FLAX PLAIN WEFT-KNITTED FABRICS: IMPACT OF PILLING ON STRUCTURE AND ELECTRICAL RESISTIVITY

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The objective of this research is to explore structural characteristics (loop length and stitch density) and electrical resistivity (volume and surface) of plain weft-knitted flax fabrics, both before and after pilling. Pilling in these fabrics was conducted using a Martindale device equipped with two abrasives: the knitted fabric under examination and a wool woven fabric. A decrease in loop length and stitch density of the knitted fabrics after pilling with both abrasives was noted, except for loop length in two lightweight samples. Before pilling, a reducing loop length and increasing other structural characteristics of the fabrics correlated with reduced resistivity. After pilling, all examined samples displayed decreased volume and surface electrical resistivity, except the sample characterized by the highest structural values, which displayed increased surface electrical resistivity after pilling with both abrasives. Fabrics subjected to pilling with the wool woven fabric showcased lower values in both volume and surface electrical resistivity.

Keywords: knitted fabric, plain, flax, pilling, structure, electrical resistivity

INTRODUCTION

As environmental concerns continue to rise, there is an increasing demand for sustainable alternatives to synthetic fibers. To meet this demand, researchers are turning to plant-based natural fibers, which are both eco-friendly and renewable. For this reason, the textile industry has long relied on natural plant fibers, particularly flax.[1] Flax fiber is one such alternative that offers a range of desirable qualities, such as strength, absorbency, UV protection, and optimal electrostatic properties. These properties make it an excellent option for many products.[2,3] However, raw flax fibers have a highly heterogeneous chemical structure, consisting of approximately 70% cellulose and 30% various non-cellulosic substances. To eliminate these non-cellulosic substances, flax fibers undergo various treatments,[2] which alter many properties of flax fibers, including their electrical resistivity. Additionally, the conditions to which flax materials are exposed during exploitation can also lead to changes in their electrostatic properties and thus their electrical resistivity. Therefore, it is important to monitor electrical resistivity to determine whether treatments or usage have increased or decreased it, thereby affecting the comfort of flax materials. Moreover, during the design of flax knitted fabrics, by selecting appropriate structural parameters, it is possible to reduce their electrical resistivity, thereby improving wearing comfort. By embracing the use of flax fiber, the textile industry can make a significant contribution to a sustainable future while still meeting the demand for high-quality products.[3-5]

Investigating the electrical resistance of textile materials, including knitted fabrics, holds significant importance for various reasons. This investigation provides valuable insights into the inherent properties of knitted materials, contributing to a deeper understanding of their characteristics, such as their water absorption behavior. Furthermore, the measurement of electrical resistance is widely utilized to assess the moisture content of knitted materials, both in post-drying processes and laboratory evaluations.[6] It is crucial to say that the electrical resistance of knitted fabric is influenced by fiber and yarn composition, yarn type, yarn fineness, knitted structure, and structural characteristics, the moisture content, electrolyte content, temperature, softening, coating, dyeing, antibacterial finishing, pilling, *etc*.[6-19]

For example, Asanovic and Stankovic[7] observed that knitted fabrics incorporating hemp fibers exhibited lower electrical resistance compared to samples made entirely of cotton. Ivanovska *et al*.[9] found that knitted fabrics with elastane exhibit volume electrical resistivities 23–27% lower than those made of 100% cotton. Additionally, their research revealed that softening processes increase the electrical resistivity of knitted fabrics. Moreover, they discovered that the *in situ* synthesis of Cu-based nanoparticles on the surfaces of knitted fabrics enables the creation of fabrics with resistivities 3.4–9.6 times lower than samples before synthesis of Cu-based nanoparticles. In further investigation, Ivanovska *et al.*[10] observed that differently softened cotton and cotton/elastane knitted fabric wastes, after adsorbing Congo Red, exhibited volume resistivities 169–737 times lower (0.008–0.037 GΩ·cm) than their resistivities before adsorption qualifying that knitted wastes as dissipative materials, which could provide antistatic protection. Asanovic *et al.*[12] observed that polyamide/elastane knitted fabric after coating with gentamicin sulfate or essential oil of *Picea abies* has decreased volume resistivity, which is more pronounced in the case of coating with essential oil of *Picea abies*. Asfand and Daukantiene[15] in their study revealed a decrease in surface and volume resistivity of cotton/antistatic polyester knitted fabrics in 1x1 rib and half Milano rib structures as the percentage of antistatic polyester increased from 10% to 35%. Additionally, the half-Milano rib knitted fabrics exhibited lower resistivity compared to the 1x1 rib knitted fabrics. Moreover, their findings indicated that raw knitted fabrics had lower electrical resistivity than dyed and softened fabrics, as well as those treated with an antibacterial finish using Polygiene VO-600. Analyzing the surface resistance of knitted fabrics varying the presence of conductive yarn (0%, 33%, 66%, and 100%), Lee[16] shown that even with just a 33% incorporation of conductive yarns, the fabrics displayed exceptionally favorable electrical characteristics. Tokarska[18] noted that a fabric sample with a smoother surface exhibited superior electrical current conduction compared to a sample with a rough surface.

