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Inventory of the Thermo-Physiological Behavior of Fabrics—A Review

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Abstract

A comprehensive literature review was performed to create an inventory of thermal-physiological quantities for fabrics from different fiber materials, material blends, and fabric structures. The goal was to derive over-arching concepts that cannot be seen by the individual studies alone. Equations of best fits suggest non-linear changes for fabric thickness, thermal and water-vapor resistance with changes in material blend ratio. Air permeability decreases with increasing fabric density and fabric weight wherein the degree of decrease differs among fabric materials, blend ratio, and fabric structure. Water-vapor transmission rates strongly depend on fabric thickness, material, and blend, but marginally depend on fabric structure as long as the fabric and material thickness remain the same.

Keywords

Thermal Resistance of Fabrics, Thermal Conductivity of Fabrics, Water-Vapor Resistance of Fabrics, Water-Vapor Transmission Rate, Inventory of Thermal-Physiological Characteristics of Fabrics, Energetics of Fabrics

1. Introduction

Since the Millenium, consumers' demand for thermo-physiological wear comfort of their clothes has increased. Consequently, various studies were performed to examine the thermal and moisture properties of fabrics from different natural, regenerated, and synthetic fibers as well as their blends (e.g. [1] [2] [3] [4]). Most of these studies focused on specific aspects like the impact of fabric structure (tightness/looseness of the weave or knit, yarn twist, yarn thickness, yarn count, weave/knit pattern, yarn-cross section, etc.) for a fiber or fibers of interest, blend ratios, or a small combination thereof (e.g. [5]-[10]). In many cases, the goal was to improve wear comfort for a specific purpose like high activities, cold weather dressing, etc. Therefore, in many studies, only quantities of immediate importance for the research questions were collected. Consequently, there rarely exist datasets that encompass both thermal and water-vapor/moisture related fabric properties or a wide suit of energetically relevant properties.

Typically, individual studies on thermal and/or moisture properties of fabrics examine only limited aspects. Nevertheless, these studies revealed that thermal resistance increases with increasing fabric thickness. Because thermal conductivity decreases as thermal resistance increases, we can say that the thermal conductivity decreases as fabric thickness decreases. Furthermore, thermal conductivity depends on fabric structure, raw material, ratio of blend, if applicable (e.g. [11] [12] [13]). Another generalization that could be made is that air permeability decreases with increasing fabric thickness and fabric weight.

Studies on the impact of fabric structure regarding weave or knit patterns showed that as the weight per unit area of fabric increases, the amount of entrapped air decreases. Because the thermal conductivity of small air bubbles or thicknesses is lower than that of fibers, thermal conductivity is higher for heavier fabrics with less still air like interlock than for less heavy fabrics like single-jersey knit [11]. Obviously, fabric structure also notably affects thermal resistance. As compared to flat fabrics, puckered fabrics like seersucker, for instance, offer enhanced thermal resistance due to the air pockets between the fabric and skin [14].

Blending yarns affects the physical properties of fabrics like thermal conductivity, thermal resistance, air and water-vapor permeability. For instance, thermal conductivity and fabric thickness of Tencel/cotton or Tencel/bamboo blends decrease with increasing fraction of Tencel fiber [13]. However, air and water-vapor permeability increase with increasing Tencel content. Because bamboo fibers are less hairy than cotton fibers, Tencel/bamboo blended fabrics have generally a lower porosity than cotton or Tencel/cotton fabrics. Water-vapor permeability of silk/Tencel blended fabrics gradually increases with increase in Tencel content with pure Tencel and Silk having the highest value and lowest value, respectively. Thermal resistance of silk/Tencel fabrics decreased significantly at 95% confidence with increasing Tencel fraction [15].

