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Thermal and electrical properties of multi-layer knitted fabric assemblies for protective clothing

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This study investigates the thermal comfort properties of knitted fabrics by analysing key parameters such as thermal conductivity, thermal resistance, and surface and volume resistivity. Single- and multi-layer fabric assemblies, comprising wool/acrylic blends with varying ratios and polypropylene fabrics with different filament counts, are examined in combination with lightweight 100% cotton and breathable fabrics. The influence of these variables on the thermal and electrical properties of knitted fabrics is systematically evaluated. The aim is to establish relationships between the thermal insulation and electrical properties of single-layer and multilayer fabric assemblies. The findings reveal that the highest thermal resistance is observed in CP9B (a three-layer assembly comprising cotton fabric, polypropylene pile-knitted fabric and breathable fabric). The highest surface and volume resistivity values are recorded in sample CP1B.

Keywords: Breathable fabric, Polypropylene, Surface resistivity, Thermal comfort, Volume resistivity, Wool/acrylic

1 Introduction

One of the most crucial roles of clothing is to obtain the ideal level of thermal comfort. When clothing is worn, the thermal balance between body heat production and thermal losses determines how comfortable it will be to wear for an extended period. The amount of heat the human body can generate varies depending on the intensity of physical activity, ranging from 80 W during sleep to over 1000 W during strenuous exertion. As a natural response to physical activity, sweating accumulates moisture in clothing textiles, altering their heat and moisture transport properties and potentially compromising thermo-physiological comfort. Most clothing fabrics provide thermal insulation; however, increased moisture content reduces their insulating capacity while decreasing water vapour permeability. These changes can disrupt the body's thermal equilibrium, leading to discomfort.

Thermal comfort encompasses multiple interrelated aspects, particularly when considering functional thermal undergarments. The importance of thermal comfort as a component of overall clothing comfort has driven significant research efforts to develop predictive models based on fixed characteristics and specific metrics. Over the past few decades, numerous metrics have been employed to characterise thermal comfort, including physiological comfort parameters. These parameters can be divided into two major clusters: (1) those based solely on the characteristics of cloth and (2) those that additionally incorporate atmospheric characteristics. Moisture absorption and sweat management are particularly crucial in developing thermal undergarments, sportswear, and activewear, where efficient sweat absorption and transmission enhance the microclimate between clothing and skin, ultimately improving wearer comfort. Extensive research has been conducted on fabric-moisture interactions to develop garments with superior moisture absorption and sweat conductive properties. Several testing standards and procedures exist to evaluate the moisture absorption and wicking behaviour of textile fabrics[1-6]. However, in moisture-absorbent and sweat-absorbing fabrics, moisture content often differs between the two fabric surfaces due to varying levels of sweat exposure during evaporation. The dynamic processes governing moisture transfer and dissipation in fabrics are pivotal

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in maintaining the heat and moisture balance within clothing[7-8].

Comfort is generally defined as the absence of discomfort or as a neutral state compared to a preferred state[9]. With the growing consumer demand for comfortable undergarments, research on fabric comfort properties has intensified[10-12]. Previous studies have explored various aspects of thermal comfort, including the role of fibre diameter in thermal radiation blocking[13], the influence of micro-denier fibres on fabric thermal properties, and the effects of fibre blends on thermal resistance. For instance, studies have demonstrated that micro-denier fibres reduce thermal conductivity and enhance thermal resistance[14,15], while blends of cotton and angora rabbit fibre beyond 25% significantly alter thermal comfort properties. Other research has examined the influence of yarn properties such as yarn count, twist, and combing processes on the thermal comfort characteristics of rib-knitted fabrics[16]. The thermal behaviour of different rib structures has also been investigated, with findings indicating that heat loss decreases as rib density increases due to greater air entrapment within bulkier structures[17]. Additionally, textured polyester filament fabrics exhibit higher thermal resistance than non-textured variants, reinforcing the impact of fabric structure on thermal insulation[18]. Other research has indicated that increased fabric porosity reduces dry-state thermal conductivity but enhances thermal conductivity when moisture content rises[19]. Key factors influencing heat transfer in fabrics include thickness, enclosed still air, and external airflow[20]. Furthermore, thermal insulation tends to increase as fabric density decreases[21].

