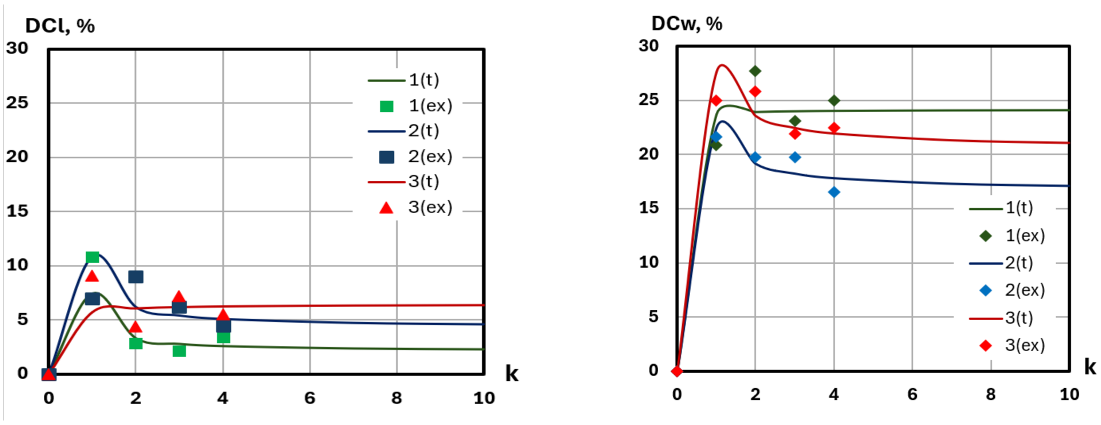
Dimensional change after washing

The lengthwise (DC_l) and widthwise (DC_w) dimensional changes of pure flax knitted fabrics were analyzed after four successive washing cycles (k = 1–4). Experimental data on dimensional changes after washing were used to calculate the theoretical dimensional change (DC_t, %) during washing cycles, using Equation (4), and presented in Table 3. The comparison of the experimental and theoretical dimensional changes after washing is shown in Figure 5.

Table 3

Potential total dimensional change (DC_p), calculated values of (a) and (b) constants for knitted fabrics after washing cycles (k)

Variant of samples	Direction of the dimensional changes in the knitted fabrics			
	Lengthwise		Widthwise	
	DC_{pl}	Dependence	DC_{pw}	Dependence
1	2.11	$DC_l = k/(-0.339 + 0.474\,k)$	24.14	$DC_w = k/(0.001 + 0.041\,k)$
2	4.31	$DC_l = k/(-0.140 + 0.232\,k)$	16.64	$DC_w = k/(-0.016 + 0.060\,k)$
3	6.47	$DC_l = k/(0.019 + 0.155\,k)$	20.51	$DC_w = k/(-0.013 + 0.049\,k)$



a) b)

Figure 5: Experimental and theoretical dimensional changes of investigated fabrics after washing: a) lengthwise (DC_l), b) widthwise (DC_w)

As shown in Figures 5a and 5b, all investigated knitted fabrics exhibit dimensional extensions in both directions (length and width). For all fabric variants, the highest lengthwise dimensional change (DC_l) occurred after the first wash (k = 1), with values of 10.8%, 7.0%, and 9.1% for fabric variants 1, 2, and 3, respectively. This was followed by a significant decrease in subsequent washing cycles, indicating effective relaxation of knitting-induced stresses and improved dimensional stability. Widthwise dimensional changes (DC_w) were consistently larger than lengthwise ones for all variants, ranging from about 16.5% to 27.7% (Fig. 5b). This behavior confirms a pronounced directional dependence of dimensional response. Overall, the results confirm strong anisotropic behavior of the knitted fabrics, with the width direction being more affected by washing-induced dimensional changes. These findings are consistent with previously reported results.[32] Notably, the first washing cycle had the greatest impact on stabilizing the dimensions of the knitted fabrics. Also, the greatest dimensional changes happened after the first two washing cycles. The present findings are in accordance with previously published data.[18,19]

