

INFLUENCE OF WASHING ON COMFORT PROPERTIES OF WOVEN FABRICS INTENDED FOR REUSABLE PROTECTIVE CLOTHING FOR MEDICAL PERSONNEL

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In this work, the influence of washing on the comfort properties of woven fabrics intended for reusable protective clothing used by medical personnel was investigated. More specifically, three different woven fabrics based on cotton in twill 3/1 weave, cotton/polyester blend in twill 2/1 weave, and cotton/polyester blend in twill 3/1 weave were investigated. Their comfort properties (air permeability, water vapor transmission rate, volume electrical resistivity, compressibility, and compressive resilience) were monitored before and after 60 washing cycles. To better understand the changes in their comfort properties caused by washing, their structural characteristics (number of threads per unit length, warp and weft crimp, mass per unit area, and thickness) and electrokinetic (zeta potential) properties were also evaluated before and after 60 washing cycles. All investigated woven fabrics showed decreased air permeability and water vapor transmission rate, as well as increased volume electrical resistivity after 60 washing cycles. Woven fabric based on cotton in a twill 3/1 weave showed reduced compressibility and increased compressive resilience after 60 washing cycles. In contrast, woven fabrics based on cotton/polyester blend in twill 2/1 and 3/1 weave showed increased compressibility and decreased compressive resilience after 60 washing cycles.

Keywords: medical protective clothing, reusable, washing, comfort properties, structural characteristics

INTRODUCTION

The rapid development of medicine and the pursuit of health protection for patients and medical personnel have led to medical textiles becoming a rapidly growing part of the textile industry in the last ten years.¹ Medical textiles have been widely used in the production of protective clothing for medical personnel (PCMP), including footwear covers, masks, scrub caps, medical uniforms, and gowns, the main role of which was to reduce the risks of exposure to hazardous substances, including body fluids, and to minimize the risk of cross-infections.²

Recently, along with the increase in environmental problems caused by medical waste, an increased use of disposable PCMP has been observed compared to reusable PCMP. Reusable PCMP typically consists of tightly woven fabrics

with a plain weave structure based on cotton, polyester, or a polyester/cotton blend. They are washed after each application and are most often used for more than 50 washing and drying cycles. Disposable PCMP typically consists of nonwoven fabrics based on polypropylene, polyester, or polyethylene. Although disposable PCMPs are often considered to have protective advantages over reusable PCMPs, they must be immediately discarded as bio-hazardous materials. There are undoubtedly significant differences between reusable and disposable PCMP in terms of structure, maintenance, and protection. However, given the increase in environmental problems caused by medical waste, the differences between reusable and disposable PCMP that are currently

attracting the most attention for consideration are those related to their environmental impact.^{3,4}

After use, all PCMPs are discarded using standard infection control measures. PCMP waste is usually labeled as infectious (contaminated with body fluids), offensive (contaminated but not infectious), or municipal (similar to household disposals). Infectious PCMP waste is incinerated at high temperatures, leading to the emission of toxic gases, which contribute to overall pollution and carbon emissions. Nevertheless, these toxic gases can be removed by gas cleaning or “scrubbing” technologies. Offensive and municipal PCMP waste is usually discarded in a landfill, while a very small proportion is recycled. Overall, it is clear that PCMP waste processing is very complex and expensive. This fact was the driving force for examining the comparable environmental impact of the application of reusable PCMP and disposable PCMP. It has been estimated that choosing reusable PCMP over disposable PCMP could reduce natural resource energy consumption (~64%), greenhouse gas emissions (~66%), blue water consumption (~83%), and solid waste generation (84%). Consequently, there is increasing interest in using reusable PCMP in the future.⁵

Regardless of whether reusable or disposable, PCMPs have the primary function of protection. However, this function must be correlated with good comfort experience for medical personnel. They are exposed to long-term and high-intensity work poses, as well as the release of body heat and moisture in a high-stress and hot environment. The aforementioned causes a feeling of discomfort among medical personnel if they wear PCMP with inadequate comfort properties. Furthermore, feelings of discomfort among medical personnel may contribute to their less efficient work, impaired performance, and even mistakes. It is therefore important to point out that inadequate comfort properties of PCMP pose hidden danger for medical personnel that significantly affects their work and consequently the well-being of patients.⁶

Considering the above, future research should focus on encouraging the application of reusable PCMPs and examining their comfort properties. Some research has studied the comfort properties of reusable PCMP.⁷⁻⁹ However, according to a detailed literature review and to the best of our knowledge, there are no studies that have examined the influence of washing on the comfort

properties of reusable PCMP. Therefore, this work investigated the influence of washing on the comfort properties of woven fabrics intended for reusable PCMP. Specifically, the comfort properties (air permeability, water vapor transmission rate, volume electrical resistivity, compressibility, and compressive resilience) of woven fabrics intended for reusable PCMP were determined and compared before and after 60 washing cycles. The choice of 60 washing cycles corresponds to the typical six-month maintenance period (including washing and ironing) for reusable PCMP. The findings of this paper provide manufacturers, suppliers, and users with valuable information, enabling them to select the most suitable reusable PCMP whose changes in the comfort properties caused by washing are acceptable from the point of view of predetermined application conditions.