Knitted fabrics experience regular interactions with machine components during garment manufacturing, engage with other textiles, and make direct contact with consumers' bodies during use.[19] Static electricity can be generated when knitted fabrics come into contact with non-fibrous or fibrous materials or through friction between them.[20] This presence of static charge on knitted fabrics can result in various undesired outcomes, including heightened dirt accumulation, challenges in cleaning, adherence to other fabrics and the human body, causing discomfort, and an increased tendency for pilling.[19]

Pilling is a fabric surface defect that occurs due to the use and washing of textile materials and represents the phenomenon characterized by the presence of small pills on the fabric surface, which consists of tangled fibers.[21,22] Various factors, such as the yarn spinning process, yarn composition, knit fabric structure, and their structural characteristics, such as the yarn loop length, as well as the finishing process, have a significant impact on the pilling performance.[21,23-34] Hossain *et al*.[30] stated that decreasing the stitch length leads to an increase in the resistance to pilling in weft knitted fabrics. Busilienė *et al*.[31] observed that washing and softening processes deteriorated the pilling resistance of the investigated knitted fabrics. Ivanovska *et al*.[32] concluded that dyed fabrics have a lower pilling propensity than bleached fabrics at the same number of pilling cycles. Ozguney[33] observed that the softener application resulted in a notable reduction in pilling formation on bamboo knitted fabrics, while that multiple washings leds to increased pilling formation.

Pilling, acknowledged as a surface flaw in textile materials, not only diminishes their visual appeal and fabric handle,[3,25,35,36] but also affects various properties including compression, strength, and comfort characteristics.[3] As reported by Asanovic *et al*.,[3] the presence of pilling in knitted fabrics, results in decreased compressibility, thickness loss, air permeability, and water retention (for knitted fabrics with lower mass per unit area), as well as reduced bursting strength and ball traverse elongation. Conversely, it leads to increased compressive resilience and water retention for knitted fabrics with the highest mass per unit area. Moreover, pilling reduced certain structural characteristics, such as the number of wales, number of courses, mass per unit area, and thickness of knitted fabrics, regardless of the type of abrasives used for pilling.[37]

Given the limited information available in the literature concerning the influence of pilling on certain properties of knitted fabrics, particularly their electrophysical properties, there is a clear imperative to explore how pilling affects the electrical resistance of these fabrics. This study holds significant importance since textile materials frequently come into contact with diverse other materials, both textile and non-textile, including human skin, potentially generating static electricity.

We have chosen to investigate flax-knitted materials due to the escalating demand for environmentally friendly and sustainable textile materials, especially those utilizing natural fibers like flax, as well as due to the multifunctional characteristics of knitted fabrics, including flexibility, elasticity, and pliancy.[38] Considering the suitability of flax knitted fabric for warm weather use, we conducted volume resistivity tests at an elevated ambient temperature of 31 °C across varying humidity levels. This choice was prompted by the phenomenon of increased sweat production in the human body at higher temperatures, leading to textile materials absorbing this moisture, and resulting in a decrease in their electrical resistivity. Moreover, existing literature lacks exploration into the impact of different abrasives on both the tendency for pilling and the electrical resistance of knitted fabrics.

This study aims to enhance our comprehension of how pilling impacts on structural characteristics (loop length and stitch density) and electrical resistivity (volume and surface) of plain weft-knitted fabrics made from pure flax yarn. Moreover, we seek to determine the sensitivity of volume versus surface electrical resistivity to these alterations. Understanding these dynamics is crucial for assessing the fabric's appropriateness across various real-world applications. Overall, this research offers valuable insights into how pilling influences some structural and electrical properties of knitted fabrics. Professionals in textile and materials science can leverage these findings to make well-informed decisions regarding the suitability of flax-knitted fabrics for their specific applications.

EXPERIMENTAL

Materials

Three plain weft-knitted fabrics produced from the flax spun yarn, with a fineness of 27×2 tex, were used as experimental material. The flax plain weft-knitted fabrics were selected for investigation because the knitting process of the plain knit structure using pure flax yarn presents fewer issues, compared to the double-knitted structure using the same yarn.[4] All studied fabrics were produced on the flat bed-knitting machine CMS 330.6 (Stoll, Germany), E12 gauge, having 16 yarn carries, 599 needles per needle bed, and one carriage with three knitting systems. The yarn was subjected to a waxing finishing process before the knitting process. During knitting, consistent yarn input tension and fabric take-downs were maintained. The knitting process was employed to determine the optimal levels of these parameters without encountering any issues. Furthermore, the position of the stitching cam on the machine was adjusted. After knitting, the fabrics were dry relaxed, and left to rest on a flat surface under standard atmospheric conditions for several days,[3] and then their structural characteristics were determined (Table 1).

Table 1
Structural characteristics of knitted fabrics

Structural characteristics	Sample 1	Sample 2	Sample 3
Loop length (*L*), mm	7.02±0.04	6.52±0.10	4.94±0.10
Numbers of wales (*W*), cm^{-1}	6.6±0.3	7.0±0.0	8.3±0.3
Numbers of courses (*C*), cm^{-1}	6.8±0.2	7.2±0.4	12.0±0.0
Stitch density (*S*), cm^{-2}	44.5±2.3	50.4±3.0	99.2±3.8
Mass per unit area (*M*), g·m^{-2}	183.0±10.0	189.0±6.0	256.0±4.0
Thickness (*T*), mm	0.713±0.028	0.726±0.029	0.806±0.025

Following dry relaxation, the investigated knitted fabrics underwent pilling assessments utilizing a Martindale device (SDL ATLAS M235 Martindale Abrasion and Pilling Tester). Pilling was induced at 7000 number of rubs (the maximum number of rubs given on the standard ISO 12945-2:2000),[39] employing two types of abrasives: the investigated knitted fabric and wool woven fabric.

Methods

Determination of structural characteristics of knitted fabrics

The loop length (*L*) in mm was determined following the standard EN 14970.[40] The results show an average of ten measurements.

The determination of the number of wales (*W*) and courses (*C*) per centimeter (cm^{-1}) in knitted fabrics was conducted by EN 14971:2006 using Method A.[41] The fabric stitch density (*S*) in loops per cm^2 (cm^{-2}) as calculated according to equation:

$$S = W \cdot C \ (\text{cm}^{-2}) \tag{1}$$

where *W* is the wales per centimeter, and *C* is the courses per centimeter.