Strength properties

The relationships between the strength characteristics and the average stitch length (l_a) of the knitted fabrics are presented in Figure 6. The results showed linear relationships between the breaking force (F), breaking force elements (F_e), and breaking elongation (ε) and the average stitch length (l_a), with coefficients of determination greater than 0.50. These findings support earlier reports on this topic.[7]

The strength properties of knitted fabrics show clear directional differences. In the length direction, the fabrics have higher breaking forces (F_l) with lower elongations (ε_l), while in the width direction, they have lower breaking forces (F_w), but much higher elongations (ε_w). This reflects the anisotropic nature of knitted structures and the orientation of load-bearing loops. As shown in Figure 6a, increasing the average stitch length (l_a) from 6.00 mm to 6.30 mm (a 4.9% increase) causes a significant drop in breaking force in both directions. Specifically, the lengthwise breaking force (F_l) drops by about 18.5%, and the widthwise breaking force (F_w) falls by roughly 12.5%. These findings confirm that longer stitch lengths result in looser fabric with reduced load capacity in both directions. In addition, the breaking force elements (F_{el} and F_{ew}) decreased by 12.9% and 11.9% in the length and width directions, respectively (Fig. 6b). The lengthwise breaking elongations (ε_l) decreased by 9.9%, while the widthwise elongation (ε_w) dropped by 18.7% (Fig. 6c).

Stretch characteristics

The length changes in the specimens during the 'loading-unloading-resting' cycle for knitted fabrics are shown in Figure 7. Based on the results, using Equations (7)-(10), the full (E), elastic (E_1), delayed (E_2), and residual (E_3) deformations in both directions of loading (length and width) were calculated and presented in Table 4. The relations between the full (E), elastic (E_1), delayed (E_2), and residual (E_3) deformations and the average stitch length (l_a) of the knitted fabrics are presented in Figure 8.

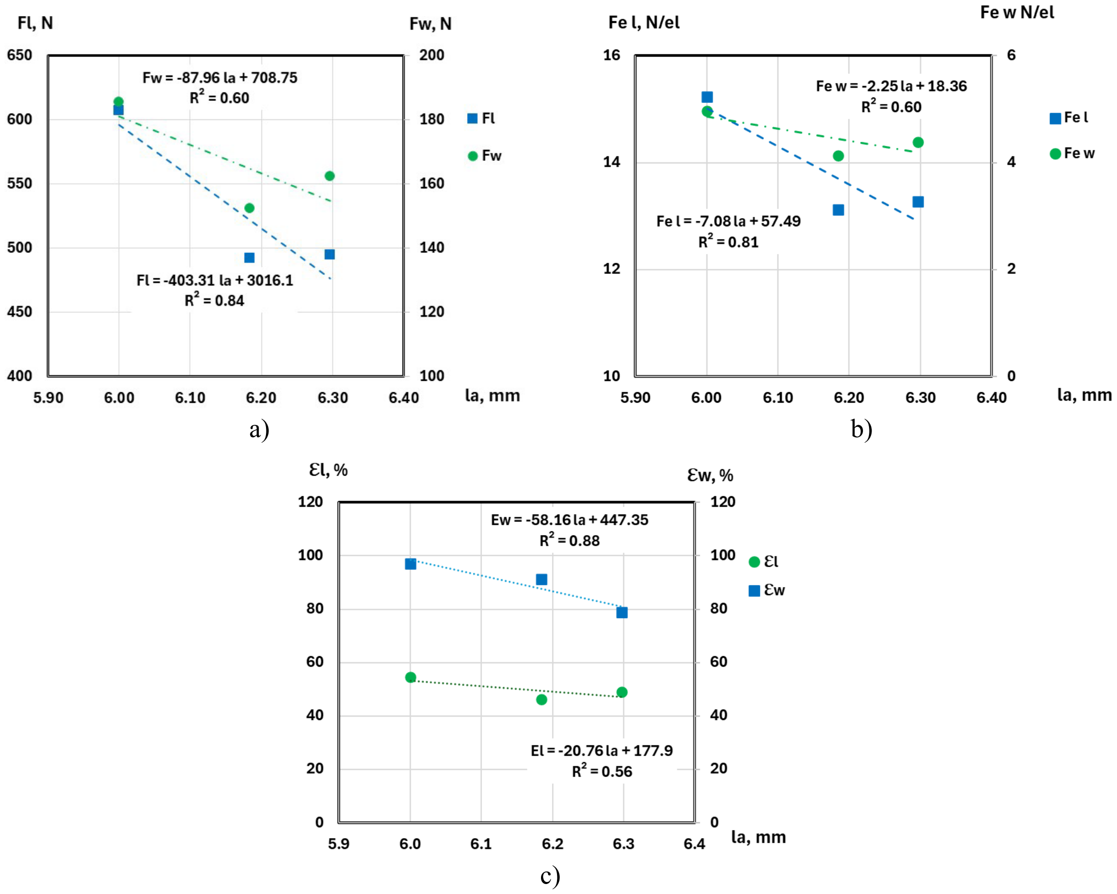
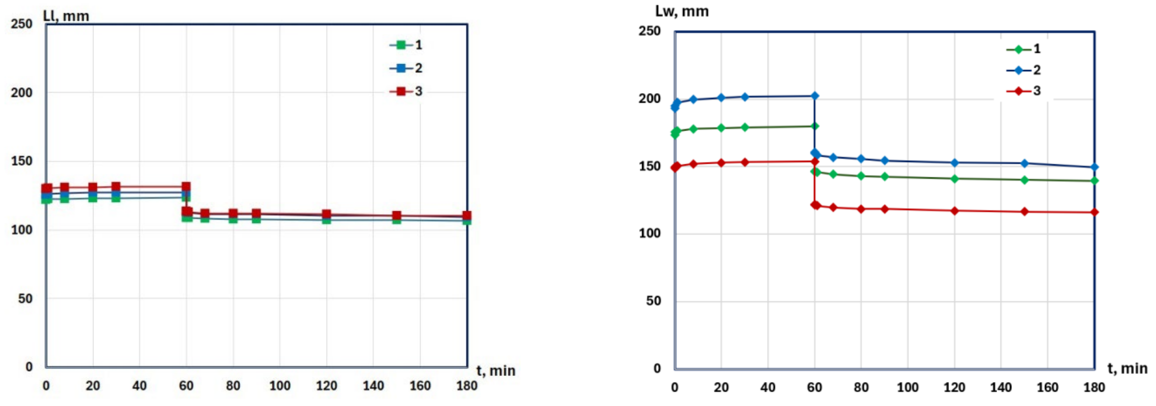