Besides blending material at the fiber level, the textile industry also uses yarns of different materials at the weft and wrap levels. Using cotton-in-warp and bamboo-in-weft plain woven fabric, for instance, yields higher air permeability, very low thermal resistance, and higher wicking rate than plain cotton or plain bamboo weaves with the same weaving parameters [13]. The relative water permeability of the cotton-in-warp and bamboo-in-weft fabric exceeded that of 100% bamboo or 100% cotton fabrics with the 100% cotton fabric having the lowest value. Wicking and evaporation vary with weave characteristics [16].

Studies showed that rinse, stone, and bleach-washing treatment of cotton,

cotton/hemp, and cotton/flax denim fabrics enhanced air permeability, thermal resistance, water retention, and reduced thermal absorption, thermal conductivity, and drying time [17].

Various studies examined the energetic behavior of plated fabrics (e.g. [18] [19] [20] [21]). Plating of Modal and micro-Modal, for instance, with different textured polyamide 6.6 yarns improved water vapor absorption, air permeability and thermal resistance as compared to conventional cotton. Plating single-jersey fabric with polyester or Lycra reduces air permeability and thermal conductivity yielding the lowest values for the Lycra-plating as compared to plain samples due to the thicker and tighter structure of the plated fabrics.

This review served to take an inventory of thermal-physiological comfort properties at the fabric level based on the literature data of the last two decades. The goal was to derive over-arching concepts that cannot be seen by the individual studies alone. To achieve this goal the thermo-physiological behavior of fabrics was analyzed as a function of fiber material, blend ratios, and fabric structure. A major focus was on finding systematic behaviors, differences and a qualitative assessment of various fabric configurations.

2. Methodology and Design of the Study

2.1. Data Collection

A literature study was performed to create an inventory of the thermo-physio logical properties of fabrics that differ in structure, material, and material blends. For each fabric the following data were collected: Fabric thickness, fabric area weight, fabric structure (weave- or knit-pattern type), fiber material, blend ratio. Additional information like yarn thickness, yarn count, tightness of knit/weave etc. was not further considered nor analyzed because these quantities are an indirect integral part of fabric weight, fabric density, and fabric thickness as well as porosity. As dependent quantities, data of at least one of the following properties were stored with their respective data of fabric thickness, fabric area weight, fabric structure, fiber material, and blend ratio, if applicable: Thermal conductivity, thermal resistance, thermal absorptivity, porosity, air permeability, water-vapor permeability, moisture vapor transmittance, relative water-vapor permeability, absorbency aka absorptance, wicking, and overall moisture management capability (OMMC).

2.2. Data Preparation

All data were converted to metric units. Fabric area weight was converted to fabric unit area weight, when the weight was given for a specific sample size. Due to differences among disciplines and regional units, terms and units for vapor permeability differ. To compare observation of the various researchers, the terms were normalized to the same units. The normalized unit for water-vapor permeability is called the water-vapor transmission rate (WVTR) aka moisture-transmission rate (MVTR). Generally, WVTR decreases with increasing fabric thickness and air temperature.

The resulting sample sizes for fabric thickness (mm), fabric weight per unit area (g/m^2), fabric density (kg/m^3), thermal conductivity (W/(K·m)), air permeability (m^3/(m^2·s)), porosity (%), thermal resistance (K·m^2/W), moisture-vapor transmittance (%) aka relative water-vapor permeability (%), thermal absorptivity (W·s$^{0.5}$/(m^2·K)), OMMC (-.-), absorbency (%), water-vapor resistance R_{et} (m^2·Pa/W), wicking (mm^2/s), water-vapor permeability (g/(m^2·h·Pa)), and normalized water-vapor transmission rate (g/(m^2·s)) were 975, 987, 909, 299, 552, 431, 360, 186, 129, 86, 68, 108, 30, 36, and 295, respectively.

2.3. Data Analysis

The resulting dataset served as a basis to create sub-datasets because not all studies reported the complete set of the abovementioned quantities. This means that a sub-dataset holds all data collected for a given thermo-physiological quantity, no matter of fabric structure, material, or blend ratio. In a further step, these sub-datasets were sorted again for these characteristics. **Table 1** lists the number of pairs for the various combinations.