To align with the experimental requisites, the fabric's mass per unit area (*M*) was not ascertained using the standard method EN 12127:1997.[42] This deviation was necessary due to the sample dimensions. Rather than the stipulated 100 cm^2 area in the standard, the samples employed possessed a 10 cm^2 area (measuring 2x5 cm). This sizing was crucial for determining volume electrical resistance. For the determination of mass per unit area, the weight (in grams) of a 10 cm^2 sample was measured. Subsequently, the knitted fabric's mass per unit area ($g \cdot m^{-2}$) was calculated. This method enabled the assessment of the samples' mass per unit area both before and after pilling, ensuring uniform conditions for comparison. Consequently, the attained results were consistent and comparable. The results represent the average of five measurements.

The thickness of knitted fabrics (*T*) in mm was measured at a pressure of 9.96 kPa using a thickness tester type 414-10 (AMES, USA). Based on the data gathered, the average of ten measurements is displayed.

Determination of knitted fabric electrical resistivity

Determining electrical resistivity involves assessing both volume and surface resistivity. The volume electrical resistance of the investigated knitted fabrics was evaluated before and after undergoing 7000 rubs to simulate pilling. This assessment was conducted in the knitted fabrics course direction using the voltage method, where direct current flowed through the sample placed between silver-plated electrodes subjected to constant high voltage.[12,19,43] To ensure accuracy, electrodes were positioned within a chamber that maintained controlled measurement conditions. It is crucial to note that the electrical resistance of textile materials is greatly influenced by relative air humidity. As materials absorb water molecules from the environment, they become more conductive. Therefore, the measurement was carried out during both the moisture sorption and desorption stages. The relative air humidity within the chamber was initially raised from 40% to 60% using a humidifier and electromotor with a compression circuit, facilitating air circulation inside the chamber. Once the maximum humidity was attained, the humidifier was removed, gradually reducing the humidity until the initial 40% value was reinstated. Throughout the entire process, two measurements were conducted for each sample, with two specimens of knitted fabric connected to the electrodes during each measurement.

Based on the determined knitted fabric volume electrical resistance (R_x) in GΩ, the volume electrical resistivity of samples (in further text volume resistivity (ρ) in GΩcm) was calculated before and after pilling at 7000 rubs, using equation:[12,43,44]

$$\rho = \frac{R_x \cdot S_F}{l} \ (\text{G}\Omega\text{cm}) \tag{2}$$

where R_x is the volume electrical resistance in GΩ, S_F is the surface of the sample's cross-section in cm^2 calculated by multiplying sample thickness and width, and l is the sample length, *i.e.,* a length between electrodes equal to 1 cm.

Throughout the moisture sorption and subsequent desorption phases from the samples, a portion of the absorbed moisture remains within the material. This retention significantly impacts the resistivity values and results in the presence of hysteresis, as depicted in Figure 1. As previously noted, the resistivity of textile materials is notably affected by both ambient air humidity and the moisture content present in the textile itself. By analyzing the ratio between the area enclosed by the hysteresis loop and the area below the sorption curve, the quantity of moisture retained in the sample after the moisture desorption from the knitted fabrics was determined.[44]

According to the standard EN 1149-1:2006,[45] the surface electrical resistivity (in further text surface resistivity (ρ_A) in TΩ) was determined for samples before and after pilling at 7000 rubs. The samples were conditioned for 24 hours at a temperature of 23 °C and relative air humidity (in further text humidity (φ) in %) of 25%. The surface resistivity on the conditioned samples was determined using an electrostatic properties tester (Mirta-Kontrol Testing Equipment). The results represent the average of three measurements.

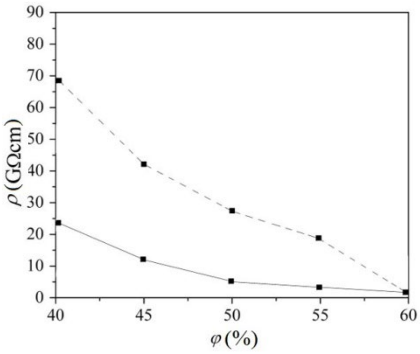

Figure 1: Hysteresis of the textile materials volume resistivity (ρ) as a function of humidity (φ);
(- - - sorption curve; — desorption curve)

Statistical analysis

The results underwent statistical analysis utilizing the *t*-test. The parameter *t* for independent samples was determined using Equation 3, whereas for dependent samples, it was calculated through Equation 4:[3,46]

$$t = \frac{\overline{x}_1 - \overline{x}_2}{\sqrt{\frac{\sigma_1^2(n_1 - 1) + \sigma_2^2(n_2 - 1)}{n_1 + n_2 - 2} \cdot \frac{n_1 + n_2}{n_1 \cdot n_2}}} \quad (3)$$

$$t = \frac{\overline{d}}{\frac{\sigma_d}{\sqrt{n}}} \quad (4)$$

where $\overline{x}_1$ and $\overline{x}_2$ are the samples' mean values of the determined characteristic, σ_1 and σ_2 are the samples' standard deviation of the determined characteristic, n_1 and n_2 are the corresponding sample sizes (n_1=n_2), $\overline{d}$ is the sample mean value of the differences of the determined characteristic before and after pilling, σ_d is the sample standard deviation of the differences, while *n* is the sample size (*n*=10).

The correlation coefficient (*r*) measures the strength of the linear connection between two variables – specifically, between loop length and other structural characteristics, as well as between electrical resistivity and a particular structural characteristic. Its calculation was determined using the following equation:[47]

$$r = \frac{\sum x \cdot y - n \cdot \overline{x} \cdot \overline{y}}{(n-1)\sigma_x \cdot \sigma_y} \quad (5)$$

where *x* is loop length, volume or surface electrical resistivity, *y* is some structural characteristic, $\overline{x}$ is the mean value of loop length, volume or surface electrical resistivity of sample's, $\overline{y}$ is mean value of some structural characteristic of sample's, σ_x and σ_y are corresponding standard deviation, and *n* is the number of data pairs (*n*=3).