Figure 6: Relations between strength characteristics and average stitch length (l_a) of knitted fabrics:
a) breaking force in the length (F_l) and width (F_w); b) breaking force element in length ($F_{e\,l}$) and width ($F_{e\,w}$);
c) breaking elongations in length (ε_l) and width (ε_w)

The total widthwise deformation (E) is approximately two to four times greater than the lengthwise deformation for all fabric variants (Table 4). This pronounced anisotropy arises from fundamental differences in the deformation mechanisms of knitted fabrics along the two directions. In particular, the width direction allows greater loop opening, rotation, and structural rearrangement under load. This behavior is clearly reflected in the distinct length changes observed during the "loading–unloading–resting" cycles, as illustrated in Figure 7, confirming the fabric's higher deformability in the width direction than in the length direction. The results obtained here reflect trends like those observed in previous research on pure flax knitted fabrics.[7]

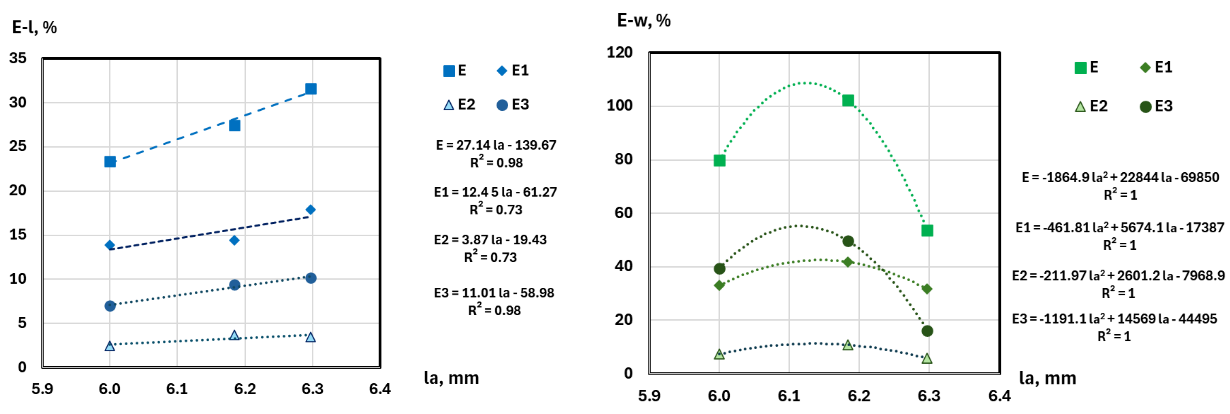
Table 4
Stretch characteristics of pure flax knitted fabrics