This procedure permits analyzing much larger samples than from individual studies alone or the few studies that provided the full set of quantities. While the sub-datasets encompass data from different studies, the impact of this disadvantage can be considered as marginal from a statistical point of view. The sample sizes of the various sub-datasets used in this study are all greater or equal to 30 (**Table 1**).

Table 1. Correlation coefficients (upper triangle), and sample size for the respective pairs (lower triangle) of fabric thickness, h, fabric unita area weight, m, thermal conductivity, Q_{TC}, air permeability, AP, porosity, η, thermal resistance, R_t, thermal absorptivity, TA, overall moisture management capacity, $OMMC$, absorbency, A, water-vapor resistance, R_{et}, wicking, W, water-vapor transmission rate, $WVTR$. Insufficient sample sizes (<30) are indicated by -.- in the upper triangle. Bold and Italic values indicate significant correlation at the 95% and 90% confidence levels.

Characteristics	Characteristics											
	h	m	Q_{TC}	AP	η	R_t	TA	$OMMC$	A	R_{et}	W	$WVTR$
h	1	0.180	0.133	−0.023	0.157	0.507	−0.310	*−0.219*	*−0.320*	*0.201*	−0.279	−0.422
m	909	1	0.084	−0.239	−0.159	0.485	0.375	0.025	0.119	0.483	−0.419	−0.160
Q_{TC}	289	262	1	0.116	0.198	−0.082	*0.765*	−0.005	-.-	0.757	*-0.778*	−0.284
AP	501	486	214	1	0.260	0.023	0.080	−0.071	−0.736	−0.383	-.-	0.070
η	368	352	74	168	1	0.157	−0.836	0.313	−0.769	−0.183	-.-	−0.633
R_t	315	284	203	238	165	1	−0.661	−0.169	*0.960*	−0.134	-.-	0.011
TA	134	97	94	56	66	129	1	-.-	-.-	−0.376	-.-	0.504
$OMMC$	75	86	6	23	27	14	0	1		−0.649	-.-	**0.901**
A	51	60	9	33	18	18	4	0	1	−0.900	0.391	0.714
R_{et}	93	100	13	72	53	69	42	20	8	1		−0.663
W	30	30	6	0	0	0	0	0	24	0	1	−0.663
$WVTR$	273	240	155	195	115	168	58	15	40	14	30	1

For each of the sub-datasets the thermo-physiological properties were analyzed at-large (*i.e.* all data of the sub-dataset together), and then separately depending on raw material, material blend, and fabric structure. The analysis focused on the detection of general behavior as well as differences in thermo-physiological characteristics related to raw material, material blend, blend ratio, fabric structure, porosity, fabric thickness, and fabric unit area weight.

Correlations between the various thermo-physiological quantities were calculated and tested for significance at the 90 and 95% confidence level (**Table 1**) using a two-tailed Student t-test [22]. In the following discussion, absolute values of correlations of 0.2 to 0.39 are referred to as weak, 0.40 to 0.59 as moderate, 0.6 to 0.79 as strong, and 0.8 to 1 as very strong.

To examine the impact of blend ratios equations of best fit were determined.