The significance of the correlation was assessed using the equation:[47]

$$t = \frac{r \cdot \sqrt{n-2}}{\sqrt{1-r^2}} \quad (6)$$

where *r* is the correlation coefficient, *n* is the number of data pairs.

RESULTS AND DISCUSSION

Structural characteristics of knitted fabrics before and after pilling

This section aims to investigate the influence of pilling on the structural characteristics of the knitted fabrics, including parameters such as the loop length (*L*), and stitch density (*S*). Our study focuses on comparing these two fabric characteristics before and after pilling at 7000 rubs (when the highest damage to knitted fabrics was observed) to comprehend the impact of pilling on these two fabric's properties. The experimental findings detailing the two structural characteristics of the analyzed knitted fabrics both before and after pilling at 7000 rubs are presented in Figure 2.

According to our investigation and the results presented in the literature,[37] the loop length (*L*) greatly influences the structural characteristics of flax knitted fabrics. The loop length (*L*) has a linear relationship with the number of wales (*W*), the number of courses (*C*), stitch density (*S*), mass per unit area (*M*), and thickness (*T*) of the knitted fabrics, as shown in Table 2. Previous research papers[4,5] also discussed the effects of loop length on the structural characteristics of knitted fabrics. The study emphasizes the importance of loop length (*L*) in determining the structural characteristics of flax-knitted fabrics.

The data in Figure 2 (a) indicate a consistent decrease in loop length across Samples 1 to 3, before and after both pilling conditions, within knitted fabrics. This decrease is attributed to adjustments in the cam setting during the knitting manufacturing process. The most notable differences between Samples 1 and 3 were observed after pilling caused by the investigated knitted fabric (36.2%), while the lowest before pilling (29.63%). Statistically significant differences in loop length among the samples, before and after pilling, were confirmed through a *t*-test (Table 3), with a consistent significance level of 0.001. Pilling had divergent effects: Samples 1 and 2 showed an increase in loop length, while Sample 3 experienced a decrease (as illustrated in Figure 2 (a)). Interestingly, only Samples 2 and 3 exhibited no statistically significant changes in loop length following pilling caused by the wool woven fabric, as indicated in Table 3. The reduction in loop length from Sample 1 to Sample 3 corresponded with an increase in stitch density (Fig. 2(b)). This trend was consistent before and after pilling. The statistical analysis in Table 3 revealed a significant difference among the investigated samples, irrespective of the stitch density, and pilling, maintaining a significance level of 0.001. After pilling, a decrease in the stitch density was observed following pilling caused by both the investigated knitted fabric and the wool woven fabric (as displayed in Fig. 2(b)). This decrease was statistically significant for all the samples after both types of pilling (Table 3).

Volume and surface electrical resistivity of knitted fabrics before and after pilling

The findings regarding the volume resistivity of the studied knitted fabrics, assessed in the course direction, and the surface resistivity both before and after pilling (utilizing both the investigated knitted fabric and wool woven fabric as abrasives), are depicted in Figure 3. The volume resistivity values of the investigated knitted fabrics were established under moisture desorption conditions, at a humidity of 40%.

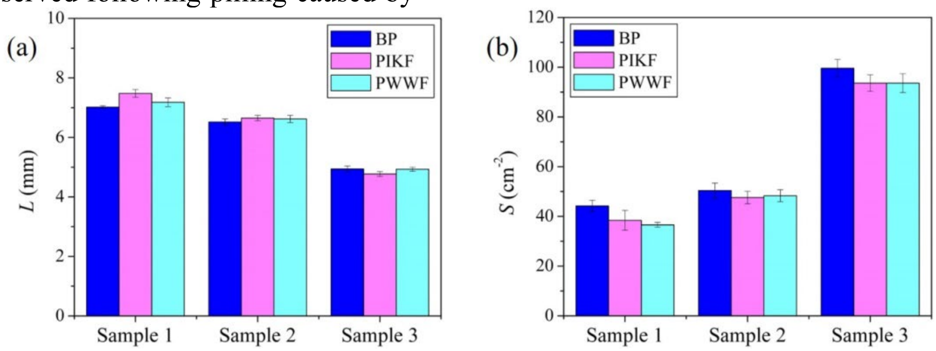

Figure 2: Structural characteristics of knitted fabrics before and after pilling: (a) loop length (*L*), (b) stitch density (*S*); (BP – before pilling; PIKF – pilling caused by the investigated knitted fabric; PWWF – pilling caused by the wool woven fabric)

Table 2
Dependences of structural characteristics and loop length (*L*) of knitted fabrics before and after pilling at 7000 rubs

Structural characteristics	Before pilling (BP)	Pilling caused by the investigated knitted fabric (PIKF)	Pilling caused by the wool woven fabric (PWWF)
Numbers of wales (*W*)	$W = -0.82L + 12.34$ (-0.9999)*	$W = -0.66L + 11.16$ (-0.9996)*	$W = -0.83L + 12.17$ (-0.9749)/
Numbers of courses (*C*)	$C = -2.67L + 25.06$ (-0.9892)/	$C = -2.11L + 21.59$ (-0.9858)/	$C = -2.56L + 24.23$ (-0.9959)/
Stitch density (*S*)	$S = -27.72L + 235.50$ (-0.9916)/	$S = -21.07L + 192.60$ (-0.9892)/	$S = -25.67L + 219.80$ (-0.9990)*
Mass per unit area (*M*)	$M = -36.86L + 436.39$ (-0.9875)/	$M = -32.00L + 393.29$ (-0.9961)/	$M = -36.23L + 415.84$ (-0.9998)*
Thickness (*T*)	$T = -0.05L + 1.03$ (-0.9947)/	$T = -0.06L + 1.07$ (-0.9914)/	$T = -0.06L + 1.07$ (-0.9966)/