EXPERIMENTAL

Materials

The experiment was conducted on three woven fabrics intended for the production of reusable PCMP. These woven fabrics are composed of yarns based on pure cotton and cotton/polyester (50%/50%) blend, with a linear density of 29.4 tex, in twill 3/1 and twill 2/1 weaves. The characterization of examined samples was done through the determination of fabric structural characteristics, such as the number of threads per unit length, warp and weft crimp, mass per unit area, and thickness. Structural characteristics of the investigated fabrics are given in Table 1. Samples 1 and 3 are undyed (white), while Sample 2 is dyed (blue color). All samples were conditioned for 24 h at the standard atmospheric conditions of 20 ± 2 °C temperature and $65 \pm 4\%$ relative air humidity before the tests.

Washing procedure

The woven fabrics were washed in a household washing machine following ISO 6330 standard¹⁰ using a commercial detergent. Washing was done according to procedure 6N at a temperature of 60 ± 3 °C. All tested woven fabrics were subjected to 60 washing cycles. After each washing cycle, the samples were dried and ironed after 1, 20, 40, and 60 washing cycles. Drying is done by Procedure C - Flat dry,¹⁰ while ironing was done with a plate temperature of 150 °C. Structural characteristics of woven fabrics after 60 washing cycles are also shown in Table 1.

Methods

Determination of structural characteristics of woven fabrics

The number of threads per unit length was determined according to standard EN ISO 7211-2:2024.¹¹ Warp crimp (c_{warp} , %) and weft crimp (c_{weft} ,

%) were calculated according to Equations 1 and 2, respectively:¹²

$$c_{warp} = \frac{L_{warp} - L_F}{L_{warp}} 100 \quad (1)$$

$$c_{weft} = \frac{L_{weft} - B_F}{L_{weft}} 100 \quad (2)$$

where L_{warp} and L_{weft} (mm) are the original length of warp and weft threads, respectively, L_F (mm) is the length of the fabric sample, *i.e.*, the length of the warp threads in the woven fabric, and B_F (mm) is the width of the fabric sample, *i.e.*, the length of the weft threads in the woven fabric.

The mass per unit area was determined according to the standard ISO 3801:1977¹³ and fabric thickness

was determined according to the standard EN ISO 5084:1996¹⁴ using a thickness tester “B-TEX Engineering”- “DFTG-1”. The linear density, number of threads per unit length, mass per unit area, and thickness were considered as the average of five measurements per sample. The warp and weft crimp were considered as the average of ten measurements per sample. The structural characteristics (number of threads per unit length, warp and weft crimp, mass per unit area, and thickness) of the woven fabrics were estimated for samples before and after 60 washing cycles.

Table 1
Structural characteristics of woven fabrics before and after 60 washing cycles

Sample	Fiber type	Weave	Number of threads per unit length, dm ⁻¹		Crimp, %		Mass per unit area, g·m ⁻²	Thickness, mm
			warp	weft	warp	weft		
Before washing								
Sample 1	Cotton 100%	Twill 3/1	490±1.58	230±1.48	4.68±0.43	2.28±0.48	218.6±0.34	0.45±0.01
Sample 2	Cotton 50% Polyester 50%	Twill 2/1	430±1.48	220±1.58	3.81±0.54	4.13±0.75	205.7±0.27	0.34±0.01
Sample 3	Cotton 50% Polyester 50%	Twill 3/1	480±1.51	250±1.48	4.98±0.94	3.66±0.60	224.1±0.25	0.41±0.01
After washing								
Sample 1	Cotton 100%	Twill 3/1	494±2.38	231±2.91	6.24±0.84	4.16±1.42	231.4±0.50	0.54±0.31
Sample 2	Cotton 50% Polyester 50%	Twill 2/1	430±2.60	220±2.54	4.25±0.81	3.74±0.55	204.4±0.35	0.39±0.01
Sample 3	Cotton 50% Polyester 50%	Twill 3/1	480±2.59	250±2.24	5.73±0.82	4.22±1.20	231.9±0.43	0.49±0.02

Determination of comfort properties of woven fabrics

Permeability of woven fabrics

Determining permeability involves assessing the air permeability and water vapor transmission rate for the samples before and after 60 washing cycles.

The woven fabrics' air permeability (AP , mm/s) was tested on the Air Permeability Tester (Tex test FKS 3300) according to the Standard EN ISO 9237:1995¹⁵ using a test area of 20 cm² and pressure difference of 100 Pa. Air permeability was determined at the standard atmospheric conditions (temperature of 20 ± 2 °C and at a relative air humidity of 65 ± 4%). The test was repeated 10 times at different locations on each sample (5 measurements from the back to face side and 5 measurements from the face to back side of the investigated woven fabrics).