3. Results and Discussion

3.1. Thermal and Air Diffusivity, Thermal Resistance, Thermal Conduction, and Porosity

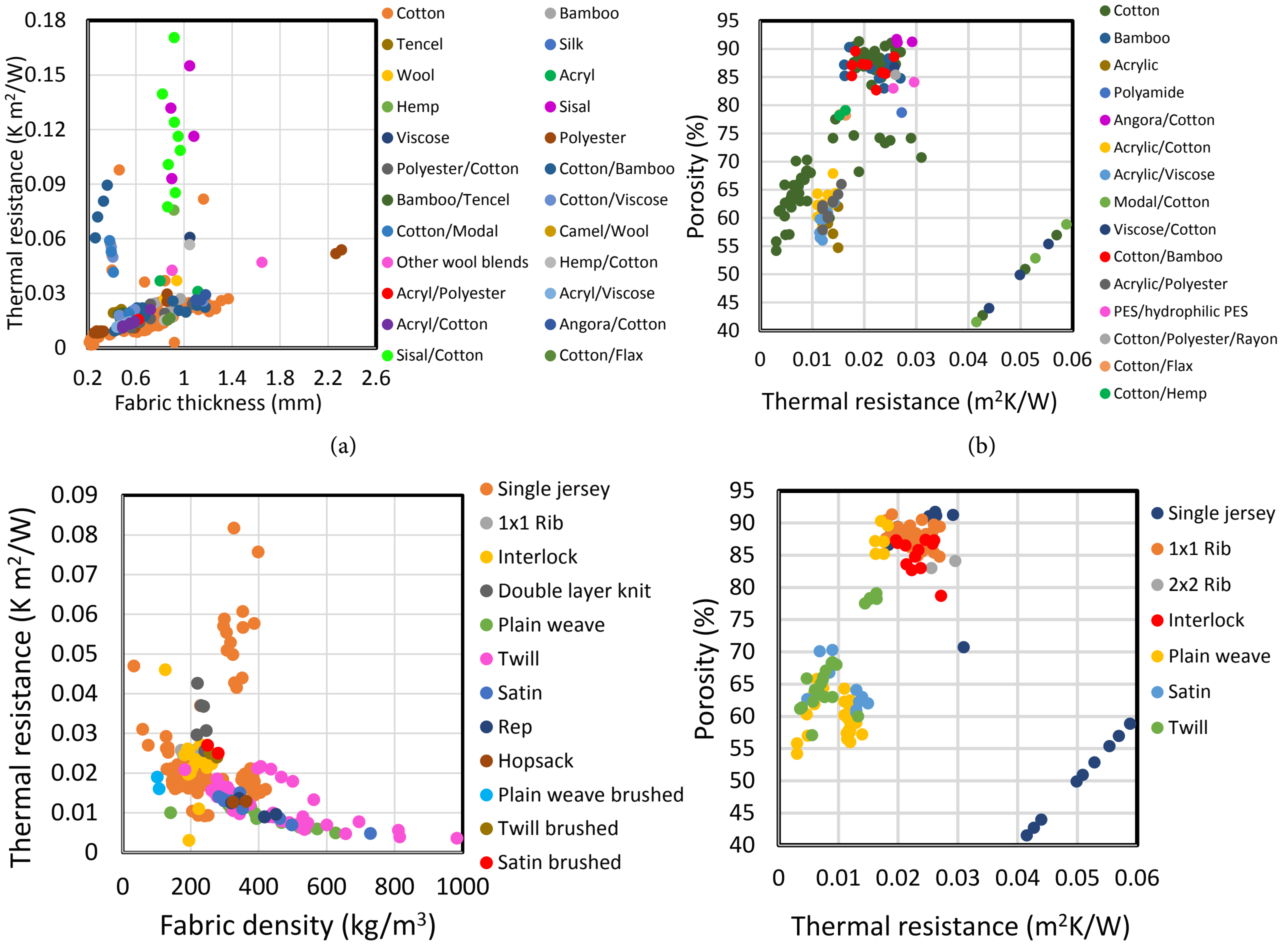
Thermal and water-vapor diffusion refers to the heat and water-vapor flow thru the air within the fabric structure, respectively. Consequently, these flows depend on the physical properties of the diffusing material (e.g., water vapor, sweat, air) and on fabric porosity. Furthermore, these flows depend on external ambient conditions like the temperature and pressure differences between the body and environment. Consequently, air and water-vapor permeability of fabrics are temporary thermal characteristics – the reason why these quantities are measured traditionally under controlled environmental conditions.

On the contrary, thermal resistance or fabric porosity, for instance, depends on the material and structural parameters of the fabric. These parameters include, among others, yarn twist, roughness, yarn count, material, and for blends, the mix ratio.