(*r*)* – Coefficient of linear correlation – the correlation is statistically significant at 0.05 level of significance, (*r*)/ – Coefficient of linear correlation – the correlation is not statistically significant

Table 3
Statistical results of the determination of knitted fabric loop length and stitch density before and after pilling at 7000 rubs and the influence of pilling on the knitted fabric structural characteristics using a *t*-test

Tested parameter	Values of parameter *t* between two different samples, before and after pilling ($df=n_1+n_2-2=18$)								
	Before pilling			Pilling caused by the investigated knitted fabric			Pilling caused by the wool woven fabric		
	$t_{1/2}$	$t_{1/3}$	$t_{2/3}$	$t_{1/2}$	$t_{1/3}$	$t_{2/3}$	$t_{1/2}$	$t_{1/3}$	$t_{2/3}$
Loop length (*L*)	14.68 (***)	61.07 (***)	35.33 (***)	16.60 (***)	56.14 (***)	49.37 (***)	9.22 (***)	42.98 (***)	38.47 (***)
Stitch density (*S*)	-5.00 (***)	-38.84 (***)	-31.89 (***)	-6.55 (***)	-35.57 (***)	-35.32 (***)	-14.48 (***)	-46.05 (***)	-32.05 (***)

Tested parameter	Values of parameter *t* regarding the influence of pilling on the knitted fabric structural characteristics ($df=n-1=9$)					
	Pilling caused by the investigated knitted fabric			Pilling caused by the wool woven fabric		
	$t_{1BP/1PIKF}$	$t_{2BP/2PIKF}$	$t_{3BP/3PIKF}$	$t_{1BP/1PWWF}$	$t_{2BP/2PWWF}$	$t_{3BP/3PWWF}$
Loop length (*L*)	-10.19 (***)	-3.40 (**)	5.69 (***)	-3.02 (*)	-1.77 (/)	0.14 (/)
Stitch density (*S*)	3.82 (**)	2.59 (*)	4.13 (**)	10.04 (***)	2.33 (*)	4.43 (**)

BP – before pilling, PIKF – pilling caused by the investigated knitted fabric, PWWF – pilling caused by the wool woven fabric, (*) 0.05 level of significance, (**) 0.01 level of significance, (***) 0.001 level of significance, (/) – no statistically significant difference, df – degrees of freedom, n – sample size

These electrical resistivity measurements were conducted on samples after pilling of knitted fabrics with both abrasives induced at 7000 rubs. The reduction in loop length from Sample 1 to Sample 3 corresponded with an increase in stitch density (Fig. 2(b)). The investigation reveals a significant influence of the structural characteristics of knitted fabrics on both volume and surface resistivity, observed before and after pilling (as shown in Figs. 2 and 3 and Table 1). The histograms in Figure 3 depict a consistent decrease in both resistivity types from Sample 1 to Sample 3. Sample 1, characterized by the highest loop length and the lowest other structural characteristics values (Table 1) displays the highest volume resistivity (Fig. 3(a)) and surface resistivity (Fig. 3(b)). In contrast, Sample 3, with the lowest loop length and highest values in all other structural characteristics, demonstrates the lowest resistivity values. As loop length decreases and other structural characteristics of the knitted fabrics increase, the knitted fabric samples become more compact. This enhanced compactness facilitates the flow of charge through the samples, resulting in decreased resistivity.

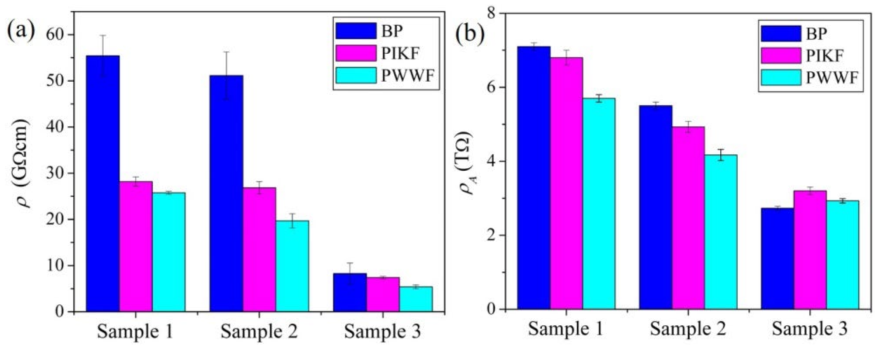

Figure 3: Electrical resistivities of knitted fabrics before and after pilling: (a) volume resistivity (ρ), (b) surface resistivity (ρ_A); (BP – before pilling; PIKF – pilling caused by the investigated knitted fabric; PWWF – pilling caused by the wool woven fabric)

Table 4
Differences in volume and surface resistivity between the investigated knitted fabrics

Investigated resistivity	Resistivity$_{(Sample1)}$/ Resistivity$_{(Sample 2)}$	Resistivity$_{(Sample1)}$/ Resistivity$_{(Sample 3)}$	Resistivity$_{(Sample2)}$/ Resistivity$_{(Sample 3)}$
Before pilling			
Volume (ρ)	1.08	6.71	6.19
Surface (ρ_A)	1.29	2.60	2.01
After pilling with the investigated knitted fabric			
Volume (ρ)	1.05	3.81	3.63
Surface (ρ_A)	1.34	2.12	1.54
After pilling with the wool woven fabric			
Volume (ρ)	1.31	5.14	3.65
Surface (ρ_A)	1.37	1.95	1.42

Notably, the differences in resistivity between samples, particularly between Sample 1 and Sample 3, are more pronounced in volume resistivity compared to surface resistivity, before and after pilling (refer to Table 4). These findings indicate that alterations in the structural characteristics of knitted fabrics have a more substantial impact on volume resistivity than on surface resistivity.