The water vapor transmission rate was determined according to the standard ASTM E-96/E96M-14.¹⁶ The

water vapor transmission rate ($WVTR$, g/h·m²) was determined according to the following equation:¹⁶

$$WVTR = \frac{G}{tA} \quad (3)$$

where G (g) is the steady state weight change, t (h) is the time (= 24 h), and A (m²) is the test area (cup mount area of 0.0041 m²). The test was performed at a temperature of 32 °C and at a relative air humidity of 50%. The water vapor transmission rate was considered as the average of three measurements per sample.

Volume electrical resistivity of woven fabrics

The volume electrical resistance of the investigated woven fabrics in the warp and weft direction, determined using the voltage method,¹⁷⁻¹⁹ both before and after 60 washing cycles, was evaluated. The measurement was carried out during the decrease of relative air humidity in the chamber in the measuring device from 50% down to 30%, at a temperature of

22±2 °C. The paper presents the volume electrical resistivity of fabrics determined at a relative air humidity of 30%. These measurement conditions are close to the testing atmosphere defined in standard EN 1149-2:1997²⁰ (air temperature: 23±1 °C and relative air humidity: 25±5%). Throughout the entire process, two measurements were conducted for each sample, with three specimens of fabric connected to the electrodes during each measurement. Based on the determined woven fabric volume electrical resistance, the volume electrical resistivity of samples (ρ , GΩcm) was calculated using the following equation:^{17,19,21}

$$\rho = \frac{R_x \cdot S_F}{l} \quad (4)$$

where R_x (GΩ) is the volume electrical resistance, S_F (cm²) is the surface of the sample's cross-section calculated by multiplying sample thickness and width, and l (1 cm) is the sample length.

Compression of woven fabrics

A thickness tester (AMES, type 414-10, USA) was used for the investigation of woven fabrics' compression (*i.e.*, compressibility and compressive resilience). The fabric thickness was measured starting with the initial pressure of 9.96 kPa, which was further progressively increased to 17.62, 43.66, 59.01, 74.34, and 103.99 kPa. After attaining the maximum pressure, the test was reversed in the same way till the complete recovery of the sample. The reported results are the mean values of five measurements per sample.

Woven fabric compressibility (C , %) and compressive resilience (RC , %) were calculated according to Equations 5 and 6, respectively:^{22,23}

$$C = \frac{T_{0c} - T_{\max}}{T_{0c}} \cdot 100 \quad (5)$$

$$RC = \frac{W'_c}{W_c} \cdot 100 = \frac{\int_{T_{0c}}^{T_{\max}} P_r \cdot dT_r}{\int_{T_{0c}}^{T_{\max}} P_c \cdot dT_c} \cdot 100 \quad (6)$$

where T_{0c} and $T_{\max}$ (mm) are the thicknesses of the woven fabric determined under the initial pressure of 9.96 kPa and under the maximum pressure of 103.99 kPa, W'_c and W_c (Pa·m) are the compression work recovery and compression work of woven fabric, P_r and P_c (Pa) are the magnitudes of pressure under recovery conditions (*i.e.* under decompression of the sample) and the magnitude of pressure that causes compression of the sample, dT_r and dT_c are the changes of sample thickness under the decompression and compression phase.

Electrokinetic properties of woven fabrics

The zeta potential (ζ) is a parameter that describes the charging behavior at the solid-liquid interface. The zeta potential of fabrics was determined by the streaming potential method using a SurPASS

Electrokinetic Analyzer (Anton Paar GmbH, Graz, Austria). A rectangular fabric sample (8 cm x 2 cm) was mounted in the cylindrical cell. To avoid the influence of fabrics' swelling on the zeta potential, the samples were pre-swelled in distilled water for 30 min before measurement. A 0.001 M KCl solution was used as the electrolyte, and the initial pH was adjusted to pH 10 with NaOH. Changes in pH (from about pH 10 to pH 3) were achieved by the addition of 0.05 M HCl during automatic titrations. Isoelectric points (IEP), the pH where the zeta potential assumes 0 mV, were determined by extrapolation of experimental data. Four measurements were performed for each sample, and the standard deviation was up to 5%.

Statistical analysis

The obtained results for comfort properties were statistically analyzed by using the *t*-test. The parameter *t* was determined using the equation:²⁴

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{\sigma_1^2(n_1 - 1) + \sigma_2^2(n_2 - 1)}{n_1 + n_2 - 2} \cdot \frac{n_1 + n_2}{n_1 \cdot n_2}}} \quad (7)$$

where $\bar{x}_1$ and $\bar{x}_2$ 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 their corresponding sample sizes ($n_1 = n_2 = 10$ for air permeability, $n_1 = n_2 = 3$ for water vapor transmission rate, and $n_1 = n_2 = 5$ for compressibility and compressive resilience).

RESULTS AND DISCUSSION

The comfort properties of the woven fabrics intended for reusable PCMP were assessed based on their permeability (air permeability and water vapor transmission rate), volume electrical resistivity, and compression (compressibility and compressive resilience).