The inventory showed that thermal resistance increases with fabric thickness for all fiber materials (**Figure 1(a)**). Except for material blends and some outliers (discussed later), the increase is almost linear, but the degree of increase differs among fiber types. Because pores entrap air, which has high thermal resistance and low thermal conductivity, porosity and fabric density affect thermal resistance (**Figure 1(b)**) and conductivity.

Except for some outliers, thermal resistance of cotton fabrics increases with increase in porosity (**Figure 1(a)**). No such generalization can be made for bamboo. Too few data exist for polyamide and acrylic for generalization. Comparison of **Figure 1(b)** and **Figure 1(d)** reveals that thermal resistance depends notably on the fabric construction. The thermal resistance of cotton twill and cotton 1 × 1 rib, for instance, notably differ due to the different porosity.

When blending fibers, fabric thickness and thermal resistance change depending on the mix ratio, blended material, yarn thickness, and tightness of the fabric structure. Filaments may intermingle, and alter the packing density, thickness, porosity,



(a) (b)

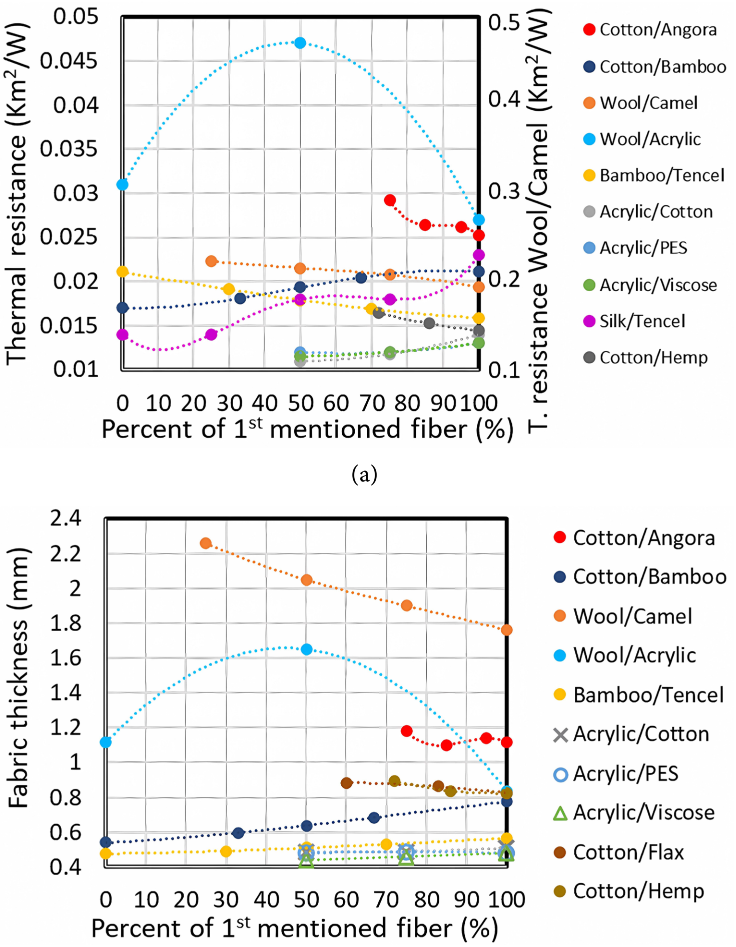
(c) (d)

Figure 1. Relationship between thermal resistance and (a) fabric thickness, (b) porosity both for fabrics from various fiber materials and blends, (c) fabric density, (d) porosity both for fabrics of different construction independent of their material. Data from: [10] [12] [13] [15] [17] [23]-[34].

and hence, thermal resistance. Equations of best fits between fabric thickness and blend ratio as well as between thermal resistance and blend ratio suggest nonlinear changes in these quantities with increasing blend ratio for some blends (e.g. Figure 2, Table 2).