Variants of samples	Direction	Type of deformation, %				Contributions		
		E	E_1	E_2	E_3	E_1/E	E_2/E	E_3/E
1	lengthwise	23.4±3.03	13.9±2.08	2.5±0.71	7.0±2.24	0.59	0.11	0.30
	widthwise	79.9±7.59	33.1± 2.04	7.4±1.14	39.4±7.61	0.42	0.09	0.49
2	lengthwise	27.5±3.54	14.4±0.89	3.7±1.14	9.4±2.22	0.52	0.14	0.34
	widthwise	102.3±7.53	41.8±3.49	10.8±4.10	49.7±4.31	0.41	0.11	0.48
3	lengthwise	31.6±3.60	17.9±2.72	3.5±0.94	10.2±2.49	0.57	0.11	0.32
	widthwise	53.7±6.46	31.7±3.27	5.8±0.65	16.2±2.89	0.59	0.11	0.30



a) b)

Figure 7: Length changes in specimens during the 'loading-unloading-resting' cycle for knitted fabrics: a) lengthwise; b) widthwise



a) b)

Figure 8: Relations between full (E), elastic (E_1), delayed (E_2), and residual (E_3) deformations and average stitch length (l_a) of the knitted fabrics: a) in length; b) in width

For all fabric variants, the total lengthwise deformation (E) ranges from 23.4% to 31.6%, increasing progressively with increasing average stitch length (l_a) from variant 1 to variant 3 (Table 4, Figs. 7 and 8). In all cases, the primary contribution originates from elastic deformation (E_1/E), accounting for approximately 52–59% of the total deformation. The contribution of delayed deformation (E_2/E) is comparatively small (11–14%), while that of residual deformation (E_3/E) is a significant secondary component, accounting for 30–34%. This indicates that lengthwise deformation is dominated by the initial elastic response, followed by a notable delayed or recoverable component.

The total widthwise deformation (E) is substantially higher than the total lengthwise deformation for all variants, with total deformation values ranging from 53.7% to 102.3% (Table 4, Figs. 7 and 8). Fabric variants 1 and 2 exhibit particularly high widthwise deformation, exceeding 79% and 100%, respectively. Like the length direction, the contribution of elastic (E_1/E) and residual (E_3/E) deformations dominates the widthwise deformation behavior, together accounting for approximately 80–90% of the total deformation. The contribution of delayed deformation (E_2/E) remains low and relatively constant (around 9–11%) across all fabric variants.

The results confirm pronounced anisotropy in deformation behavior, with widthwise deformation significantly exceeding lengthwise deformation due to loop geometry and greater structural mobility in the transverse direction. The dominance of elastic (E_1/E) and residual (E_3/E) contributions suggests that both immediate elastic deformation and delayed structural rearrangement play key roles in the mechanical response of the knitted fabrics, while the contribution of the delayed deformation (E_2/E) is only marginal.

The results reveal strong linear relationships between the different types of lengthwise deformations and the average stitch length (l_a), with coefficients of determination exceeding 0.70 (Fig. 8a). An increase in stitch length consistently results in higher values for all lengthwise deformation components, indicating a systematic loosening of the fabric structure in this direction. In contrast, the relationship between widthwise deformations and average stitch length is nonlinear (Fig. 8b), reflecting more complex deformation mechanisms involving loop rotation, opening, and structural rearrangement in the width direction.