In addition to thermal comfort, the electrostatic properties of fabrics are an essential consideration, particularly in extreme cold weather clothing systems. Clothing is typically composed of either natural or synthetic fibres, with synthetic fabrics exhibiting a higher propensity for generating electrostatic charge (ESC) through friction. Human exposure to electrostatic fields can pose potential hazards, as charge accumulation on fabric surfaces can reach thousands of volts[22]. The triboelectric effect, which occurs when materials come into contact and separate, governs charge generation in textiles[23]. The underlying mechanisms include electron transfer, ion transfer, and material relocation, with contact electrification influenced by differences in material properties and environmental conditions[24]. Studies have demonstrated that synthetic fibres generate significantly higher electrostatic charges compared to natural fibres such as cotton. The triboelectric ranking of textile fibres indicates varying charge polarity among different materials, affecting their electrostatic performance[25-26].

This study aims to evaluate the influence of textile quality on the thermal insulation properties and electrostatic charge generation of inner-layer fabrics designed for extreme cold weather conditions. By examining the surface and volume resistivity characteristics of single-layer and multilayer fabrics, the research seeks to determine how material composition and structural configuration impact thermal and electrostatic performance.

2 Materials and Methods

Nine samples of wool/acrylic knitted fabric with different blend ratios (30:70, 50:50 & 70:30) and nine samples of polypropylene filament (24, 48 & 66 filaments) were prepared using different knitted structure (Plain, rib & pile) on a V-flat knitted machine. Additionally, one sample of 100 % cotton fabric and one sample of lightweight, waterproof, and breathable fabric membranes were selected for evaluation. The breathable fabric comprises three layers: expanded polytetrafluoroethylene (ePTFE) protected by a knitted fabric layer on one side and a woven fabric layer on the other. Samples details are provided in Table 1. The following abbreviations are used: WA (wool/acrylic), CWA (cotton/wool/acrylic), CWAB (cotton/wool/acrylic/breathable), P (polypropylene), CP (cotton/polypropylene) and CPB (cotton/polypropylene/breathable).

2.1 Physical Properties of Fabrics

Fabric samples were conditioned at standard atmospheric conditions (20 ± 2°C, 65 ± 2% RH) for 24 h. Stitch densities were measured using a counting glass following ASTM D3775-03 and ASTM D-3887 standards. Yarn linear density and areal density were measured by cutting 10 cm × 10 cm samples and weighing them using an electronic balance and values multiplied by 100 as per ASTM D 1059 standard. Fabric thickness was measured as per the ASTM D 1777-96 (2002) standard using a Shirley thickness gauge under a pressure of 7 g/cm^2, with an accuracy of 0.01 mm. Ten readings were taken per sample, and the averages and standard errors were calculated.

2.2 Thermal Properties of Fabrics

Thermal conductivity and resistance were evaluated using a thermal conductivity tester,

