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Linear regression analysis of properties related to moisture management using cotton–polyester knitted fabrics

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Abstract

The complex evaluation of thermo-physiological comfort for a particular garment is still challenging, as it depends on the different structural parameters and individual properties of textiles. Measurement of relevant fabric characteristics requires very specific laboratory equipment, such as an M 290 moisture management tester (SDL ATLAS) or similar. For this reason, it is obvious that there is a great demand to predict the overall moisture management capability (*OMMC*) based on the individual properties that are responsible for clothing comfort and testing according to different standards rather than *OMMC*-specific calculation using the M 290 tester. Therefore, in this research, linear regression analysis was performed using MATLAB software to predict the *OMMC* for cotton–polyester fabrics knitted in two patterns, namely 1 × 1 rib and half-Milano rib, using four percentages of fibers. Water vapor permeability, water vapor resistance, water absorption capacity, water absorption time, and air permeability were used as input variables for linear regression analysis to predict the *OMMC* of fabrics. The performed analysis has shown that the *OMMC* is directly dependent on the relative water vapor permeability and air permeability, and the linear regression equation suggested in this research can predict the suitability of a textile for a particular garment concerning its moisture management behavior.

Keywords

Moisture management, linear regression analysis, knitted fabric, antistatic polyester, 1 × 1 rib, half-Milano

Moisture management is a key factor that influences the comfort level of each type of clothing. Comfort properties are divided into three groups, namely mechanical comfort, thermo-physiological comfort, and sensorial comfort. Thermo-physiological comfort mainly comprises thermal and moisture management comfort; however, in this research only the moisture management properties of fabrics are focused on to develop the mathematical relationship between them. Moisture management properties include clothing performance in terms of the water absorption capacity, water absorption time, water vapor permeability, water vapor resistance, overall moisture management capability (*OMMC*), etc. However, the moisture management properties of clothing are influenced by many factors, for example, fiber content and structure, yarn structure, fabric structure, treatment type, etc.

Many researchers have studied the moisture management properties of knitted fabrics. The morphology of the fiber and the yarn and the cross-sectional area are among the main factors that alter moisture management and many other properties. The effect of fiber morphology on the moisture management properties of knitted fabrics manufactured using Coolmax® yarns and multifilament polyester yarns were studied and it was concluded that the fabrics manufactured from Coolmax® channeled yarns show better moisture management compared to those manufactured from multifilament polyester yarns due to the channeled surface of the yarns.[1] The percentage of different fibers in the mixture also affects the moisture management properties.[2] In addition, the number of filaments in the yarn and the texture of the yarns, whether ring- or rotor-type yarns, show different behavior to manage the liquid moisture property of knitted fabrics.[3,4] The fineness of the yarn also affects the water vapor permeability.[5–7]

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The type of raw materials, such as the geometry of synthetic or natural fibers, and the fineness of the fibers also affect the properties of the fabrics. Polyester fabrics showed better moisture management than cellulosic fabrics due to their low moisture absorption and higher wicking.[8] Different cross-sectional shapes of the fibers also affect their moisture management capacity. The trilobal cross-sectional shape of polyester fibers showed greater moisture management than round cross-sectional polyester fibers.[9,10] Research shows that even within the group of natural fibers, such as cotton, bamboo, jute, hemp, etc., differences exist concerning their moisture management. The increase in the percentage of bamboo in the fiber mixture can improve some properties of bamboo fabrics compared to cotton fabric,[11] contrary to the change in the $OMMC$ of fabrics with a higher percentage of cotton fibers in their content.[12] Furthermore, the design of double-sided fabrics improves the moisture management properties of textiles; for example, due to its hydrophobic nature and good wicking performance, polyester is preferred for the back side applied next to human skin in a garment.[13,14] Natural collagen fiber also improves the moisture management property in fabrics.[15]

The fabric structure is another factor that influences the moisture management properties of textiles. For example, tight fabric does not allow water vapor to pass through it, consequently demonstrating its water vapor resistance.[16,17] Similarly, tight-knitted fabrics show decreased liquid moisture transport. However, loose-knitted fabrics show poor moisture management properties, such as the liquid moisture absorption rate, spread speed, and maximum wetting radius.[18] An increase in the tightness of the fabric also influences the increase in the wicking height of the fabrics.[19,20] Furthermore, the higher cover factor of the fabrics influences the lower $OMMC$ of the fabrics.[21] The cover factor is also related to tightness or looseness, for example, mesh or high-porous fabrics show low water vapor resistance.[22,23] The fabric thickness changes the water evaporation rate and the air permeability of knitted fabrics.[24,25]

Treatment of fibers or fabrics is an effective way to achieve the required moisture management concerning a specific function of the textile.[26,27] Different types of fabric treatment, such as washing, bleaching, dyeing, softening, and specific functional finishes and coatings (antibacterial, water repellent, fire retardant, etc.) can alter the moisture management properties of fabric. For example, treatment with anionic or cationic softeners or bleaching can alter the water vapor permeability[28] and the water vapor resistance[29] of fabric. Alternatively, casein-based material can change the maximum wetting radius and the one-way transport index of fabric.[30]

The reviewed literature has shown that the textile properties responsible for the comfort of clothing, such as moisture management,[1–4,8,18] water vapor permeability, water vapor resistance,[16,17,27] wicking,[13,15,19,21] $OMMC$,[12,21] the water evaporation rate,[24,25] air permeability,[24,25] and others, vary differently depending on a variety of factors. However, there has not been prior development of linear regression equations for forecasting the comprehensive $OMMC$ of textiles. The $OMMC$ is typically assessed through a moisture management test using an M 290 Moisture Management Tester (SDL ATLAS) based on experimental testing of individual properties or information available in the literature. Such a linear regression equation will help the clothing manufacturer or the customer to select the most suitable fabric for a particular piece of clothing. In addition, it will provide a simple method to understand the fabric performance without involving the non-destructive fabric testing method. Therefore, this research aimed to develop a linear regression equation that will be suitable to predict the $OMMC$ of cotton–polyester knitted fabrics by using the moisture management properties of fabrics.

Materials and methods

Tested materials

Two knitted fabric patterns, namely 1 × 1 rib (MR) and half-Milano rib (MM), were applied to knit the fabric samples with a fully automatic flat knitting machine, an M-100 (model 2016, MATSUYA, Japan) of 14 gauge. The settings of the knitting machine were kept constant for fabric knitting using yarns made in four different percentages of cotton (CO) and antistatic polyester (PET_A) fiber mixtures (Table 1). Three groups of samples were prepared. The first sample group consisted of raw fabrics marked with codes MR1–MR4 and MM1–MM4. The second sample group was dyed and treated with Aquasoft SI® hydrophilic softener fabrics, marked with codes MR1S–MR4S and MM1S–MM4S. The third sample group was dyed, softened, and treated with Polygiene VO-600 antibacterial finish fabrics, marked with codes MR1(S + P)-MR4(S + P) and MM1(S + P)-MM4 (S + P). A THIES MINISOFT dyeing machine (model 1995, Germany) and CH9555 Tobel machine (Santex) were used for the application of the softener and the antibacterial finish, Polygiene VO-600. The technological parameters for the softening were as follows: 20 g/L concentration, 40–50°C temperature, and 15–30 min duration; and for the antibacterial finishing: 25 g/L concentration, 30–40°C temperature, and 20–30 min duration. To characterize the structure of the developed knitted fabrics, the mass per unit area, the fabric thickness, the wale, and the course densities were determined according to the standards ISO

Table 1. Characteristics of the investigated knitted fabrics (CO: cotton; PET$_A$: antistatic polyester; the yarn producer was Haining TAIERXIN New Materials Co., Ltd)