Non-creasing properties

The coefficient of non-creasing (CR) exhibits a clear dependence on the average stitch length (l_a) and differs between the length (CR_l) and width (CR_w) directions. In both directions, the non-creasing coefficient values show a linear trend with a coefficient of determination greater than 0.50 (Fig. 9).

Increasing the average stitch length (l_a) reduced both fabric weight (W_s) and thickness (t) (Fig. 4b), thereby decreasing the non-creasing coefficient in both directions (CR_l, CR_w), as clearly illustrated in Figure 9. As the average stitch length (l_a) increases from 6.00 mm to 6.30 mm (by 4.9%), the lengthwise non-creasing coefficient (CR_l) decreases by 5.7%, indicating a reduced ability of the fabric to recover from creasing in the length direction. This trend suggests that longer stitch lengths produce fabrics with less weight and thickness, making them more prone to permanent lengthwise creasing. In contrast, the widthwise non-creasing coefficient (CR_w) remains relatively stable, with a total variation of only 3.1% across the investigated average stitch length range (l_a). This stability can be attributed to the higher inherent elasticity and greater loop mobility in the width direction, which promotes more effective crease recovery even as the fabric structure becomes looser.

Overall, these results confirm a pronounced anisotropic crease-recovery behavior, with average stitch length exerting a greater influence on lengthwise non-creasing properties than on widthwise properties.

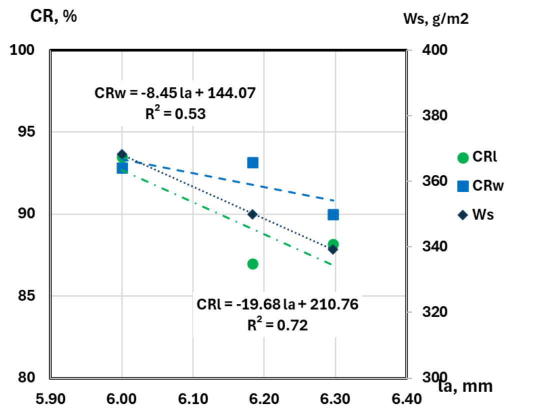


Figure 9: Relation between non-creasing coefficient (CR), fabric weight (W_s), and average stitch length (l_a) of knitted fabrics

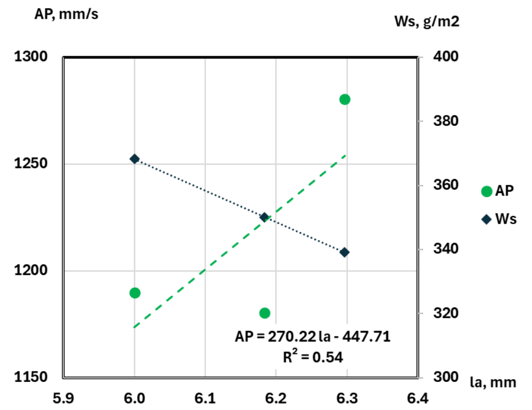


Figure 10: Relation between air permeability (AP), fabric weight (W_s) and average stitch length (l_a) of knitted fabrics

Air permeability

The air permeability (AP) and fabric weight (W_s) of knitted fabrics show a clear dependence on the average stitch length (l_a) and a linear trend (Fig. 10).

Increasing the average stitch length (la) led to reductions in both fabric weight (W_s) and thickness (t) (Fig. 4b), which in turn decreased air permeability (AP), as illustrated in Figure 10. When the average stitch length (l_a) increases from 6.00 mm to 6.30 mm (a 4.9% rise), the air permeability improves by 7.6% (from 1190.0 to 1280.4 mm/s). This confirms that average stitch length is an effective structural parameter. The rise in air permeability reflects a decrease in fabric density and the formation of a more open loop structure with larger inter-yarn spaces, which allows better airflow through the fabric. The influences of average stitch length and fabric density on air permeability have been noted in a previous study.[16] Therefore, adjusting the average stitch length (l_a) can be a practical way to enhance the breathability of knitted fabrics, without altering the raw material or the overall fabric structure.