Permeability of woven fabrics

Air permeability refers to a fabric's ability to allow air to pass through a given area.¹⁹ In general, air permeability largely depends on the fiber type and fabric structural characteristics.^{19,25,26} Water vapor permeability, measured by the water vapor transmission rate (WVTR), indicates the ability of a fabric to transfer moisture vapor to the environment. The higher values signify better moisture management and a drier fabric.²⁷ Water vapor transmission rates are primarily affected by fabric thickness and fiber type, while fabric structure has a minimal impact as long as thickness remains consistent.^{27,28} Both of these characteristics, air permeability and water vapor transmission rate,

are crucial for clothing comfort, as restricted air flow and restricted transfer of moisture vapor to the environment can lead to discomfort for the wearer.^{19,26,28} The measured values of air permeability and water vapor transmission rate for the investigated woven fabrics are presented in Figure 1.

The results in Figure 1(a) show that before washing, Sample 1 exhibited 46.60% higher air permeability than Sample 3 among the samples with the same twill 3/1 weave. This difference is likely due to Sample 1 having a lower overall warp and weft thread density (720 dm^{-1} vs. 730 dm^{-1}) and a lower over-crimp percentage (6.96% vs. 8.64%) (Table 1). After 60 washing cycles, the same trend persists, with Sample 1 maintaining 29.13% higher air permeability than Sample 3. A lower fabric density increases the space between yarns (macropores), thereby enhancing the fabric's air permeability.¹⁹ Before washing, among the samples with the same fiber type (cotton/polyester blend), but different weaves (Fig. 1(a)), Sample 2 exhibited 42.38% higher air permeability than Sample 3. Similar to the trend observed in samples with the same weave, this difference is attributed to the lower overall fabric density (650 dm^{-1} vs. 730 dm^{-1}) and lower over-

crimp percentage (7.94% vs. 8.64%) of Sample 2 compared to Sample 3 (Table 1). After 60 washing cycles, the same trend persists, with Sample 2 maintaining 29.04% higher air permeability than Sample 3. Statistical analysis using the *t*-test (Table 2) indicates a statistically significant difference in air permeability based on fiber type and weave structure, both before and after washing, with a significance level of 0.001 in all cases. Furthermore, Figure 1(a) illustrates that washing decreases the air permeability of all investigated fabrics, which is consistent with previous research conducted by E. Acar *et al.* on cotton fabrics.²⁹ The most significant reduction is observed in Sample 1 (27.57%), while the least reduction occurs in Sample 3 (3.87%). This can be attributed to the increase in overall fabric density in Sample 1 (from 720 dm^{-1} to 725 dm^{-1}) and a substantial rise in the over-crimp percentage (from 6.96% to 10.40%). In contrast, Sample 3 shows no change in overall fabric density and a much smaller increase in the over-crimp percentage (from 8.64% to 9.95%). According to *t*-test results, all samples exhibit a statistically significant difference in air permeability before and after 60 washing cycles (Table 2).

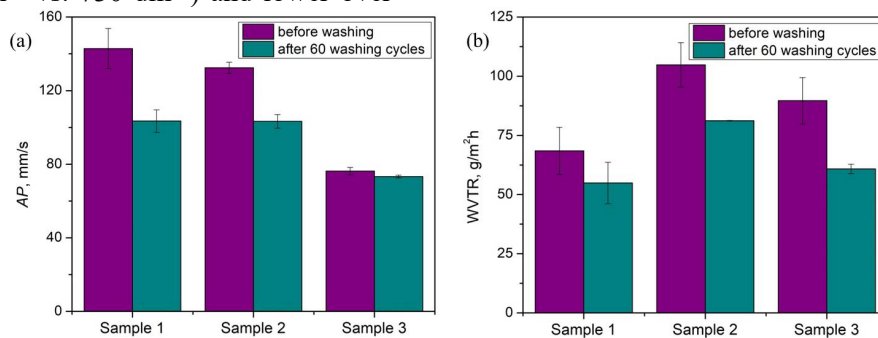


Figure 1: Permeability of woven fabrics before and after 60 washing cycles: (a) air permeability (*AP*), (b) water vapor transmission rate (*WVTR*)

Table 2

Statistical results for woven fabric air permeability and water vapor transmission rate using *t*-test

Tested parameter	Values of parameter t based on fiber type		Values of parameter t based on weave structure		Values of parameter t based on washing		
	$df = n_1 + n_2 - 2 = 18$ for AP , $df = n_1 + n_2 - 2 = 4$ for $WVTR$						
	$t_{1/3(bw)}$	$t_{1/3(aw)}$	$t_{2/3(bw)}$	$t_{2/3(aw)}$	$t_{1(bw)/1(aw)}$	$t_{2(bw)/2(aw)}$	$t_{3(bw)/3(aw)}$
AP	13.39(***)	10.94(***)	34.05(***)	17.74(***)	7.04(***)	13.64(***)	2.89(**)
$WVTR$	-3.38(*)	-1.46(/)	2.49(/)	22.29(***)	2.28(/)	5.62(**)	6.44(**)

AP – air permeability, *WVTR* – water vapor transmission rate, bw – before washing, aw – after washing, (*) – 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