Sample code	Fiber composition (%)	Yarn linear density (tex)	Wale density (cm^{-1})	Course density (cm^{-1})	Fabric thickness (mm)	Mass per unit area (g/m^2)
1 × 1 rib knitted fabrics (MR)						
MR1	90% CO, 10% PET$_A$	28.1 × 3	15.00 ± 0.50	10.60 ± 0.60	1.95 ± 0.04	597.73 ± 0.09
MR1S			16.00 ± 0.00	12.00 ± 0.00	1.82 ± 0.02	611.50 ± 0.06
MR1 (S + P)			16.00 ± 0.00	12.00 ± 0.00	1.80 ± 0.02	603.60 ± 0.05
MR2	80% CO, 20% PET$_A$	28.1 × 3	15.00 ± 0.50	11.00 ± 0.00	1.95 ± 0.05	577.60 ± 0.10
MR2S			16.00 ± 0.00	12.00 ± 0.00	1.78 ± 0.02	607.10 ± 0.06
MR2 (S + P)			16.00 ± 0.00	12.00 ± 0.00	1.80 ± 0.01	608.10 ± 0.06
MR3	70% CO, 30% PET$_A$	18.5 × 4	14.60 ± 0.50	10.60 ± 0.60	1.90 ± 0.03	565.73 ± 0.05
MR3S			16.00 ± 0.00	12.00 ± 0.00	1.84 ± 0.01	528.70 ± 0.05
MR3 (S + P)			16.00 ± 0.00	12.00 ± 0.00	1.87 ± 0.02	616.40 ± 0.09
MR4	65% CO, 35% PET$_A$	14.8 × 3	15.80 ± 0.50	11.60 ± 0.60	1.89 ± 0.02	511.07 ± 0.12
MR4S			16.00 ± 0.00	12.00 ± 0.00	1.71 ± 0.01	524.90 ± 0.07
MR4 (S + P)			16.00 ± 0.00	12.00 ± 0.00	1.81 ± 0.02	509.60 ± 0.08
Half-Milano knitted fabrics (MM)						
MM1	90% CO, 10% PET$_A$	28.1 × 3	14.00 ± 0.50	13.80 ± 0.50	1.96 ± 0.04	587.33 ± 0.09
MM1S			16.00 ± 0.00	18.00 ± 0.00	1.80 ± 0.02	642.40 ± 0.08
MM1 (S + P)			16.00 ± 0.00	18.00 ± 0.00	1.83 ± 0.01	641.20 ± 0.05
MM2	80% CO, 20% PET$_A$	28.1 × 3	14.20 ± 0.50	13.80 ± 0.50	1.95 ± 0.05	588.40 ± 0.09
MM2S			16.00 ± 0.00	18.00 ± 0.00	1.77 ± 0.01	659.30 ± 0.05
MM2 (S + P)			16.00 ± 0.00	18.00 ± 0.00	1.79 ± 0.02	658.30 ± 0.05
MM3	70% CO, 30% PET$_A$	18.5 × 4	13.00 ± 0.50	13.80 ± 0.50	1.91 ± 0.04	544.67 ± 0.05
MM3S			16.00 ± 0.00	18.00 ± 0.00	1.86 ± 0.01	577.60 ± 0.04
MM3 (S + P)			16.00 ± 0.00	18.00 ± 0.00	1.94 ± 0.02	667.60 ± 0.06
MM4	65% CO, 35% PET$_A$	14.8 × 3	14.00 ± 0.50	12.20 ± 0.50	1.91 ± 0.03	498.13 ± 0.07
MM4S			16.00 ± 0.00	16.00 ± 0.00	1.83 ± 0.01	539.30 ± 0.06
MM4 (S + P)			16.00 ± 0.00	16.00 ± 0.00	1.82 ± 0.02	506.70 ± 0.04

3801:1998,[31] ISO 5084:2000,[32] and EN 14971:2006,[33] respectively.

Testing methodology of the water absorption capacity water absorption time, relative water vapor permeability, water vapor resistance, and air permeability

The water absorption capacity (WAC) and the water absorption time (WAT) of the developed knitted fabrics were determined according to the ISO 20158:2018[34] standard. The relative water vapor permeability ($RWVP$) and water vapor resistance (R_{et}) were determined by applying a non-destructive method performed with a PERMETEST (Sensora Instrument, Czech Republic) according to ISO 11092:2014[35] standards. The air permeability of the fabrics (R_{air}) was tested according to the EN ISO 9237:1995[36] standard. The results of the tested properties are presented in Table 2. Before all testing procedures, fabric samples were conditioned under the standard atmospheric conditions defined in the ISO 139:2005[37] standard.

Moisture management test

The moisture management test was performed using the M290 tester (SDL ATLAS) (Figure 1) according to the AATCC 195:2011 standard.[38] According to the test method, the measurement, evaluation, and classification of the moisture management properties, such as the top wetting time, bottom wetting time, top absorption rate, bottom absorption rate, top maximum wetted radius, bottom maximum wetted radius, top spreading speed, bottom spreading speed, accumulative one-way transport index ($AOWTI$), and $OMMC$ of fabrics were performed.

Table 2. Summary of the separate properties related to moisture management

	Water absorption capacity (*WAC*) (%)		Water absorption time (*WAT*) (s)		Relative water vapor permeability (*RWVP*) (%)		Absolute water vapor resistance (R_{et}) (Pa·m^2·W^{-1})		Air permeability (R_{air}) (mm/s)
Fabric code	Face	Back	Face	Back	Face	Back	Face	Back	Face
1 × 1 rib knitted fabrics (MR)									
MR1	7.4	5.7	–	–	45.3	45.5	52.5	52.4	409
MR1S	184.7	184.2	6.7	7.5	42.6	42.5	9.1	9.0	117
MR1 (S + P)	185.7	200.1	9.6	9.3	40.8	40.7	9.5	9.5	120
MR2	4.2	4.6	–	–	44.3	44.3	33.8	33.6	424
MR2S	182.1	181.8	8.4	8.5	44.2	44.1	8.5	8.5	140
MR2 (S + P)	180.5	178.7	10.4	10.6	44.6	44.6	8.8	8.8	123
MR3	6.0	6.5	–	–	45.2	45.4	21	21.1	480
MR3S	227.3	223.8	11.9	11.5	46.5	46.5	7.8	7.8	175
MR3 (S + P)	185.1	185.8	11.7	11.2	45.8	45.8	8.3	8.3	145
MR4	4.7	5.7	–	–	45.0	45.0	8.2	8.2	497
MR4S	204.9	206.7	11.7	11.7	47.0	47.0	7.7	7.7	183
MR4 (S + P)	229.7	231.3	11.3	11.6	47.4	47.4	8.4	8.4	214
Half-Milano knitted fabrics (MM)									
MM1	6.5	4.2	–	–	44.4	44.4	45.8	45.5	333
MM1S	171.5	171.8	3.8	9.7	39.8	39.7	9.5	9.4	87
MM1 (S + P)	180.3	179.1	5.8	11.3	38.7	38.6	9.7	9.7	77
MM2	7.3	3.1	–	–	43.0	43.1	31.1	31.1	358
MM2S	162.3	164.8	5.3	10.9	43.3	43.2	8.8	8.9	100
MM2 (S + P)	165.6	168.2	6.5	15.4	42.1	42.5	9.6	9.7	83
MM3	5.0	4.7	–	–	43.2	43.0	20.2	20.2	376
MM3S	205.6	202.8	8.0	16.8	45.2	45.2	8.2	8.1	124
MM3 (S + P)	174.7	176.1	7.5	17.4	43.8	43.8	9.1	9.2	102
MM4	8.9	2.4	–	–	45.0	45.0	7.9	7.9	407
MM4S	219.0	220.3	7.7	12.5	44.7	44.7	8.4	8.4	166
MM4 (S + P)	236.7	217.3	5.3	17.5	44.5	43.4	7.7	7.8	180