Main defects during the knitting process of pure flax knitted fabrics

The use of pure flax yarns in knitted fabrics is generally lower than that of flax-containing blended yarns, as reported in previous studies.[11,16] One of the main factors affecting the knitting process is the type of knit stitch employed.[17] Pure flax yarn is primarily used for making fabrics on flat knitting machines. In contrast, its use in circular knitting on circular machines is more challenging due to the yarn's limited flexibility and lower elasticity.[16,7] In this context, the selection of stitch type becomes particularly important. A combination of single and double stitches is more suitable, as it facilitates knitting with pure flax yarn while maintaining fabric quality and dimensional stability.[16]

The knitting process for Swiss double piqué fabrics is strongly influenced by the yarn's physical and mechanical properties, particularly its smoothness, breaking strength, elongation before breaking, and overall flexibility. During knitting and later use, yarns face repeated tensile, bending, and frictional stresses that can cause damage or breakage if the yarn isn't sufficiently elastic or uniformly structured.

Pure flax yarn is known for its high breaking force (880 cN), but also for significant irregularity, with a coefficient of variation (CV) around 25.2%.[16,7] It also has a low breaking elongation of 2.01%, with considerable variability (CV≈17.9%). This combination of high strength and limited, irregular stretchability indicates that the yarn has poor elastic deformability – meaning it can hardly stretch under tension. Compared with blended flax yarns, pure flax yarn exhibits lower elasticity and a reduced ability to withstand dynamic stresses during knitting.

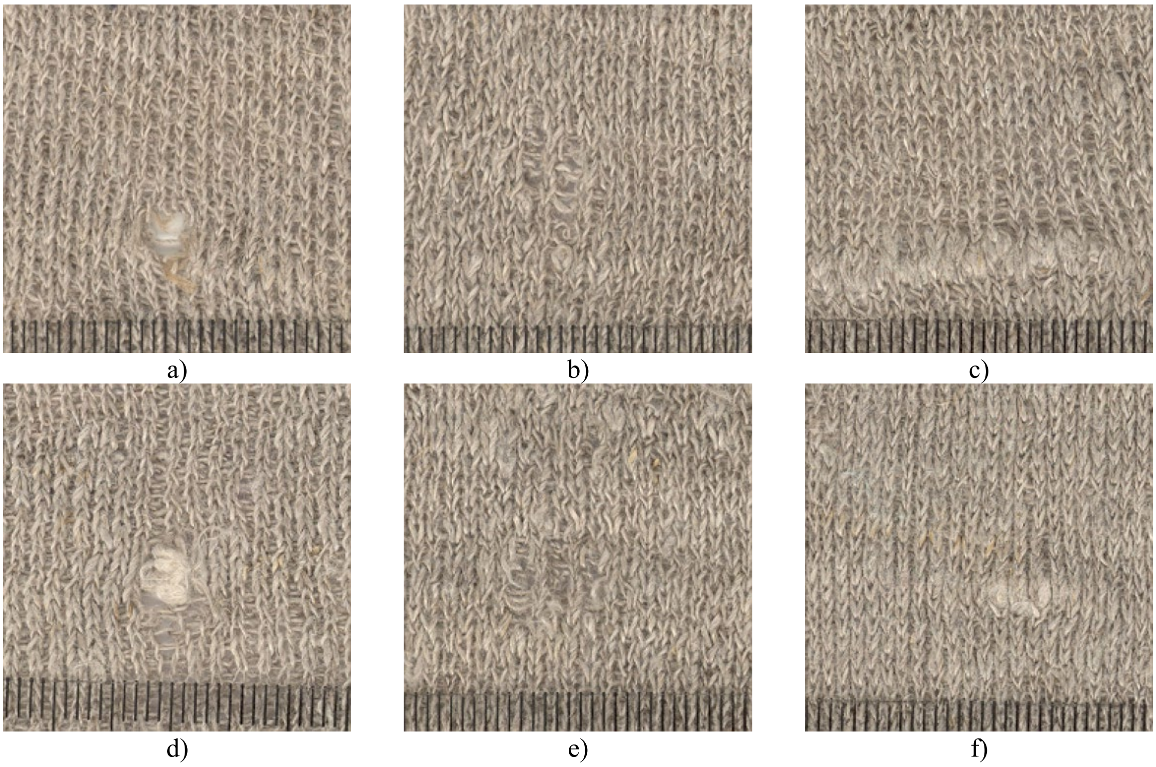


Figure 11: Photos of defects of pure flax knitted fabrics: a) and d) holes in the knitted fabrics, b) and e) dropped knit loops, c) and f) irregular knit loop shapes