Pilling induces alterations in both investigated resistivity values across all observed samples, as depicted in Figure 3. A consistent decrease in volume resistivity for all samples (Fig. 3(a)) and a reduction in surface resistivity for Samples 1 and 2 (Fig. 3(b)) were observed after pilling with both the investigated knitted fabric and the wool woven fabric. However, Sample 3 exhibited an increase in surface resistivity after pilling (Fig. 3(b)), regardless of the fabric used for pilling. The most substantial decrease in volume resistivity after pilling with the investigated knitted fabric (approximately 50%) was evident in Sample 1, which possessed the highest loop length and the lowest stitch density (Fig. 2). Similarly, after pilling with the wool woven fabric, Sample 2 displayed the greatest reduction in volume resistivity (about 62%). Conversely, Sample 3 showed the smallest decrease in volume resistivity after pilling with both the investigated knitted fabric (around 10%) and the wool woven fabric (approximately 35%). Regarding surface resistivity, the highest reduction was observed in Sample 2 after pilling with the wool woven fabric (about 24%), while the least reduction was noted in Sample 1 after pilling with the investigated knitted fabric (approximately 4%).

The decrease in electrical resistivities of knitted fabrics following pilling presents an unexpected outcome. Pilling leads to increased loop length for Samples 1 and 2, accompanied by a decrease in the stitch density (as depicted in Fig. 2). Logically, these alterations should result in increased resistivity for the samples. However, during the pilling process, pills emerge on the fabric's surface along with an uptick in surface fuzzing. The augmented surface fuzzing of knitted fabrics after pilling potentially contributes to the unexpected decrease in their resistivity. This fuzz, visibly present on the fabric surface after pilling (as illustrated in Fig. 4 (b) and (c)), covers a substantial portion of the fabric's surface and fills the spaces between the loops. Consequently, this phenomenon aids in facilitating the easier flow of directional movement of charge through the sample, thereby leading to a decrease in resistivity.[14] Conversely, the rise in surface resistivity of Sample 3 after pilling can be attributed to its notably high stitch density, which complicates the removal of formed pills from the fabric's surface. Considering that surface resistivity measurement primarily involves current flow on the sample surface, the higher pill presence, coupled with reduced surface fuzzing in Sample 3 compared to the other samples (as evident in Fig. 4 (b) and (c)), results in retained charges on its surface. This circumstance contributes to an increase in Sample 3's surface resistivity.

Furthermore, after pilling, the resistivity values of the knitted fabrics are lower when pilling was caused with the wool woven fabric in contrast to pilling with the investigated knitted fabrics (as depicted in Fig. 3). The reason for the differences in the resistivities of the knitted fabrics after pilling with two different abrasives should be searched in the changes in the knitted fabrics induced by pilling. The surface appearance of the investigated knitted fabrics after pilling at 7000 rubs with the investigated knitted fabric (as shown in Fig. 4(b)) highlights a more pronounced presence of pills of varied sizes and densities on the specimen surface in comparison to pilling with the wool woven fabric (as shown in Fig. 4(c)).

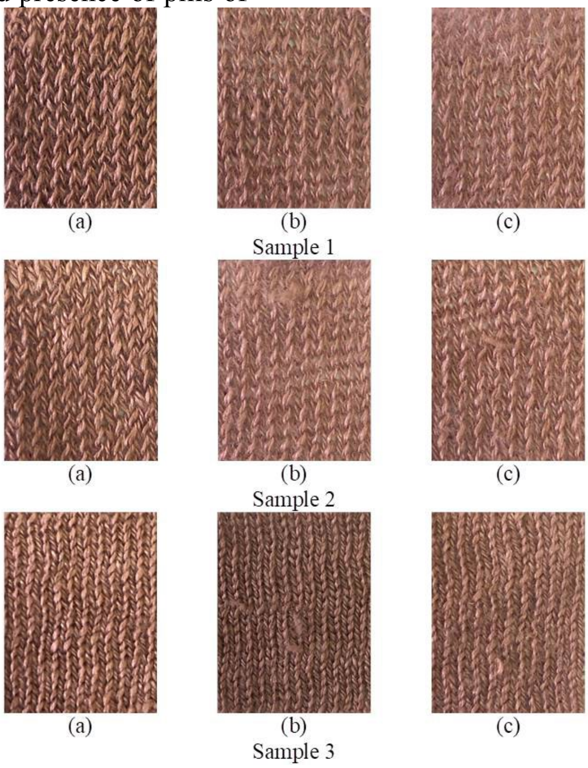

Figure 4: Surface appearance of plain knitted fabrics at 5× magnification: (a) before pilling; (b) after pilling with the investigated knitted fabric (7000 rubs); (c) after pilling with the wool woven fabric (7000 rubs)

This observation likely contributes to charge accumulation on the samples, impeding their movement through the fabric, and ultimately resulting in higher resistivity values. The regression analysis conducted for both electrical resistivities before pilling and after pilling samples is displayed in Table 5.

Before pilling, the regression analysis indicates an almost linear relationship between volume resistivity and the number of courses, mass per unit area, and thickness of the knitted fabrics (-0.9998, -0.9999, -0.9989, respectively), exhibiting statistical significance at a 0.05 level.

However, despite the high values of the coefficient of linear correlation between surface resistivity and loop length, stitch density, mass per unit area, and thickness of the knitted fabrics (0.9896, -0.96671, -0.9565, -0.9712, respectively), the correlation lacks statistical significance.The stronger alignment between volume resistivity and the analyzed structural characteristics in comparison to surface resistivity confirms that alterations in the structural properties of knitted fabrics exert a more significant influence on volume resistivity than on surface resistivity (refer to Table 5).