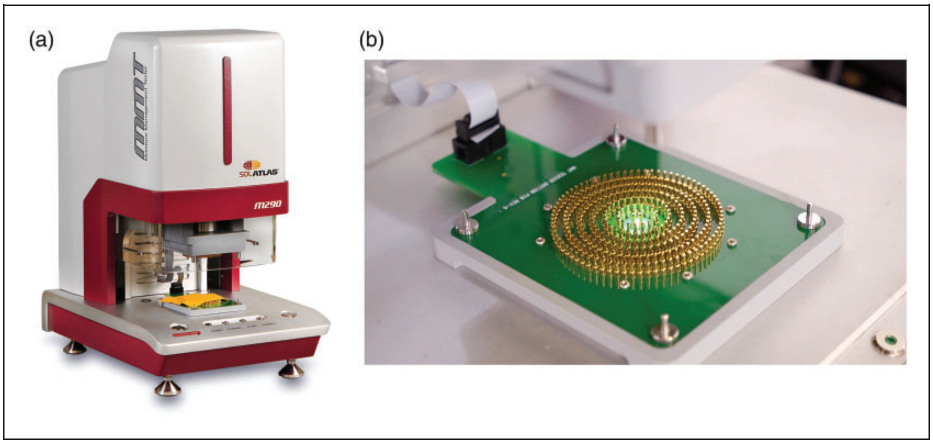

Figure 1. Moisture management tester (a) and lower sensor (b). (https://sdlatlas.com/products/mmt-moisture-management-tester#product-testmaterials)

Two test specimens were cut diagonally in 6.35 mm × 6.35 mm dimensions across the width of the fabric and a 9 g sodium chloride solution (NaCl) (USP grade) was prepared in 1 L of distilled water and its electrical conductivity was adjusted to 16 ± 0.2 milli Siemens (mS) at 25°C. This conductive test solution was used to provide a conductive medium to the instrument sensors to check moisture movement in the test specimen fabric. The test specimens were placed on the lower sensor, the upper sensor was placed on top of it,

Table 3. Summary of all the moisture management test (MMT) results

Fabric code	Top wetting time (s)	Bottom wetting time (s)	Top absorption rate (%/s)	Bottom absorption rate (%/s)	Top maximum wetted radius (mm)	Bottom maximum wetted radius (mm)	Top spreading speed (mm/s)	Bottom spreading speed (mm/s)	Accumulative one-way transport index (*AOWTI*) (%)	Overall moisture management capability (*OMMC*)
1 × 1 rib knitted fabrics (MR)										
MR1	8.28	0.00	21.32	0.00	5.00	0.00	0.60	0.00	–469.98	0.00
MR1S	7.04	6.64	11.21	23.76	10.00	10.00	1.25	1.23	219.12	0.36
MR1 (S + P)	6.24	6.72	10.97	21.34	10.00	10.00	1.25	1.24	136.95	0.26
MR2	5.80	5.80	32.70	32.70	0.00	10.00	0.0	1.23	881.81	0.58
MR2S	5.91	6.20	10.23	21.40	10.00	10.00	1.37	1.29	177.73	0.31
MR2 (S + P)	5.95	6.77	5.65	10.50	5.00	5.00	0.71	0.61	51.60	0.14
MR3	6.25	6.20	22.62	14.04	2.50	2.50	0.18	0.39	56.47	0.28
MR3S	5.99	5.91	9.92	22.53	10.00	10.00	1.41	1.33	184.02	0.32
MR3 (S + P)	6.20	6.48	10.83	21.30	10.00	10.00	1.34	1.29	113.53	0.24
MR4	8.44	6.36	25.00	27.99	0.00	5.00	0.00	0.66	691.70	0.55
MR4S	5.84	6.12	12.66	25.62	12.50	10.00	1.51	1.37	156.74	0.30
MR4 (S + P)	5.68	6.08	15.69	23.73	12.50	10.00	1.70	1.42	84.17	0.22
Half-Milano knitted fabrics (MM)										
MM1	9.95	0.00	25.7	0.00	5.00	0.00	0.49	0.00	−133.48	0.00
MM1S	8.28	8.04	9.38	17.18	10.00	10.00	1.09	1.09	87.02	0.18
MM1 (S + P)	6.36	7.20	11.98	14.07	10.00	10.00	1.23	1.17	33.56	0.12
MM2	8.77	3.88	35.74	17.75	2.50	2.50	0.28	0.62	−110.89	0.30
MM2S	6.36	6.64	9.08	18.09	10.00	10.00	1.26	1.22	109.05	0.22
MM2 (S + P)	6.64	7.20	11.03	14.54	10.00	10.00	1.21	1.16	50.98	0.14
MM3	9.64	6.20	28.6	13.08	2.50	5.00	0.26	0.74	-23.14	0.29
MM3S	6.24	6.68	12.43	19.83	10.00	10.00	1.31	1.20	93.08	0.20
MM3 (S + P)	7.04	7.95	12.72	16.29	10.00	10.00	1.18	1.04	31.20	0.11
MM4	6.92	6.92	32.6	27.16	2.50	2.50	0.17	0.35	52.18	0.31
MM4S	6.59	6.52	6.30	10.11	5.00	5.00	0.64	0.65	45.69	0.13
MM4 (S + P)	7.32	6.96	11.12	17.10	10.00	10.00	1.33	1.27	45.69	0.15

and the instrument was locked. The measurement time was set at 120 s, and at the end of the 120 s test time, the software automatically stopped the test and calculated all the parameters presented in Table 3.

The moisture management tester software calculates the $OMMC$ of knitted fabric using

$$OMMC = C_1 \times AR_{B_{ndv}} + C_2 \times AOWTI_{ndv} + C_3 \times SS_{B_{ndv}} \tag{1}$$

where AR_B is the bottom absorption rate, %/s; $AOWTI$ is the $AOWTI$, %; and SS_B is the spreading speed, mm/s; $C_1 = 0.25$, $C_2 = 0.5$, and $C_3 = 0.25$ are the weights of the parameters without dimensions, such as AR_{B_ndv}, the absorption rate bottom; R_{ndv}, the one-way transport capability; and SS_{Bndv}, the spreading speed.

Results and discussion

Water absorption capacity water absorption time, relative water vapor permeability, water vapor resistance, and air permeability

A summary of the fabric properties, that is, WAC, WAT, $RWVP$, water vapor resistance (R_{et}), and air permeability (R_{air}), that significantly influence clothing comfort is presented in Table 2. Using these parameters, the correlation matrices presented in Tables 4–7 were studied to determine the influence of the input variables on the $OMMC$ for knitted fabrics of both knit patterns (1×1 rib and half-Milano rib), as well as for both types of their treatments (S and (S + P) samples). In Table 2, the mean values of the parameters were reported, but the statistical analysis was performed using all the experimental values measured for each of the five specimens in a sample group.

Minitab 17 statistical software based on the one-way analysis of variance (ANOVA) method was applied to evaluate whether the influence of knit pattern and treatment on the investigated parameters of knitted fabrics manufactured in four different fiber contents that are presented in Figures 2–6 (Table 2) is significant or not. The influence of the tested variables was maintained significant when $P_{value} < 0.05$.