The limited and uneven extensibility of pure flax yarn increases the risk of yarn breakage during loop formation, especially in complex structures like the Swiss double piqué stitch. Variations in thickness and stiffness lead to uneven loop formation, unstable loop transfer, and difficulty securing both old and new loops. This results in common problems such as frequent yarn breaks, which result in holes in the knitted fabrics (Fig. 11a and 11d), needle damage, dropped knit loops (Fig. 11b and 11e), and irregular knit loop shapes (Fig. 11c and 11f), which negatively affect fabric appearance and uniformity.

Yarn flexibility is also crucial for successful knitting.[7] Yarns that are more flexible and less stiff adapt better to the repeated bending and tension cycles encountered during knitting. Conversely, the stiffness and inelasticity of pure flax yarn increase friction and stress at the needle hook and sinker, reducing machine efficiency, increasing waste, and lowering productivity.

In summary, the mechanical properties of pure flax yarn – high strength irregularity, low elongation, and limited flexibility – pose significant challenges in knitting and lead to structural defects in the fabric. These drawbacks indicate the need for yarn modifications, blending, or surface treatments to improve processability and fabric quality.

CONCLUSION

The results confirm that average stitch length is a key parameter governing the structural, mechanical, and functional properties of pure flax Swiss double piqué knitted fabrics, produced on a circular knitting machine. Increasing the average stitch length resulted in systematic and predominantly linear structural changes, notably a marked reduction in the number of wales per centimeter, while the number of courses per centimeter remains relatively stable. The corresponding decreases in fabric stitch density reflect the formation of a more open and less compact fabric structure. Structural loosening with increasing average stitch length leads to reduced fabric weight and generally lower thickness, indicating decreased compactness, with minor deviations at the highest average stitch length attributable to loop rearrangement.

Dimensional changes occur in both directions, with the greatest occurring after the first washing cycle, followed by progressive stabilization during subsequent washings. Widthwise dimensional changes are consistently larger than lengthwise changes, confirming pronounced anisotropy and highlighting the importance of initial laundering for dimensional stability.

Mechanical behavior is strongly direction-dependent. Higher breaking forces and lower breaking elongations are observed in the length direction, whereas the width direction exhibits greater extensibility, but lower strength. Increasing the average stitch length significantly reduces breaking force and breaking elongation, as a breaking force element, in both directions, confirming the formation of a mechanically weaker structure.

Deformation behavior is also highly anisotropic, with widthwise deformation exceeding lengthwise deformation by a factor of two to four. Lengthwise deformation increases linearly with stitch length and is dominated by elastic and residual components, whereas widthwise deformation exhibits nonlinear behavior due to complex loop-opening and rotation mechanisms.

Functional performance is significantly influenced by average stitch length and fabric weight. Increased average stitch length reduces fabric weight, resulting in decreased lengthwise crease recovery, but substantially improves air permeability by promoting a more open fabric structure. Although average stitch length adjustment enables effective tailoring of fabric properties, the knitting of Swiss double piqué fabrics from pure flax yarn remains limited by the yarn's low elasticity and strength irregularity. Therefore, improvements in yarn uniformity and extensibility are essential for achieving high-quality flax knitted fabrics.

Overall, the study establishes integrated relationships among average stitch length, fabric structure, repeated-washing behavior, directional mechanical response, deformation recovery, crease resistance, and air permeability. These findings provide a basis for selecting knitting parameters according to the required balance among comfort, durability, material efficiency, and processability. Nevertheless, the circular knitting of pure flax Swiss double piqué fabrics remains challenging because of the yarn's low elasticity and irregular mechanical properties. Improvements in yarn uniformity, flexibility, and extensibility are therefore essential for enhancing knitting efficiency and achieving consistently high-quality fabric.

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