As previously noted, surface resistivity measurements primarily involve current flow on the sample surface, while volume resistivity measurements entail current flow through the sample without flowing over the surface of the sample. Consequently, surface irregularities present in the samples before pilling have a more pronounced impact on surface resistivity compared to volume resistivity.

The regression analysis results show that the coefficients of linear correlation between electrical resistivities and the structural characteristics of knitted fabrics decrease after pilling in comparison to the values observed before pilling. These findings suggest that the changes induced by pilling play a significant role in determining resistivity after the process, particularly concerning surface resistivity.

Table 5
Coefficient of linear correlation between electrical resistivities and structural characteristics of knitted fabrics before and after pilling at 7000 rubs

Variables	Volume resistivity	Surface resistivity
	Before pilling	
Loop length (*L*)	0.9885(/)	0.9896(/)
Number of courses (*C*)	-0.9998(*)	/
Stitch density (*S*)	/	-0.9667(/)
Mass per unit area (*M*)	-0.9999(*)	-0.9565(/)
Thickness (*T*)	-0.9989(*)	-0.9712(/)
	After pilling with the investigated knitted fabric	
Loop length (*L*)	0.9253(/)	0.9702(/)
Number of courses (*C*)	-0.9968(/)	/
Stitch density (*S*)	/	-0.9245(/)
Mass per unit area (*M*)	-0.9877(/)	-0.9456(/)
Thickness (*T*)	-0.9935(/)	-0.9309(/)
	After pilling with the wool woven fabric	
Loop length (*L*)	0.9998(*)	0.9411(/)
Number of courses (*C*)	-0.9920(/)	/
Stitch density (*S*)	/	-0.9251(/)
Mass per unit area (*M*)	-0.9995(*)	-0.9487(/)
Thickness (*T*)	-0.9908(/)	-0.9110(/)

(*) – the correlation is statistically significant at 0.05 level of significance, (/) – the correlation is not statistically significant

Influence of humidity on the knitted fabrics' volume resistivity before and after pilling

The measurement of the volume resistance of textile materials can be realized both when the humidity increases (during moisture sorption) and when the humidity decreases (during the moisture desorption from the samples). Figure 5 shows the effect of the humidity decreasing from 60% down to 40% on the knitted fabric volume resistivity determined in the course direction, before pilling (Fig. 5(a)), after pilling with the investigated knitted fabric (Fig. 5(b)), and after pilling with the wool woven fabric (Fig. 5(c)).

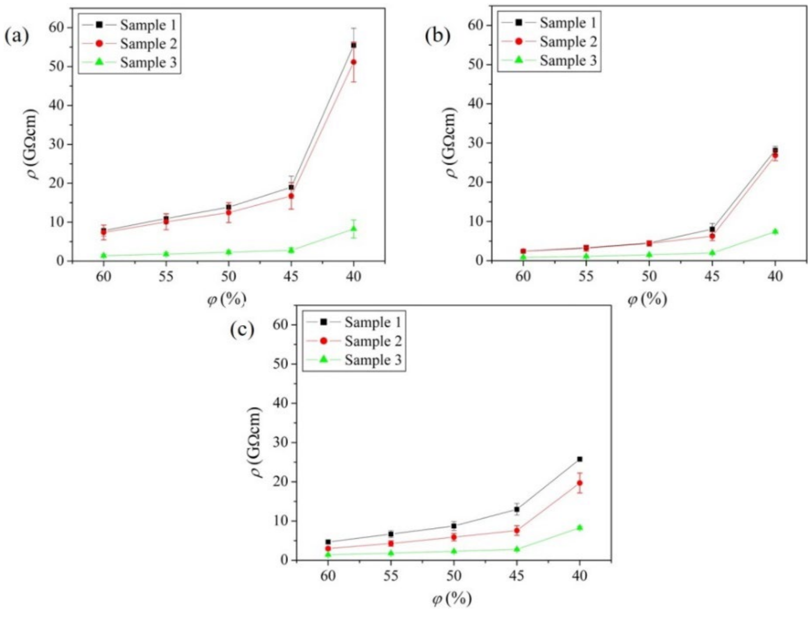

Figure 5: Influence of humidity (φ) on knitted fabrics' volume resistivity (ρ): (a) before pilling; (b) after pilling with the investigated knitted fabric (7000 rubs); (c) after pilling with the wool woven fabric (7000 rubs)

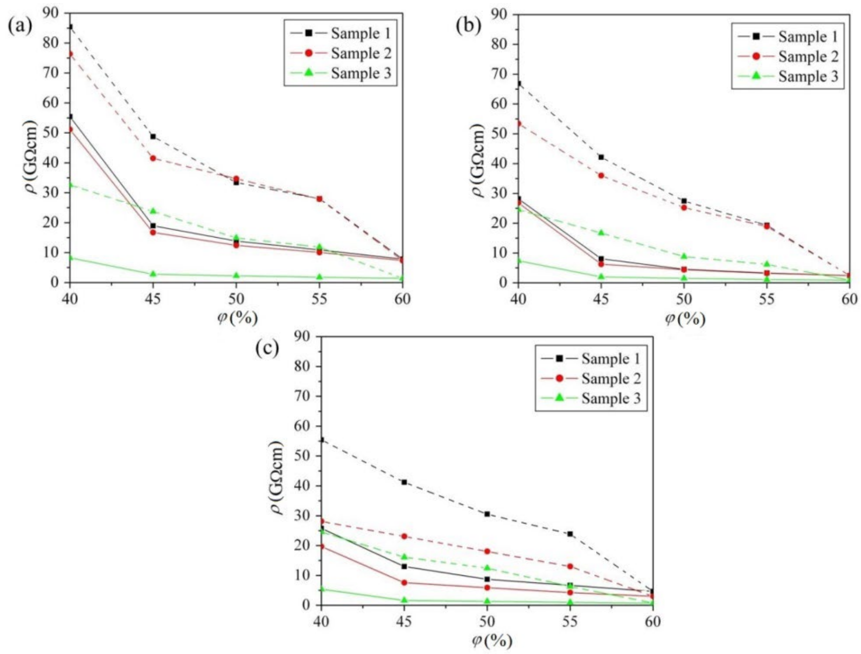

Figure 6: Hysteresis of knitted fabrics' volume resistivity (ρ) as a function of humidity (φ): (a) before pilling; (b) after pilling with the investigated knitted fabric (7000 rubs); (c) after pilling with the wool woven fabric (7000 rubs); (- - - sorption curve; — desorption curve)