Figure 2 shows that the WAC of all the investigated knitted fabrics was significantly dependent on the two investigated treatments and showed the same tendencies in their changes. The WAC was increased after fabric treatments as a result of the removal of impurities and other additional materials, such as natural waxes, pectin, yarn wax, etc., from the fabrics. Natural waxes and pectin for CO fibers and yarn wax are used to reduce resistance in machine parts, and do not allow

Table 4. Correlation matrix of the influence of input variables on the value of the overall moisture management capability (*OMMC*) for softened and antibacterial treated (S + P) 1 × 1 rib knitted fabrics (*RWVP*: relative water vapor permeability; R_{et}: absolute water vapor resistance; R_{air}: air permeability; WAC_1: water absorption capacity m_1; WAC_2: water absorption capacity m_2; *WAT*: water absorption time)

	OMMC	*RWVP*	R_{et}	R_{air}	WAC_1	WAC_2	*WAT*
OMMC	1	**−0.9117**	0.7105	−0.7149	0.6304	0.6053	−0.6489
RWVP	**−0.9117**	1	−0.9557	0.7939	−0.5651	−0.3505	0.9002
R_{et}	0.7105	−0.9557	1	−0.6300	0.3151	0.0609	−0.9692
R_{air}	−0.7149	0.7939	−0.6300	1	−0.9141	−0.6445	0.6496
WAC_1	0.6304	−0.5651	0.3151	−0.9141	1	0.8798	−0.2969
WAC_2	0.6053	−0.3505	0.0609	−0.6445	0.8798	1	0.0517
WAT	−0.6489	0.9002	−0.9692	0.6496	−0.2969	0.0517	1

Table 5. Correlation matrix of the influence of input variables on the value of the overall moisture management capability (*OMMC*) for softened and antibacterial treated (S + P) half-Milano knitted fabrics (*RWVP*: relative water vapor permeability; R_{et}: absolute water vapor resistance; R_{air}: air permeability; WAC_1: water absorption capacity m_1; WAC_2: water absorption capacity m_2; *WAT*: water absorption time)

	OMMC	*RWVP*	R_{et}	(R_{air})	WAC_1	WAC_2	*WAT*
OMMC	1	0.5932	**−0.8591**	**0.8948**	−0.9321	**−0.9626**	−0.6714
RWVP	0.5932	1	−0.7479	0.7240	−0.4864	−0.4657	0.1703
R_{et}	**−0.8591**	−0.7479	1	−0.9970	0.9235	0.6892	0.4614
(R_{air})	**0.8948**	0.7240	−0.9970	1	−0.9469	−0.7405	−0.5156
WAC_1	−0.9321	−0.4864	0.9235	−0.9469	1	0.8244	0.7633
WAC_2	−0.9626	−0.4657	0.6892	−0.7405	0.8244	1	0.6856
WAT	−0.6714	0.1703	0.4614	−0.5156	0.7633	0.6856	1

Table 6. Correlation matrix of the influence of input variables on the value of the overall moisture management capability (*OMMC*) for dyed and softened (S) 1 × 1 rib knitted fabrics (*RWVP*: relative water vapor permeability; R_{et}: absolute water vapor resistance; R_{air}: air permeability; WAC_1: water absorption capacity m_1; WAC_2: water absorption capacity m_2; *WAT*: water absorption time)

	OMMC	*RWVP*	R_{et}	R_{air}	WAC_1	WAC_2	*WAT*
OMMC	1	**−0.8841**	0.8815	−0.8820	−0.8090	0.8084	−0.8251
RWVP	**−0.8841**	1	−0.9982	0.9999	0.9728	−0.9164	0.9912
R_{et}	0.8815	−0.9982	1	−0.9974	−0.9843	0.8907	−0.9941
(R_{air})	−0.8820	0.9999	−0.9974	1	0.9698	−0.9211	0.9907
WAC_1	−0.8090	0.9728	−0.9843	0.9698	1	−0.8019	0.9739
WAC_2	0.8084	−0.9164	0.8907	−0.9211	−0.8019	1	−0.8793
WAT	−0.8251	0.9912	−0.9941	0.9907	0.9739	−0.8793	1

Table 7. Correlation matrix of the influence of input variables on the value of overall moisture management capability (*OMMC*) for dyed and softened (S) half-Milano knitted fabrics (*RWVP*: relative water vapor permeability; R_{et}: absolute water vapor resistance; R_{air}: air permeability; WAC_1: water absorption capacity m_1; WAC_2: water absorption capacity m_2; *WAT*: water absorption time)

	OMMC	*RWVP*	R_{et}	R_{air}	WAC_1	WAC_2	*WAT*
OMMC	1	−0.4802	0.4443	**−0.9408**	−0.2201	0.8335	−0.5897
RWVP	−0.4802	1	−0.9893	0.7412	0.9613	−0.6678	0.9493
R_{et}	0.4443	−0.9893	1	−0.7208	−0.9613	0.7052	−0.9726
R_{air}	**−0.9408**	0.7412	−0.7208	1	0.5292	−0.9204	0.8266
WAC_1	−0.2201	0.9613	−0.9613	0.5292	1	−0.4826	0.8715
WAC_2	0.8335	−0.6678	0.7052	−0.9204	−0.4826	1	−0.8498
WAT	−0.5897	0.9493	−0.9726	0.8266	0.8715	−0.8498	1

water to absorb due to their hydrophobic nature; therefore, CO fibers need to be scoured.[39] However, 1 × 1 rib knitted fabrics showed an insignificant difference ($P_{value} > 0.05$ according to the ANOVA results) in *WAC* compared to half-Milano knitted fabrics.

In Figure 3, the *WAT* of raw fabrics is not given due to the absence of water absorption in raw fabrics even after 120 s of time limit. Figure 3 also shows a significant effect of fabric treatment and pattern on the *WAT* of fabrics, since $P_{value} < 0.05$ for all the fabric patterns and treatment cases. Water absorption occurred in the fabrics after treatment. When analyzing the effect of the fabric patterns, it was shown that 1 × 1 rib knit fabrics showed a longer *WAT* than half-Milano rib knit fabric for the S and (S + P) samples due to the high shrinkage of half-Milano fabric. In addition, in Figure 3 the *WAT* is given for the technical back side of the half-Milano rib knit fabrics. It showed that as a result of differences in the structure of the technical face and technical back of half-Milano rib knitted fabrics, the *WAT* was found to be different. The technical back of the half-Milano rib knitted fabrics showed a high value of *WAT* due to the presence of a tight-knit structure on the technical back of the fabrics.

The changing tendencies of the investigated moisture management and R_{air} properties of all knitted fabrics are presented in Table 2, but were not analyzed in every detail in this investigation, since a very detailed analysis was carried out in our previous research.[40] This research aims to suggest the linear regression equation between the parameters presented in Table 2 and the results obtained by the MMT that provides the *OMMC* (Table 3). The ANOVA confirmed that the *RWVP* of the knitted fabrics (Figure 4) was independent of both types of treatment, namely dyeing and softening (S samples) and dyeing, softening, and antibacterial finishing ((S + P) samples) as the $P_{value} > 0.05$. However, half-Milano knitted fabrics showed significantly ($P_{value} < 0.05$) lower *RWVP* values than the 1 × 1 rib knitted fabrics for both S and (S + P) samples. However, the lower *RWVP* values of the half-Milano knitted fabrics was considered to be due to the more complicated fabric structure that causes more shrinkage than in the 1 × 1 rib fabrics.

The R_{et} value of the fabrics (Figure 5) was dependent on the fabric treatment, but the influence of the fabric patterns was not found to be significant, as ANOVA showed $P_{value} > 0.05$. However, R_{et} values in fabrics increased due to wet treatments that influence relaxation and shrinkage of the fabrics and cause a tighter fabric structure with smaller spaces or lower porosity[39] than those of untreated fabrics. Dyeing, softening, and antibacterial treated (S + P) fabrics showed insignificantly lower R_{et} values than dyeing and softening treated (S) samples, seemingly due to an extra wet treatment (application of antibacterial finish) that caused an insignificant difference in the shrinkage of fabric.