Among the samples with the same weave (Fig. 1(b)), Sample 1 exhibited a lower water vapor

transmission rate than Sample 3, both before and after washing. According to the literature, water

vapor can diffuse through textile structures either by simple diffusion through the air spaces between fibers and yarns or along the fiber itself. Furthermore, a material's diffusivity increases with higher moisture regain.³⁰ Based on this, Sample 1 was expected to have a higher water vapor transmission rate than Sample 3 due to its lower overall fabric density (720 dm^{-1} vs. 730 dm^{-1} , Table 1), which creates larger spaces between yarns, and because it is composed entirely of hygroscopic fibers (cotton with higher moisture regain) compared to Sample 3, which contains a cotton/polyester blend. Additionally, research indicates that water vapor transmission rates decrease with increasing fabric thickness.^{27,28} The results indicate that Sample 1 had a lower water vapor transmission rate than Sample 3, likely due to its greater thickness (0.45 mm vs. 0.41 mm, Table 1), suggesting that thickness is the dominant factor influencing water vapor transmission in this case. This trend remains consistent after 60 washing cycles. When comparing samples with the same fiber type but different weaves, Figure 1(b) shows that Sample 2 exhibited a higher water vapor transmission rate than Sample 3, due to its lower thickness (0.34 mm vs. 0.41 mm, Table 1) and lower overall fabric density (650 dm^{-1} vs. 730 dm^{-1} , Table 1). This trend persists even after 60 washing cycles. Statistical analysis using the *t*-test shows a statistically significant difference in water vapor transmission rate between Samples 1 and 3 before washing ($t_{1/3(\text{bw})} = -3.38$) and between Samples 2 and 3 after washing ($t_{2/3(\text{aw})} = 22.29$). Additionally, Figure 1(b) shows that washing affects the water vapor transmission rate by reducing it across all investigated fabrics. This is because washing increases the thickness of all woven fabrics (from 0.45 mm to 0.54 mm for Sample 1, from 0.34 mm to 0.39 mm for Sample 2, and from 0.41 mm to 0.49 mm for Sample 3). The greatest reduction in water vapor transmission rate due to washing is observed in Sample 3 (32.15%), while the smallest reduction occurs in Sample 1 (19.79%). According to the *t*-test results, Samples 2 and 3 exhibit a statistically significant difference in water vapor transmission rate before and after 60 washing cycles (Table 2).

Volume electrical resistivity of woven fabrics

During use, the interaction between the fabric itself and its contact with the wearer's body generates static electricity, resulting in several undesirable effects, such as fabrics clinging to the

body or other textiles and causing discomfort when worn. These effects are particularly pronounced in synthetic fabrics, which have extremely high electrical resistance.^{18,19,31,32} Therefore, electrical resistance should be taken into account as a key factor in fabric comfort, particularly in the production of reusable PCMP. Literature suggests that the electrical resistance of textile materials depends on fiber type, fabric structural characteristics, and moisture content.^{18,31,33} Figure 2 presents the volume electrical resistivity (in further text: resistivity) at 30% relative air humidity (in further text: humidity) for the three investigated woven fabrics in both warp and weft directions, measured before and after 60 washing cycles.

The results in Figure 2 indicate that Sample 1 exhibits the lowest resistivity, followed by Sample 3, while Sample 2 shows the highest resistivity in both the warp and weft directions, as well as before and after washing. The higher number of warps compared to wefts (Table 1) facilitates the directional movement of charge in all investigated samples in the warp direction, resulting in lower resistivity values. The significantly low resistivity of Sample 1 (cotton fabric) can be attributed to the hydrophilic nature of cotton fibers. Due to the presence of numerous hydroxyl groups, cotton fibers readily absorb and retain moisture through interactions between their hydroxyl groups and water molecules in the air, leading to a reduction in resistivity. Compared to Sample 1, Sample 3 was produced from a blend of cotton and polyester fibers. According to the literature, polyester fibers have compact, non-polar molecular chains with extremely high crystallinity and orientation, resulting in a lower capacity for water retention and, consequently, a higher resistivity value.^{18,31,33} Therefore, for samples produced in the same twill 3/1 weave (Samples 1 and 3), it was expected that Sample 3, produced from a cotton/polyester blend, would exhibit significantly higher resistivity than Sample 1, which consists solely of cotton fibers. However, this was not the case. The reason lies in the fact that the resistivity of fiber-blend fabrics is largely influenced by the component with lower resistivity (in this case, cotton), which primarily facilitates the directional movement of charge,¹⁹ resulting in slightly higher resistivity of Sample 3 than that of Sample 1. It is known that the isoelectric point (IEP) is an indicator of the chemistry of functional groups present on the material surface and is used to describe the acidity

or basicity of the material surface. With increasing acidic functionalities, the IEP becomes lower; and with increasing basic functionalities, the IEP becomes higher. Considering that surface functional groups interacting with water in terms of acid-base reactions give a hydrophilic character to the material surface, IEPs can also be regarded as an indicator of the material's hydrophilicity. Accordingly, a shift in IEP towards lower values indicates higher hydrophilicity for materials with acidic surface functional groups, and a shift in IEP towards higher IEP values indicates higher hydrophilicity for materials with basic surface functional groups.³⁴ Based on the above, the higher hydrophilicity of Sample 1 compared to Sample 3 is confirmed by their IEPs (Fig. 3(a)): Sample 1 has a lower IEP compared to Sample 3 (2.18 and 2.44 for Sample 1 and Sample 3, respectively).