Table 1 — Physical properties of knitted fabrics

Fabric code	Structure	Composition (wool: acrylic)/ no. of filaments	Wale /inch	Courses/ inch	Areal density g/m^2	Thickness mm
			Wool/ acrylic knitted fabric			
WA1	Plain	30:70	14	17	161.58 ± 0.42	1.23 ± 0.021
WA 2	Rib	30:70	17	27	438.04 ± 0.47	1.93 ± 0.016
WA 3	Pile	30:70	13	24	467.34 ± 0.49	3.21 ± 0.030
WA 4	Plain	50:50	13	16	162.52 ± 0.47	1.24 ± 0.020
WA 5	Rib	50:50	15	26	409.35 ± 0.47	1.94 ± 0.022
WA 6	Pile	50:50	14	27	452.41 ± 0.43	3.39 ± 0.044
WA 7	Plain	70:30	13	16	163.90 ± 0.50	1.25 ± 0.017
WA 8	Rib	70:30	17	26	408.69 ± 0.31	2.04 ± 0.026
WA 9	Pile	70:30	14	25	458.04 ± 0.43	3.42 ± 0.025
			Polypropylene knitted fabric			
P1	Plain	24	16	22	181.01 ± 0.38	1.21 ± 0.023
P2	Rib	24	16	28	344.99 ± 0.37	1.54 ± 0.016
P3	Pile	24	17	28	351.81 ± 0.30	2.43 ± 0.030
P4	Plain	48	15	23	239.41 ± 0.36	1.31 ± 0.023
P5	Rib	48	15	28	445.69 ± 0.26	1.82 ± 0.025
P6	Pile	48	15	28	345.94 ± 0.35	2.36 ± 0.031
P7	Plain	66	16	24	202.51 ± 0.39	1.11 ± 0.028
P8	Rib	66	14	25	377.02 ± 0.44	1.58 ± 0.025
P9	Pile	66	14	24	348.70 ± 0.43	2.21 ± 0.035
			Cotton knitted & breathable fabric			
Cotton	Plain	---	26	35	126.78 ± 0.30	0.41 ± 0.003
	Breathable[a]		--	--	193.76 ± 0.31	0.40 ± 0.002

[a] This is made of three layers: ePTFE, knitted and woven fabrics

following ASTM C518. Heat flux sensors recorded the heat flow and a thickness sensor measured the fabric thickness. Ten samples were tested, and the averaged results were statistically analysed.

The conductive heat flux (H_c) in one dimension for a pure solid substance is explained by Fourier's law:

$$H_c = k\frac{dT}{dx} \qquad ...(1)$$

where H_c is conductive heat flux, T; temperature, and k; thermal conductivity constant.

2.3 Surface Resistivity (S_R) and Volume Resistivity (V_R)

Surface resistivity was measured following AATCC 76-1995 and ASTM D257. Ten measurements per sample were taken, and the average values were used to calculate volume resistivity. The resistivity was determined using the following equation:

$$R = R_f\,\frac{l}{d} \qquad \ldots(2)$$

Where R is resistance (ohm); R_f, surface resistivity (Ω/cm^2); l, distance between electrodes; and d, width of each electrode.

Volume resistivity was measured using the following equation:

$$\rho_s = \frac{7.1\ R_f}{t} \qquad \ldots(3)$$

where ρ_s is the fabric volume resistivity(ohm-cm); and t, fabric thickness.

3 Results and Discussion

The thermal comfort characteristics of the samples, including thermal resistance, thermal conductivity, surface resistivity, and volume resistivity, are examined and discussed below. The fabric codes presented in figures and tables are arranged based on plain, rib, and pile structures.

3.1 Thermal Resistance in Multi-Layer Assembly

3.1.1 Effect of Single-Layer Clothing

Figures 1 (a) & (b) and Table 2 indicate that the wool/acrylic composition exhibits higher thermal resistance in the plain knit structure compared to the rib knit structure, which demonstrates lower thermal resistance. The pile knit structure, however, shows higher thermal resistance due to protruding fibres that trap more air, thereby enhancing thermal insulation. As shown in Fig. 1 (b), samples are produced with yarns containing 24, 48, and 66 filaments, each having a denier of 5.5, 4.3, and 2.6, respectively.