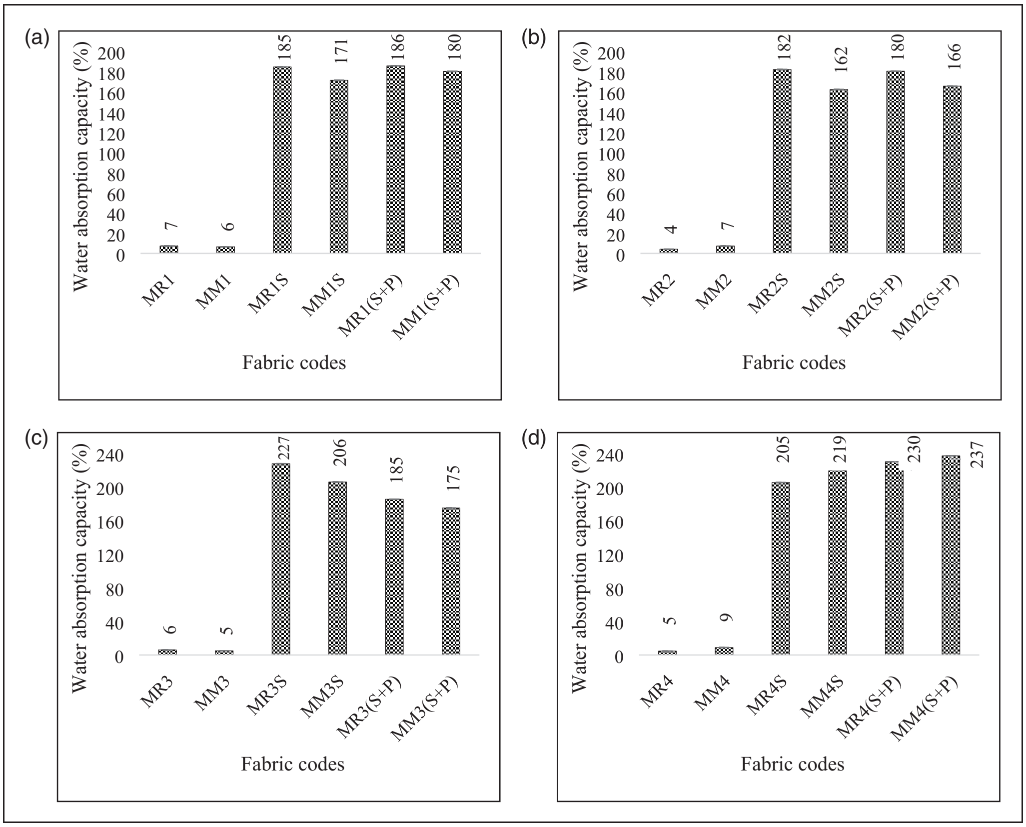

Figure 2. Water absorption capacity (*WAC*) of (1 × 1 rib knitted fabrics (MR)); half-Milano knitted fabrics (MM)), dyed and softened (S), and dyed, softened, and treated with antibacterial finish (S + P) samples of knitted fabrics: 90% cotton (CO), 10% antistatic polyester (PET_A) (a); 80% CO, 20% PET_A (b); 70% CO, 30% PET_A (c); 65% CO, 35% PET_A (d).

The R_{air} value of the fabrics was significantly (the ANOVA showed $P_{value} = 0$) dependent on both knit patterns and both treatments S and (S + P) (Figure 6). This can be explained because of the removal of impurities from the fabrics by wet treatments as well as shrinkage, causing a more compact fabric structure that influenced the lower R_{air} values of the fabrics treated with both the S and the (S + P) treatments compared to those of raw fabrics. Furthermore, it is seen that the (S + P) samples have lower R_{air} values, seemingly due to an additional wet treatment of the antibacterial finish that causes greater shrinkage of the fabrics, except for MR4 (S + P) and MM4 (S + P). The fabric patterns also showed significant effects ($P_{value} = 0$) on the R_{air} values. The half-Milano rib knitted fabric showed lower R_{air} values than 1 × 1 rib knitted fabrics due to the more complicated fabric structure that influenced greater shrinkage after the additional treatment and resulted in fewer open spaces for air to pass through.

Moisture management

The results of the MMT that are related to the dynamic liquid transfer properties and show the transportation of liquids or sweat that accumulate on human skin, but do not provide any information on the transmission of antistatic knitted fabrics, are presented in Table 3. The MMT provides the parameters that elaborate fabric behavior in different directions and on different surfaces and are used to calculate the $OMMC$ and the $AOWTI$.

For the linear regression equation, only the $OMMC$ was considered. However, since both the $OMMC$ and the $AOWTI$ are complex characteristics related to the thermo-physiological comfort of clothing, they were analyzed in more detail to identify their changes due to differences in fiber content, knit pattern, and treatment. Parameters such as the top wetting time, bottom wetting time, top absorption rate, bottom absorption rate, top maximum wetted radius, bottom maximum wetted radius, top spreading speed, and bottom spreading speed were necessary for the calculations of $OMMC$ and $AOWTI$ (Table 3).

When analyzing the $AOWTI$ shown in Figure 7, it was found that the $AOWTI$ was higher for samples of the 1 × 1 rib knit fabrics than for those of the half-Milano knit pattern, as well as for samples S than for samples (S + P). The application of both types of sample treatment significantly decreased the $AOWTI$ if compared with raw samples for both knit patterns,

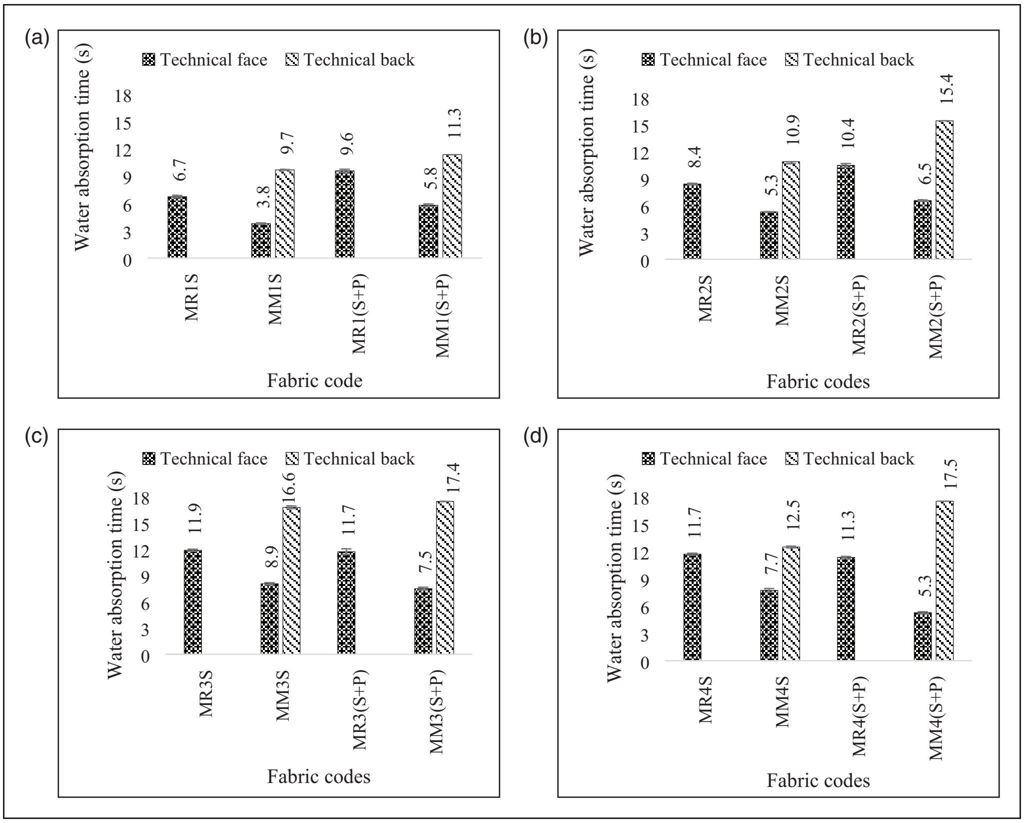

Figure 3. Water absorption time (*WAT*) of (1×1 rib knitted fabrics (MR)); half-Milano knitted fabrics (MM)), dyed and softened (S), and dyed, softened, and treated with antibacterial finish (S + P) samples of knitted fabrics: 90% cotton (CO), 10% antistatic polyester (PET_A) (a); 80% CO, 20% PET_A (b); 70% CO, 30% PET_A (c); 65% CO, 35% PET_A (d).

except for the fabrics that have the 70% CO and 30% PET_A fiber mixture.