When comparing samples of the same fiber type (50% cotton/50% polyester), but different weaves (twill 2/1-Sample 2 and twill 3/1-Sample 3), unexpected results were observed. Previous studies on wool fabrics in plain and twill 2/2 weaves indicated that twill-weave fabrics exhibited up to 46% lower resistivity than plain-weave samples.³⁵ However, the histograms in Figure 2 show that Sample 2, with a twill 2/1 weave, has significantly higher resistivity than Sample 3, with a twill 3/1 weave-approximately 41 times higher in the warp direction and 56 times higher in the weft direction. The significant difference in resistivity cannot be solely attributed to variations in the weave of the tested fabrics. Instead, the observed differences are likely due to the fact that Sample 2 was the only dyed fabric among the three tested samples. It is assumed that the dye used for Sample 2 interacted with the free hydroxyl groups of the cotton fibers, reducing the

number of hydroxyl groups available to bind with water molecules from the air. This reduction in moisture absorption significantly increased the resistivity of Sample 2. The higher IEP of Sample 2 (2.75) compared to Sample 3 (2.44) (Fig. 3(a)) indicates a lower number of free hydroxyl groups of cotton fibers in Sample 2 compared to Sample 3, confirming that the dye used to obtain Sample 2 interacted with the free hydroxyl groups of cotton fibers in Sample 2.

Additionally, Figure 2 illustrates that washing alters the resistivity of woven fabrics. Washing leads to an increase in resistivity for all investigated fabrics, both in the warp direction (approximately 184 times for Samples 1 and 3, and 12 times for Sample 2) and in the weft direction (approximately 164 times for Sample 1, 8 times for Sample 2, and 148 times for Sample 3). The smallest increase in resistivity in Sample 2 is likely due to the presence of dye on the fabric fibers, which reduces the detergent's impact on the fibers themselves. Literature suggests that washing can cause chemical degradation of cotton and polyester fibers,³⁶⁻³⁸ while Agarwal *et al.*³⁹ observed that the washing process can lead to fabric surface damage due to mechanical action. Chemical degradation of cotton and polyester fibers caused by washing is reflected in a decrease in their degree of polymerization, *i.e.*, molecular chain scission.^{37,38}

Considering all samples, a shift in IEP to lower values after washing is evident (Fig. 3(b), (c), and (d)); molecular chain scission was likely accompanied by the formation of new hydrophilic groups of acidic character. Since increased hydrophilicity is known to reduce resistivity, it was expected that washing would lower the resistivity of the fabrics.

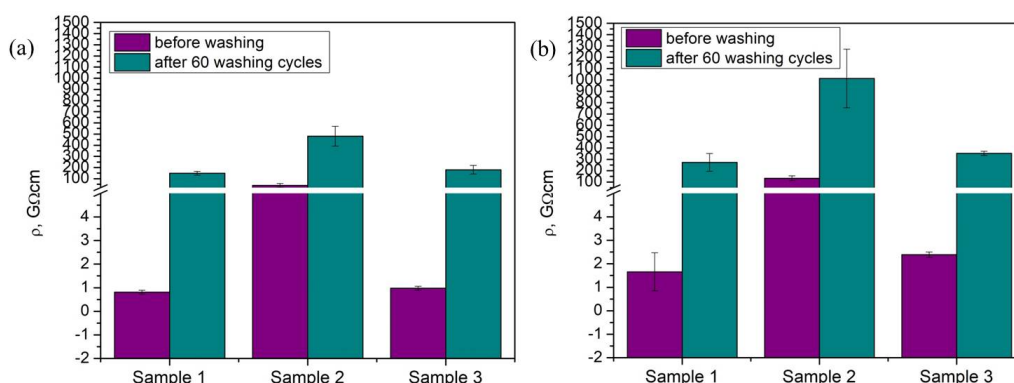
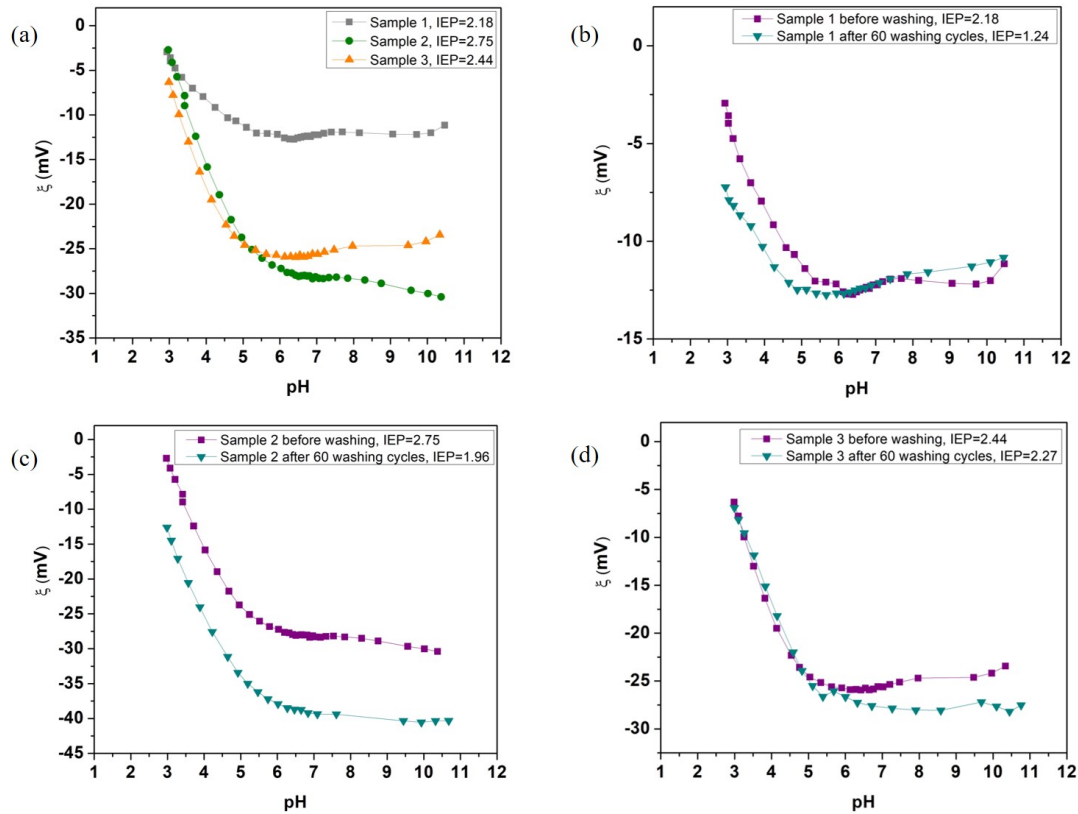