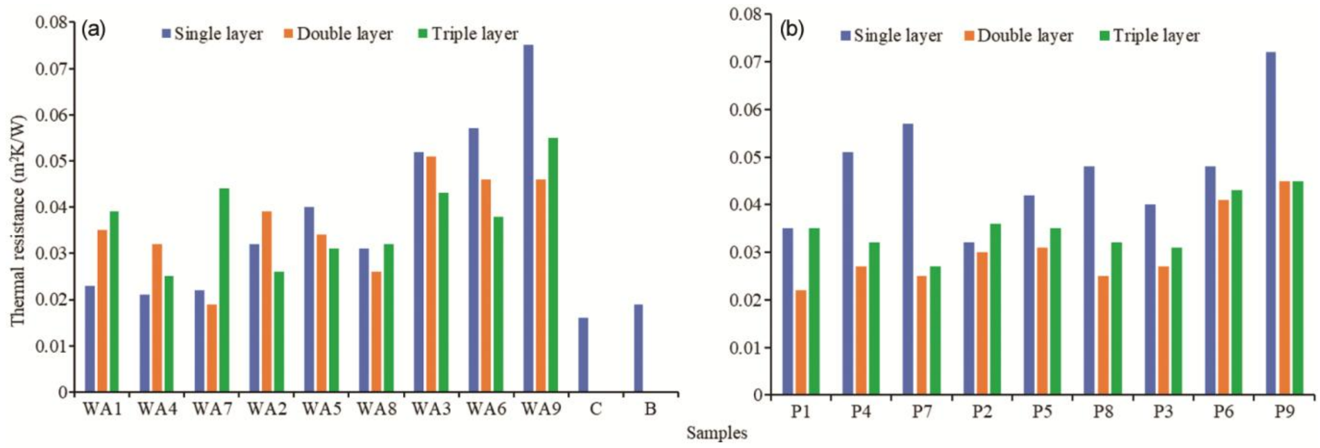


Fig. 1 — Thermal resistance of multi-layer assemblies (a) cotton, wool/acrylic and breathable fabric, and (b) cotton, polypropylene and breathable fabric

Table 2 —Thermal properties, surface and volume resistivity of knitted fabrics

Fabric code	Thickness mm	Thermal conductivity W/m K	Thermal resistance m^2K/W	Surface resistivity (10^{11}) Ω/cm^2	Volume resistivity (10^{11}) Ω-cm
			Single-layer fabric		
WA1	1.5	0.067	0.023	6.60	31.24
WA4	1.6	0.079	0.021	5.30	23.52
WA7	1.6	0.075	0.022	5.00	22.19
WA2	2.6	0.081	0.032	6.0	16.39
WA5	2.4	0.069	0.04	4.00	11.83
WA8	2.5	0.082	0.031	4.80	13.63
WA3	3.7	0.071	0.052	6.90	13.24
WA6	3.7	0.065	0.057	4.05	7.77
WA9	3.8	0.051	0.075	4.70	8.78
C	0.4	0.025	0.016	0.08	1.42
B	0.4	0.022	0.019	0.75	13.31
P1	1.3	0.039	0.035	6.98	38.12
P4	1.5	0.031	0.051	7.3	34.55
P7	1.3	0.024	0.057	6.6	36.05
P2	1.6	0.05	0.032	5.85	25.96
P5	2.0	0.048	0.042	7.5	26.63
P8	1.7	0.035	0.048	6.6	27.57
P3	2.5	0.062	0.04	5.3	15.05
P6	2.6	0.054	0.048	5.6	15.29
P9	2.5	0.035	0.072	7.0	19.88
			Double-layer fabric		
CWA1	1.9	0.055	0.035	0.250	0.93
CWA4	2.0	0.063	0.032	0.170	0.60
CWA7	2.0	0.11	0.019	0.280	0.99
CWA2	3.0	0.077	0.039	0.034	0.08
CWA5	2.9	0.081	0.034	0.550	1.35
CWA8	2.9	0.11	0.026	0.032	0.08
CWA3	4.1	0.081	0.051	0.039	0.07
CWA6	4.1	0.089	0.046	0.170	0.29
CWA9	4.2	0.092	0.046	0.033	0.06
CP1	1.7	0.076	0.022	0.027	0.11

(*Contd*.)