The *AOWTI* represents the ability of the fabric to transport liquid from the top surface (which is in contact with the human skin) to the bottom surface. A higher value of the *AOWTI* indicates a higher moisture transport capability of the fabric.

The values of the *OMMC* calculated according to Equation (1) are presented in Table 3. The *OMMC* value of the raw fabrics that had the highest amount (90%) of CO fibers (samples MR1 and MM1) for both knit patterns was equal to zero, seemingly due to impurities and waxes in their structure that were removed later due to applied treatment. However, for the other fiber contents, it was the highest for the raw fabrics and decreased due to the applied treatment in the following sequence: raw samples → samples S → samples (S + P), except for the case of sample MM4 (S + P). The *OMMC*s of the half-Milano fabrics were lower than those of the 1×1 rib knitted fabrics, except for the raw fabric of both knit patterns with the 70% CO/30% PET_A fiber mixture. A higher *OMMC* value shows a higher overall moisture magement capability of the fabric.

Linear regression analysis

The correlation matrix of the influence of the factors investigated (Table 2) on the value of the *OMMC* (Table 3) created using the MATLAB software is presented in Table 4. The statistical evaluation of the experimental results for the softened and antibacterial treated samples (S + P) of the developed knitted fabrics has estimated that some *OMMC*s have a significantly higher standard deviation than the rest. A linear regression analysis for the raw knitted fabrics was not performed since they were not used to produce final clothing.

In Table 4, it is seen that there is a very strong negative correlation between the *OMMC* and the *RWVP*: $\rho = -0.9117$, when $P_{value} < 0.05$ for the softened and antibacterial treated (S + P) 1×1 rib knitted fabrics. Therefore, this parameter must be included in the regression equation. The remaining parameters do not statistically affect the *OMMC*, but Table 4 shows that there is a strong correlation between the *OMMC* and R_{air}: $\rho = 0.7149$, when the $P_{value} = 0.1$. When the $P_{value} = 0.1$ is chosen, then both parameters can be evaluated. Thus, for the analyzed case, we obtained

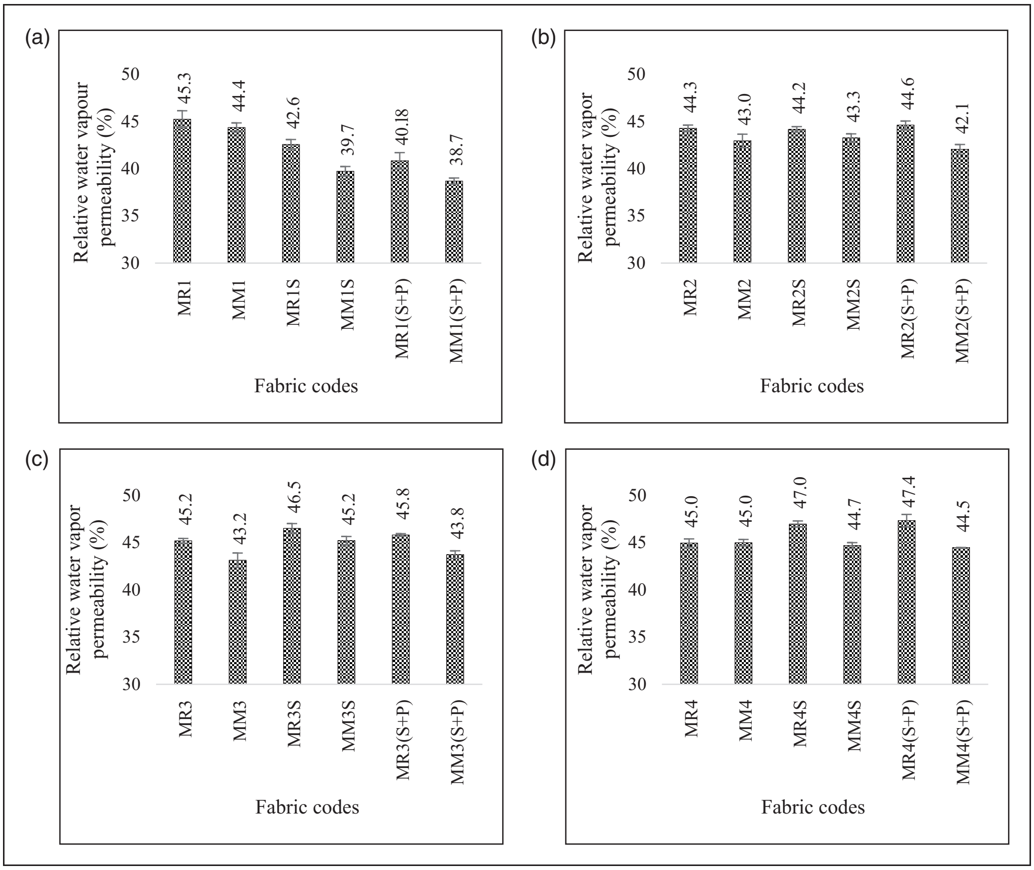

Figure 4. Relative water vapor permeability (*RWVP*) of (1 × 1 rib knitted fabrics (MR)); half-Milano knitted fabrics (MM)), dyed and softened (S), and dyed, softened, and treated with antibacterial finish (S + P) samples of knitted fabrics: 90% cotton (CO), 10% antistatic polyester (PET_A) (a); 80% CO, 20% PET_A (b); 70% CO, 30% PET_A (c); 65% CO, 35% PET_A (d).

$$OMMC_{1\times 1\,rib\,(S+P)} = 0.4405 - 0.0041 \cdot X1 - 0.0001 \cdot X3 \tag{2}$$

where $X1$ is the $RWVP$ and $X3$ is the air permeability (R_{air}).

The analysis of the coefficients in Equation (2) shows that the coefficient next to $X3$ is very small (this was also shown by the statistical analysis of correlations). Furthermore, from the correlation matrix given in Table 4, it is evident that there is a very strong correlation between R_{et} and the WAT: $\rho = -0.9692$, when $P_{value} < 0.05$.

A similar analysis was also carried out for softened and antibacterial-treated (S + P) half-Milano knitted fabrics (Table 5).

In Table 5, it can be seen that there is a very strong negative correlation between $OMMC$ and WAC_2: $\rho = -0.9626$, when $P_{value} < 0.05$, WAC_1: $\rho = -0.9321$, when $P_{value} < 0.1$, and R_{air}: $\rho = 0.8948$, when $P_{value} < 0.1$.

Different parameters influence the $OMMC$ of 1 × 1 rib knitted fabrics and half-Milano knitted fabrics.

If trying to keep Equation (2) analyzed for the 1 × 1 rib knitted fabrics (which is not entirely correct, because the change in $RWVP$ does not affect the half-Milano knitted fabrics), we obtain

$$OMMC = 0.1247 - 0.0006 \cdot X1 + 0.0003 \cdot X3 \tag{3}$$

where $X1$ is the $RWVP$ and $X3$ is the air permeability (R_{air}).

Then

$$OMMC = 0.4307 - 0.0079 \cdot X4 - 0.014 \cdot X5 \tag{4}$$

where $X4$ is WAC_1 and $X5$ is WAC_2.

Thus,

$$OMMC = 0.3934 + \ 0.0001 \cdot X3 - 0.0008 \cdot X4 - 0.0151 \cdot X5 \tag{5}$$

where $X3$ is the air permeability (R_{air}); $X4$ is WAC_1; and $X5$ is WAC_2.