Figure 2: Resistivity (ρ) of woven fabrics before and after 60 washing cycles: (a) warp direction, (b) weft direction


 Figure 3: Zeta potential (ζ) of woven fabrics (a) before and (b, c, d) after 60 washing cycles

However, while molecular chain scission enhances fiber hydrophilicity, it also disrupts the continuous flow of electricity through the disrupted fiber structure. Specifically, it is assumed that molecular chain scission, combined with fabric surface damage, interferes with the directional movement of charge in Samples 1, 2, and 3, ultimately leading to an increase in their resistivity.

Compression of woven fabrics

Woven fabrics intended for clothing purposes, especially reusable PCMP, must possess softness. A fabric that compresses easily under a compression load is generally perceived as soft.^{23,40} Figure 4 displays the compressibility and compressive resilience results for all tested woven fabrics, both before and after 60 washing cycles.

Figure 4(a) shows that before washing, among the samples with the same weave, Sample 1 exhibited higher compressibility than Sample 3, likely due to its lower total warp and weft density (720 dm^{-1} vs. 730 dm^{-1}), lower over-crimp percentage (6.96% vs. 8.64%), and lower surface mass (218.6 gm^{-2} vs. 224.1 gm^{-2}) (Table 1). When the fabric density is lower (*i.e.*, a lower number of threads per unit length in warp and weft

direction), the spaces between the yarns increase, allowing easier compression of the fabric and resulting in higher compressibility. Furthermore, when the over-crimp percentage of woven fabric is lower, under the same compression load, the compression is easier, resulting in higher compressibility. However, after 60 washing cycles, Sample 1 exhibited lower compressibility than Sample 3, likely due to an increase in Sample 1 density (from 720 dm^{-1} to 725 dm^{-1}), while Sample 3 density remained unchanged. Furthermore, cellulose molecules' reorganization in low-ordered parts of cotton fibers induced by wash-dry cycles should not be neglected.⁴¹ Statistical analysis using the *t*-test (Table 3) confirms a statistically significant difference in compressibility between Samples 1 and 3, both before and after washing ($t_{1,3(\text{bw})} = 4.28$ and $t_{1,3(\text{aw})} = -5.16$, respectively). Regarding fabrics made from the same cotton/polyester blend, but with different weaves (Fig. 4 (a)), no statistically significant difference in compressibility was observed between Samples 2 and 3, as confirmed by statistical analysis (Table 3). Additionally, Figure 4(a) shows that washing reduces the compressibility of the cotton fabric (Sample 1) while slightly increasing the compressibility of the cotton/polyester blend fabrics (Samples 2 and

3). This trend is likely due to the increase in the total warp and weft density observed only in Sample 1 (from 720 dm^{-1} to 725 dm^{-1}), with no changes in Samples 2 and 3. Furthermore, Sample 1 exhibited the highest increase in over-crimp percentage (49.42%), whereas Samples 2 and 3

showed minimal increases of 0.63% and 15.16%, respectively. According to the t -test results, only Sample 1 exhibits a statistically significant difference in compressibility before and after 60 washing cycles ($t_{1(bw)/1(aw)} = 8.76$, Table 3).