Table 2 —Thermal properties, surface and volume resistivity of knitted fabrics (*Contd.*)

Fabric code	Thickness mm	Thermal conductivity W/m K	Thermal resistance m^2K/W	Surface resistivity (10^{11}) Ω/cm^2	Volume resistivity (10^{11}) Ω-cm
CP4	1.9	0.072	0.027	0.170	0.64
CP7	1.7	0.068	0.025	0.280	1.17
CP2	2.0	0.067	0.03	0.090	0.32
CP5	2.4	0.078	0.031	0.550	1.63
CP8	2.1	0.084	0.025	0.030	0.11
CP3	2.9	0.11	0.027	0.120	0.29
CP6	3.0	0.075	0.041	0.170	0.40
CP9	2.9	0.065	0.045	0.033	0.08
			Triple-layer fabric		
CWA1B	2.3	0.061	0.039	0.590	1.82
CWA4B	2.4	0.11	0.025	0.042	0.12
CWA7B	2.4	0.055	0.044	0.510	1.51
CWA2B	3.4	0.13	0.026	0.061	0.12
CWA5B	3.2	0.11	0.031	0.750	1.66
CWA8B	3.3	0.11	0.032	0.082	0.18
CWA3B	4.5	0.11	0.043	0.100	0.16
CWA6B	4.5	0.12	0.038	0.290	0.46
CWA9B	4.6	0.083	0.055	0.033	0.05
CP1B	2.1	0.060	0.035	0.077	0.26
CP4B	2.3	0.077	0.032	0.220	0.68
CP7B	2.1	0.078	0.027	0.340	1.15
CP2B	2.4	0.068	0.036	0.230	0.68
CP5B	2.8	0.08	0.035	0.540	1.37
CP8B	2.5	0.084	0.032	0.750	2.13
CP3B	3.3	0.110	0.031	0.280	0.60
CP6B	3.4	0.078	0.043	0.130	0.27
CP9B	3.3	0.075	0.045	0.390	0.84

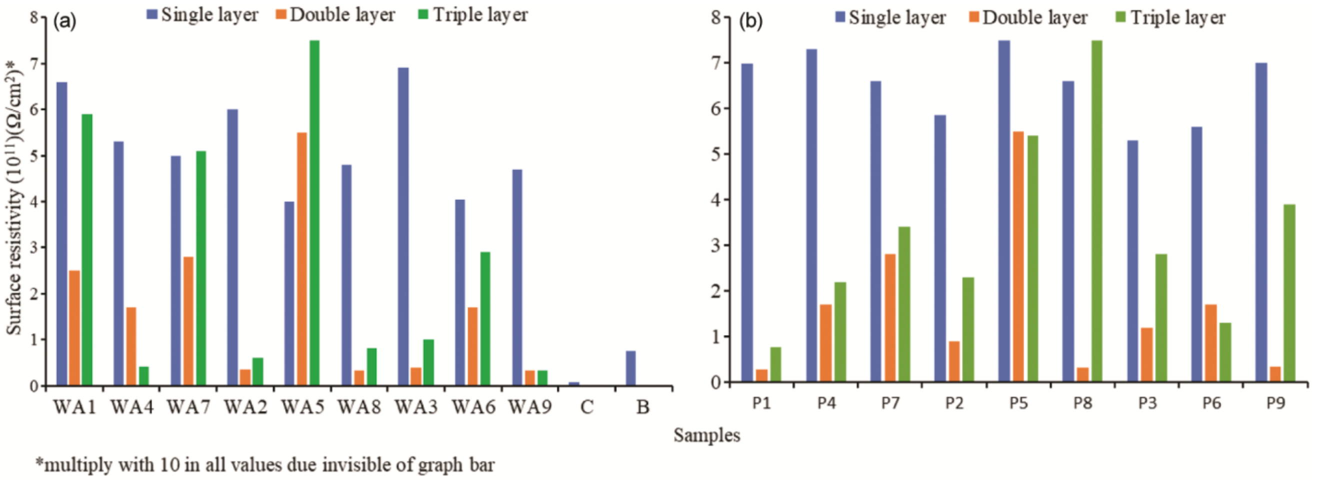
Samples with a higher filament count exhibit improved thermal insulation across all knitted fabric structures—plain, rib, and pile. The finer denier yarn, with a larger surface area, entraps more air, resulting in increased thermal resistance. The highest thermal resistance (0.072 m²K/W) is recorded in sample P9, a pile knit fabric with the finest denier.