As can be seen in Equation (5), the parameters $X3$ and $X4$ have almost no influence on the $OMMC$,

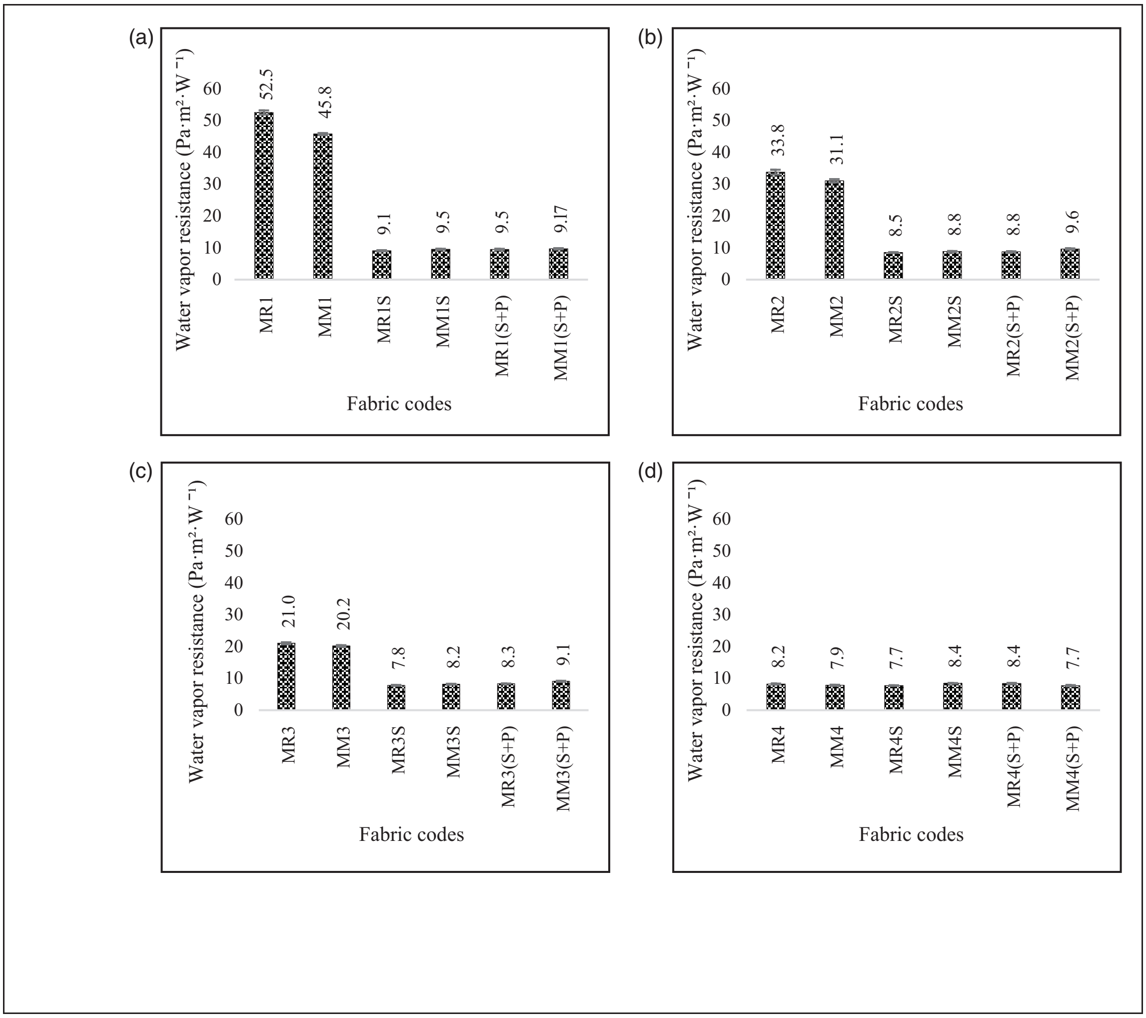

Figure 5. Water vapor resistance (R_{et}) of (1 × 1 rib knitted fabrics (MR)); half-Milano knitted fabrics (MM)), dyed and softened (S), and dyed, softened, and treated with antibacterial finish (S + P) samples of knitted fabrics: 90% cotton (CO), 10% antistatic polyester (PET_A) (a); 80% CO, 20% PET_A (b); 70% CO, 30% PET_A (c); 65% CO, 35% PET_A (d).

as shown by the correlation matrix presented in Table 5 (it is influenced by the parameter $X5$, when $P_{value} < 0.05$). Then we obtain

$$OMMC_{half-Milano\ (S+P)} = 0.5293 - 0.0222 \cdot X5 \qquad (6)$$

where $X5$ is WAC_2.

Furthermore, from the correlation matrix (Table 5) it can also be observed that there is a very strong correlation between R_{et} and R_{air}: $\rho = -0.997$, when $P_{value} < 0.05$.

To make it easier to draw a conclusion, a repeated analysis was performed to take a general linear regression equation with the data obtained for the dyed and softened samples (S) (Tables 6 and 7).

It can be seen in Table 6 that there is a strong negative correlation between $OMMC$ and $RWVP$: $\rho = -0.8841$, when $P_{value} < 0.1$. Therefore, this parameter must be included in the linear regression equation. The remaining parameters do not statistically affect the $OMMC$, but Table 6 shows that there is a strong correlation between the $OMMC$ and R_{air}: $\rho = 0.882$, when the $P_{value} = 0.1$. If the significance level is chosen as $P_{value} = 0.1$, then these two parameters can be included in the equation; the P_{value} was set to 0.1 here to include the strong correlation parameters and keep the equation like Equation (2).

Thus, we obtain

$$OMMC_{1\times1\ rib\ (S)} = 6.2776 - 0.1683 \cdot X1 + 0.0106 \cdot X3 \qquad (7)$$

where $X1$ is the $RWVP$ and $X3$ is the air permeability (R_{air}).

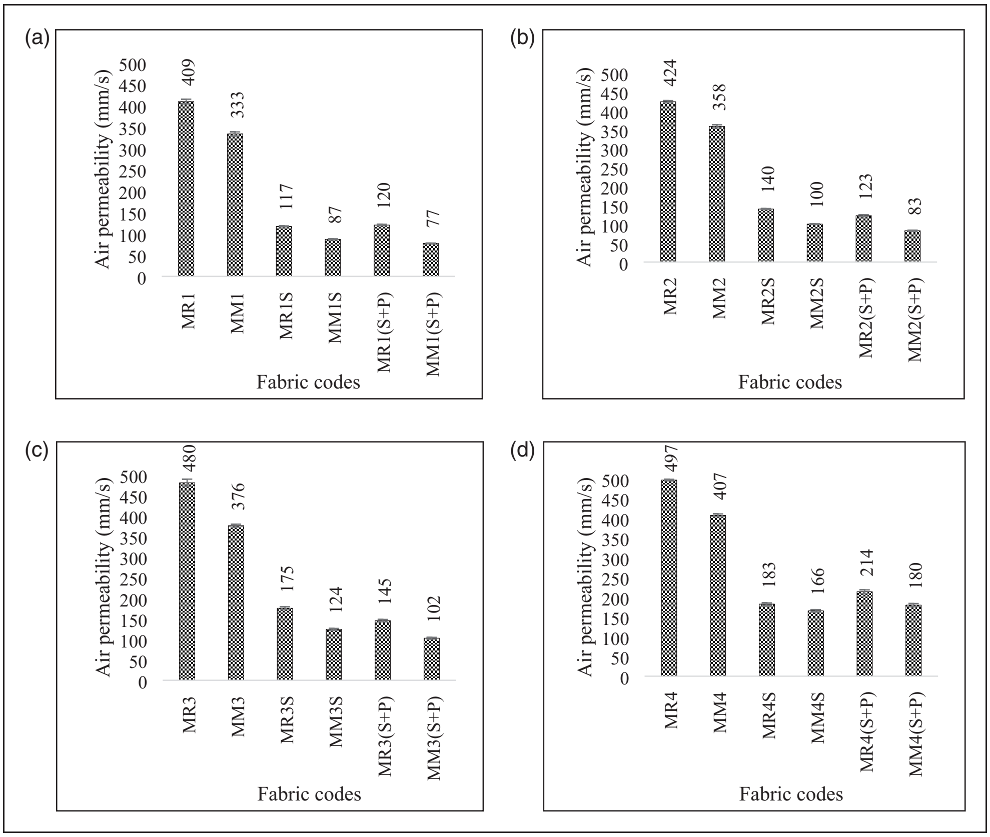

Figure 6. Air permeability (R_{air}) of (1 × 1 rib knitted fabrics (MR)); half-Milano knitted fabrics (MM)), dyed and softened (S), and dyed, softened, and treated with antibacterial finish (S + P) samples of knitted fabrics: 90% cotton (CO), 10% antistatic polyester (PET_A) (a); 80% CO, 20% PET_A (b); 70% CO, 30% PET_A (c); 65% CO, 35% PET_A (d).