Table 6
Sorbed moisture retained in knitted fabric samples during moisture desorption

Sample	Sorbed moisture retained in the sample, %		
	Before pilling	After pilling with the investigated knitted fabric	After pilling with the wool woven fabric
Sample 1	66.0	80.6	77.1
Sample 2	67.0	79.3	71.4
Sample 3	88.4	87.0	88.8

A decrease in humidity caused an increase in the volume resistivity across all tested samples, evident both before pilling (Fig. 5(a)) and after pilling (Fig. 5(b) and (c)). These findings align with previous literature.[8,12,14,19,44,48-51] At higher humidity, the fibers absorb more moisture,[8] wherein water ions neutralize surface charges on textile materials,[48,49] thereby enhancing electrical conductivity, while reducing resistivity in the tested samples.

During the humidity decreasing from 60% to 40%, Samples 1 and 2 exhibited the most significant increase in volume resistivity before pilling. This outcome might be linked to their higher loop length and lower number of courses, influencing moisture interaction with flax fiber hydroxyl groups and with surface adsorption. It can be assumed that during moisture sorption, a higher amount of moisture was adsorbed on the surface of Samples 1 and 2, considering their low stitch density. Therefore, during the decreasing of humidity, it was easier to remove a higher amount of moisture adsorbed on the surface of the samples, which led to a significant increase in the resistivity of those two samples.

Conversely, after pilling, the formation of fuzz and pills on the knitted fabric surfaces (Fig. 4(b) and (c)) probably contributed to difficulties in water molecule desorption. This resulted in prolonged moisture retention within the material, leading to higher quantities being held for a longer duration.

This phenomenon could be the additional reason for decreasing the volume resistivity of all samples after pilling. To confirm such an assumption, from the ratio between the surface within the hysteresis loop and the surface below the sorption curve (Fig. 6), the portion of sorbed moisture retained in the sample after moisture desorption from the knitted fabrics was determined, and the obtained results are shown in Table 6.

The data in Table 6 reveal that Sample 3 maintains similar moisture content regardless of whether pilling is applied or not. In contrast, Samples 1 and 2 exhibit notably higher moisture content after pilling. This increased moisture presence after pilling contributes to their lower volume resistivity, as evidenced by the findings depicted in Figures 3(a), 5 and 6.

CONCLUSION

This study presents significant findings on structural characteristics and electrical resistivity of plain single jersey knitted fabrics made from pure flax yarn. The research focuses on the loop length and stitch density and volume and surface electrical resistivity of these fabrics before and after pilling, which was evaluated using a Martindale device equipped with two abrasives: the knitted fabric under examination and a wool woven fabric. Based on the analysis of the research results, the following conclusions can be drawn.

The abrasion-induced pilling resulted in a decrease loop length and stitch density, except for loop length in two lightweight samples. Similarly, pilling generated by the investigated knitted fabric caused significant alterations in loop length and stitch density for all samples. However, pilling caused by the wool woven fabric did not yield statistically significant changes in loop length for Samples 2 and 3.

The investigation results indicate a correlation between the structural characteristics (loop length, number of courses, stitch density, mass per unit area, and thickness) of knitted fabrics and the volume resistivity at 40% humidity and surface resistivity at 25% humidity, both before pilling and after pilling at 7000 rubs.

Following pilling with both abrasives, a decrease in volume resistivity was noted compared to before pilling levels. Surface resistivity decreased after pilling for knitted fabrics, except in the most compact sample, where an increase was observed regardless of the fabric used for pilling generation. After pilling, resistivity values were higher when pilling was induced with the investigated knitted fabric than with wool woven fabric. Notably, Sample 2 experienced the most significant decrease in volume resistivity (~62%) and surface resistivity (~24%) after pilling with the wool woven fabric.

Changes in the structural characteristics were observed to exert a more pronounced impact on the volume resistivity compared to the surface resistivity of knitted fabrics. Before pilling, a significant correlation existed between volume resistivity and relevant structural characteristics, whereas such a correlation was absent for surface resistivity and structural characteristics. Correlation analyses confirmed that irregularities existing on the fabric surface before pilling had a greater effect on surface resistivity than on volume resistivity. However, the decrease in the coefficients of linear correlation between electrical resistivities and the structural characteristics of knitted fabrics after pilling compared to values before pilling suggests that changes caused by pilling play a dominant role in determining resistivity after pilling.

Apart from structural characteristics, the abrasion process, and the abrasive type, humidity also played a role on the volume resistivity of knitted fabrics. As humidity decreased from 60% to 40%, there was a consistent increase in volume resistivity across all investigated samples, both before pilling and after pilling at 7000 rubs. The most notable increase in volume resistivity due to decreasing humidity was observed in two lightweight samples before pilling. Furthermore, analyzing the hysteresis of volume resistivity revealed that the samples retained more moisture after pilling compared to their before pilling. This moisture retention likely contributed to the decreased volume resistivity of knitted fabrics following the pilling process.

Assessing fabric suitability for diverse uses is crucial. This research offers significant insights into how pilling affects both loop length and stitch density, as well as electrical properties of flax-based knitted fabrics. Professionals in textile and materials science can leverage these findings to make informed decisions regarding the suitability of flax-knitted fabrics for particular applications.

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