3.1.2 Effect of Double-Layer Clothing

In the second set of experiments, a lightweight cotton fabric is added as a liner material. Figure 1 (a) shows that increasing the wool component by 30 to 70% decreases thermal resistance in all fabric structures, namely plain (0.035- 0.019 m^2K/W), rib (0.039-0.026 m^2K/W), and pile knit (0.051-0.046 m^2K/W). The overall thermal resistance of the two-layer assembly decreases due to the adhesion of the cotton fabric to the wool layer, reducing air entrapment. Similarly, in PP knitted fabrics, the addition of cotton decreases overall thermal insulation in all knitted structures. The reduced air-entrapping properties of the combined PP and cotton layers result in lower thermal resistance. However, in a pile knit structure with finer denier yarn, the sticking of cotton fabric is not prominent, and its thermal resistance remains relatively unaffected. Among these samples, CP9 exhibits superior thermal resistance.

3.1.3 Effect of Triple-Layer Clothing

The third set of experiments introduces a breathable fabric as an outer layer. Figure 1 (a) demonstrates that the addition of this microporous breathable fabric significantly reduces thermal resistance in all knitted structures—plain (0.035-0.019 m^2K/W), rib (0.039-0.026 m^2K/W), and pile (0.051-0.046 m^2K/W). The outer layer is a microporous breathable fabric that is highly moisture permeable fabric and will conduct thermal energy, reducing overall heat build-up. This phenomenon has resulted in decreased thermal insulation properties. In another



*multiply with 10 in all values due invisible of graph bar

Fig. 2 — Surface resistivity of multi-layer assemblies (a) cotton, wool/acrylic, & breathable fabric, and (b) cotton, polypropylene & breathable fabric

experiment, PP fabric is sandwiched between cotton and breathable fabric. As shown in Fig. 1 (b), the thermal resistance of the triple-layer assembly remains comparable to that of the double-layer assembly. Since PP fibre has a negligible moisture content, the breathable outer layer does not significantly alter overall moisture permeability, resulting in thermal resistance values similar to those of the PP-cotton double-layer system.

3.2 Surface and Volume Resistivity of Clothing

Surface and volume resistivity depends on the accumulation of static electric charge. Hydrophobic fibres tend to accumulate static charges, whereas hydrophilic fibres dissipate them due to the dielectric properties of water and moisture[10]. In textiles, fibres with higher moisture content (cotton, viscose and wool) effectively dissipate static electric charge while those with lower moisture content (PP, polyester and polyethylene) accumulate them[14].

3.2.1 Effect of Single-Layer Clothing

As shown in Fig. 2 (a), an increase in wool content from 30% to 70% in wool/acrylic blends leads to a decrease in surface and volume resistivity across all knitted structures—plain (6.6-5.0 Ω/cm^2), rib (6.0-4.8 Ω/cm^2), and pile (6.9-4.7 Ω/cm^2). For PP fabric samples, moisture content significantly affects resistivity; therefore, this property does not depend on the denier of the filament content but rather on the knitting structure. The surface resistivity remains consistent across all samples, as it is a surface property. In the PP samples, the surface is PP fibre. Volume resistivity is not dependent on the knitting surface but depends on the fabric thickness, which is influenced by the knitting structure. Thicker fabrics exhibit lower volume resistivity.

3.2.2 Effect of Double-Layer Clothing

In another set of experiments, with the addition of one layer of light weight cotton fabric over wool/acrylic knitted fabric and PP fabric, both surface resistivity and volume resistivity significantly decreased to a greater extent [Fig. 2 (b)], and the cotton fabric (moisture content: 8.5%) dissipated the overcharge build-up. This has been displayed by both classes of samples. For pile fabric samples, wool/acrylic with a cotton layer has shown better results than PP cotton (CP-9) layer samples because wool has inherent moisture content properties.