In addition, from the obtained correlation matrix (Table 6) it can also be observed that there is a very strong correlation between R_{et} and the following:

- $RWVP$: $\rho = -0.9982$ ($p < 0.05$);
- R_{air}: $\rho = 0.9999$ ($p < 0.05$);
- WAT: $\rho = 0.9912$ ($p < 0.05$).

There is a very strong negative correlation between the $OMMC$ and R_{air}: $\rho = -0.9408$, when $P_{value} < 0.05$ for the dyed and softened samples (S) of half-Milano knitted fabrics (Table 7). All other parameters do not statistically affect the $OMMC$, since their $P_{value} > 0.1$.

Therefore, it is observed from the analysis discussed that the antibacterial treatment changed all parameters very significantly. Thus, we obtain

$$OMMC = 0.3126 - 0.0011 \cdot X3 \tag{8}$$

where $X3$ is the air permeability (R_{air}).

If the $X1$ parameter is also included, we obtain

$$OMMC_{half-Milano\ (S)} = 0.0355 + 0.0075 \cdot X1 - 0.0014 \cdot X3 \tag{9}$$

where $X1$ is the $RWVP$ and $X3$ is the air permeability (R_{air}).

Therefore, in the general case, it is suggested to use

$$OMMC = a + b \cdot X1 + c \cdot X3 \tag{10}$$

where $X1$ is the $RWVP$ and $X3$ is the air permeability (R_{air}).

Equation (10) shows the dependence of the $OMMC$ on the $RWVP$ and air permeability of the fabrics. Clothing must evaporate the sweat of the human body, which is always produced at different rates depending on the environment. When human activity increases more sweat is produced and, before complete evaporation, it starts condensing. In this case, absorption and liquid transport occur in the clothing fabric through capillary action to remove moisture.[39] The evaporation of sweat from human skin is the fundamental requirement of clothing to maintain moisture management that depends on its permeability to water vapor.[41] When sweat or moisture evaporates, it passes through the pores of the fabrics; this is known as the permeability of the fabrics. As the $RWVP$ and R_{air} of fabrics are dependent on the porosity of the fabrics,

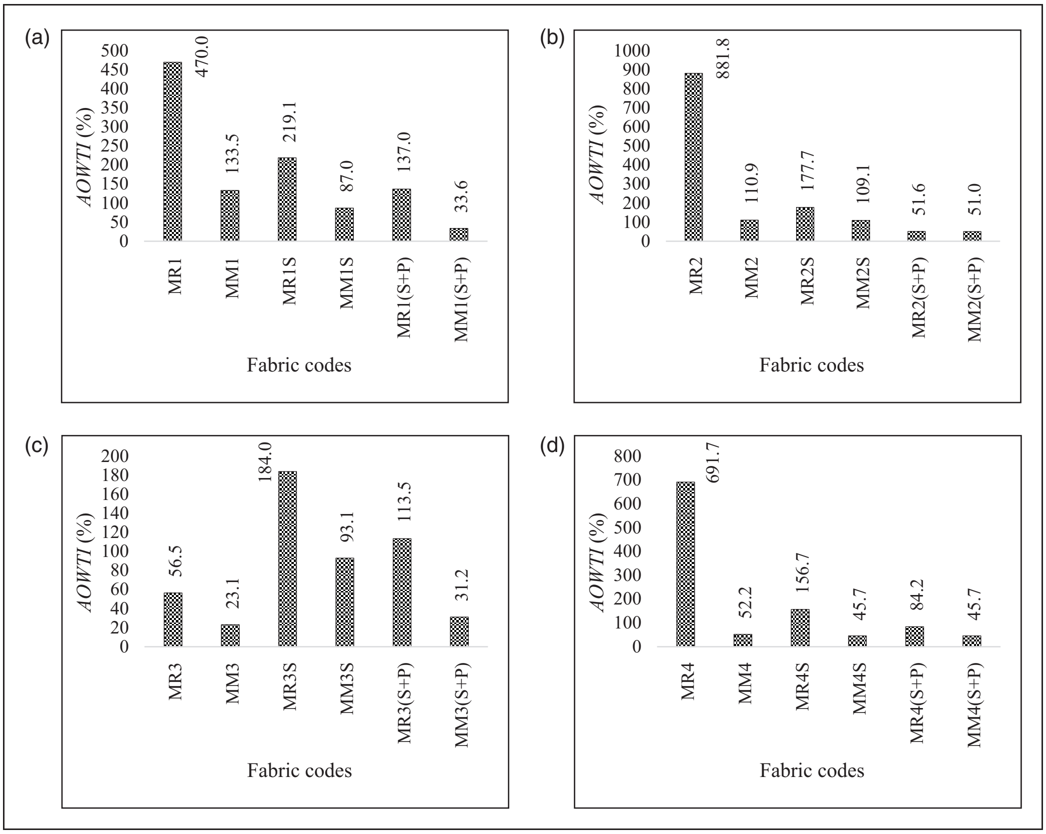

Figure 7. Accumulative one-way transport index (AOWTI) of (1 × 1 rib knitted fabrics (MR)); half-Milano knitted fabrics (MM)), dyed and softened (S), and dyed, softened, and treated with antibacterial finish (S + P) samples of knitted fabrics: 90% cotton (CO), 10% antistatic polyester (PET_A) (a); 80% CO, 20% PET_A (b); 70% CO, 30% PET_A (c); 65% CO, 35% PET_A (d).

it helps to understand the ability of the fabric to pass through air and moisture. If the $RWVP$ is high, then the sweat evaporation is also high.

Furthermore, from the obtained correlation matrix obtained (Table 7), it can also be observed that there is a very strong correlation between the following:

1. The R_{et} and:

- $RWVP$: $\rho = -0.9893$, when $P_{value} < 0.05$;
- WAT: $\rho = -0.9726$, when $P_{value} < 0.05$.

2. The WAC_1 and:

- $RWVP$: $\rho = 0.9613$, when $P_{value} < 0.05$;
- R_{et}: $\rho = -0.9613$, when $P_{value} < 0.05$.

The results reported here confirm that the suggested linear regression equations can reliably predict the textile properties related to clothing comfort having a significantly lower number of input variables required to determine experimentally.

Conclusion

This research presents a linear regression equation to calculate the $OMMC$ of antibacterial and antistatic knitted fabrics by using other factors, such as the $RWVP$, the water vapor resistance (R_{et}), the WAC, the WAT, and the air permeability (R_{air}) of the knitted fabrics. This linear regression equation has incorporated these factors to predict the $OMMC$, which showed a high correlation with the $OMMC$ of antibacterial and antistatic knitted fabrics with a $P_{value} < 0.05$. The $RWVP$ ($X1$) and air permeability ($X3$) are the main factors that can predict the $OMMC$ of knitted fabrics with the linear regression equation: $OMMC = a + b \cdot X1 + c \cdot X3$. From the correlation matrix, it is found that strong correlations exist between the absolute water vapor resistance (R_{et}) and both the $RWVP$ and the WAT, and the WAC has a strong correlation with the $RWVP$ and the water vapor resistance (R_{et}). As a result, the suggested linear regression equation allows one to predict these parameters for knitted fabrics.

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