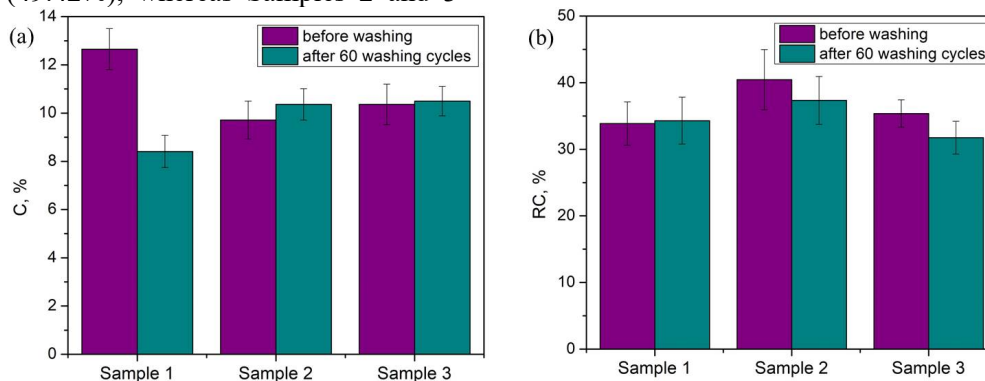


Figure 4: Compression of woven fabrics before and after 60 washing cycles: (a) compressibility (C), (b) compressive resilience (RC)

Table 3
Statistical results for woven fabric compressibility and compressive resilience using t -test

Tested parameter	Values of parameter t based on fiber type		Values of parameter t based on weave structure		Values of parameter t based on washing		
	$t_{1/3(bw)}$	$t_{1/3(aw)}$	$t_{2/3(bw)}$	$t_{2/3(aw)}$	$t_{1(bw)/1(aw)}$	$t_{2(bw)/2(aw)}$	$t_{3(bw)/3(aw)}$
C	4.28(**)	-5.16(***)	-1.26(/)	-0.35(/)	8.76(***)	-1.42(/)	-0.30(/)
RC	-0.89(/)	1.32(/)	2.29(/)	2.88(*)	-0.20(/)	1.20(/)	2.53(*)

C – compressibility, RC – compressive resilience, bw – before washing, aw – after washing, (*) – 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

The elastic recovery of woven fabric after compression, a property that can be evaluated by measuring its compressive resilience, is also important for woven fabrics.²³ As shown in Figure 4(b), the compressive resilience of the tested fabrics before washing indicates that Sample 2 has the highest compressive resilience, while Sample 1 has the lowest. The greater compressive resilience of the cotton/polyester blend fabrics (Samples 2 and 3) compared to the cotton fabric (Sample 1) can be attributed to differences in their fiber type. Namely, literature¹² indicates that polyester fibers have superior elastic recovery compared to cotton fibers, contributing to the higher compressive resilience of cotton/polyester fabrics. Washing results in a slight increase in the compressive resilience of the cotton fabric, but a decrease for the cotton/polyester fabrics. The decrease in compressive resilience of the cotton/polyester fabrics may be attributed to washing at 60°C , which probably reduces the elastic recovery of

PES fibers, leading to lower compressive resilience in Samples 2 and 3. Statistical analysis using the t -test shows a statistically significant difference in compressive resilience only between Samples 2 and 3 after washing ($t_{2/3(aw)} = 2.88$). Additionally, a significant difference in compressive resilience before and after 60 washing cycles is observed only for Sample 3 ($t_{3(bw)/3(aw)} = 2.53$, Table 3). The lack of a significant decrease in compressive resilience during washing for Sample 2 can probably be attributed to the presence of dye, which acted as a plasticizer for the PES fibers,⁴² reducing the loss of elastic recovery of PES fibers during washing.

CONCLUSION

The findings of this study showed that washing caused changes in the comfort properties of woven fabrics, based on cotton in twill 3/1 weave, cotton/polyester blend in twill 2/1 weave, and cotton/polyester blend in twill 3/1 weave, intended for the production of reusable PCMP.

All woven fabrics showed decreased air permeability and water vapor transmission rate (up to 27.57% for air permeability and up to 32.15% for water vapor transmission rate in the case of fabric based on cotton in twill 3/1 weave and fabric based on cotton/polyester blend in twill 3/1 weave, respectively) after 60 washing cycles. Also, all woven fabrics showed increased volume electrical resistivity (approximately up to 184 times in the case of fabric based on cotton and cotton/polyester blend in twill 3/1 weave) after 60 washing cycles. Woven fabric based on cotton in twill 3/1 weave showed reduced compressibility (for 33.52%) and increased compressive resilience (for 1.30%) after 60 washing cycles. In contrast, woven fabrics based on cotton/polyester blend in twill 2/1 and 3/1 weave showed increased compressibility (up to 6.69% in the case of fabric based on cotton/polyester blend in twill 2/1 weave) and decreased compressive resilience (up to 10.23% in the case of fabric based on cotton/polyester blend in twill 3/1 weave) after 60 washing cycles.

The results presented in this study could help manufacturers, suppliers, and users to select a woven fabric intended for reusable PCMP whose changes in comfort properties caused by washing are acceptable from the point of view of predetermined application conditions.

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