3.2.3 Effect of Triple-Layer Clothing

With the addition of the breathable fabric (ePTFE) to the two-layer system, no significant changes in surface or volume resistivity are observed in PP samples. The surface resistivity and volume resistivity are higher than for the wool/acrylic layer system; this is because PP knitted fabric is a hydrophobic fibre. The wool/acrylic system maintains lower resistivity due to wool's hydrophilic nature, and its static electric charge is dissipated. Figure 3 (a) shows that in pile fabric samples, wool/acrylic blends exhibit lower surface and volume resistivity compared to PP samples. Notably, surface resistivity remains consistent across the two-layer and three-layer assemblies.

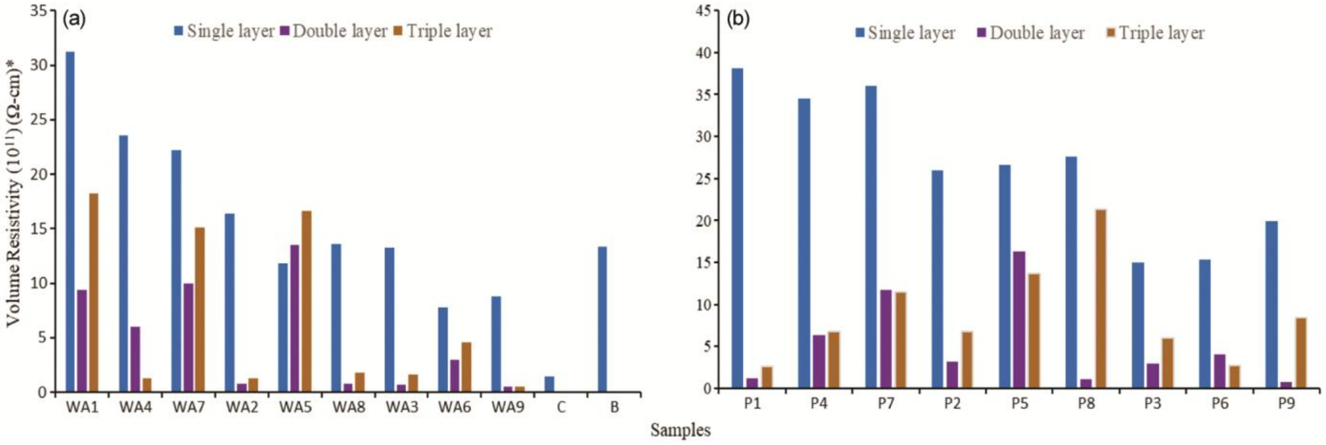


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Fig. 3 — Volume resistivity of multi-layer assemblies (a) cotton, wool/acrylic & breathable fabric, and (b) cotton, polypropylene & breathable fabric

4 Conclusion

The present study evaluates the thermal resistance, surface resistivity and volume resistivity of a multilayer fabric assembly comprising a lightweight cotton knitted inner layer (next to the skin), wool/acrylic and polypropylene knitted middle layer, and breathable waterproof outer layer. The findings indicate that single-layer polypropylene (P9) pile structure knitted fabrics exhibit the highest thermal resistance, while polypropylene (P3) pile structure knitted fabrics demonstrate the lowest surface and volume resistivity. In the two-layer assembly, thermal resistance values and surface resistivity are nearly identical in samples CWA9 and CP9, with similar volume resistivity. In the three-layer assembly, thermal resistance and volume resistivity remain consistent in samples CWA4B and CWA2B, whereas sample CWA9B shows the lowest surface resistivity, and CP9B demonstrates the highest thermal resistance. Therefore, a three-layer fabric assembly with a lightweight cotton knitted inner layer, polypropylene with a higher filament count as the middle layer, and a breathable waterproof outer layer provide superior comfort properties. These findings contribute to the development of thermally insulating and antistatic clothing for extremely cold climates using polypropylene pile-knitted fabric with a higher filament count.

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