Conduction of heat is a heat transfer by molecules. Thermal conductivity of fabrics made from the same fibers depends on the fabric specific mass (fabric thickness times weight per unit area of fabric) aka fabric density. For fabrics from only one material, thermal conductivity increases with increasing fabric density because the decrease in porosity means an increase in material molecules. However, the slope varies among materials (Figure 3).

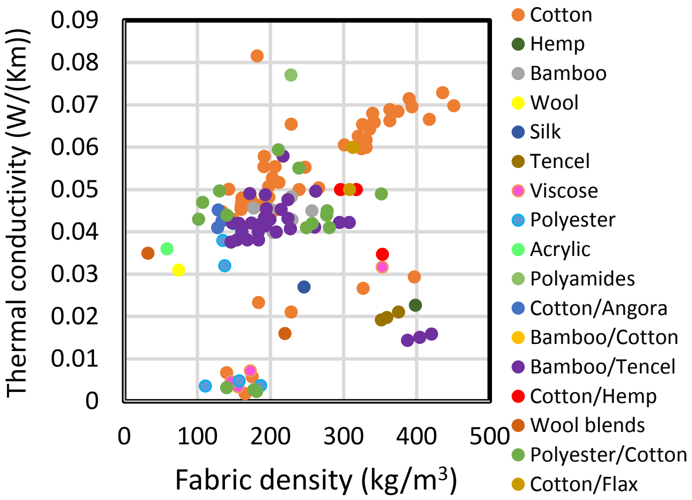
In Figure 3, the wool blends are wool/polyester, wool/silk, and wool/cotton, while all other blends only differ by the mixing ratio of the blends' fibers. Comparison of these wool blends, for instance, with the blends that differ only by the blend ratio reveals that the type of material blend notably affects the resulting thermal conductivity. The same also applies when comparing other blends.



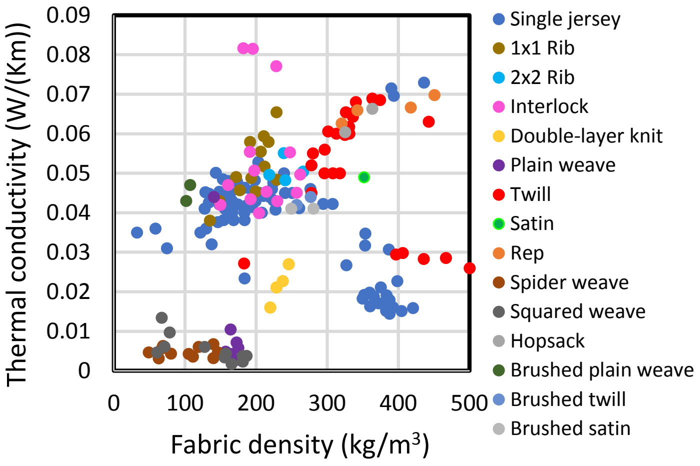
(a)

(b)

Figure 2. Relationship between blend ratio and (a) thermal resistance, and (b) fabric thickness. In (a), the right y-axis applies for wool/camel, while the left y-axis is valid for all other blends. Trendlines have the color code of the blend. See Table 2 for equations of best fit and percent of correlation. No data on thickness were available for Silk/Tencel. Data from: [12] [13] [15] [17] [35] [36] [37].



(a)



(b)

Figure 3. Relationship between thermal conductivity and fabric density for (a) different fabric materials and blends independent of fabric structure, (b) different fabric structure types independent of fabric material. Color code differs among panels. In (a) and (b), only data for materials/blends and fabric structure with more than one value-pair for these parameters are shown for readability. Data from: [2] [5] [10] [11] [12] [13] [17] [23] [24] [26] [27] [29] [30] [31] [33] [37]-[44].

Table 2. Equations of best fit and percent of correlation, R^2, between blend ratio, x, fabric thickness, h, and thermal resistance, R_T for the data shown in **Figure 1**. No thickness data were available for Silk/Tencel.

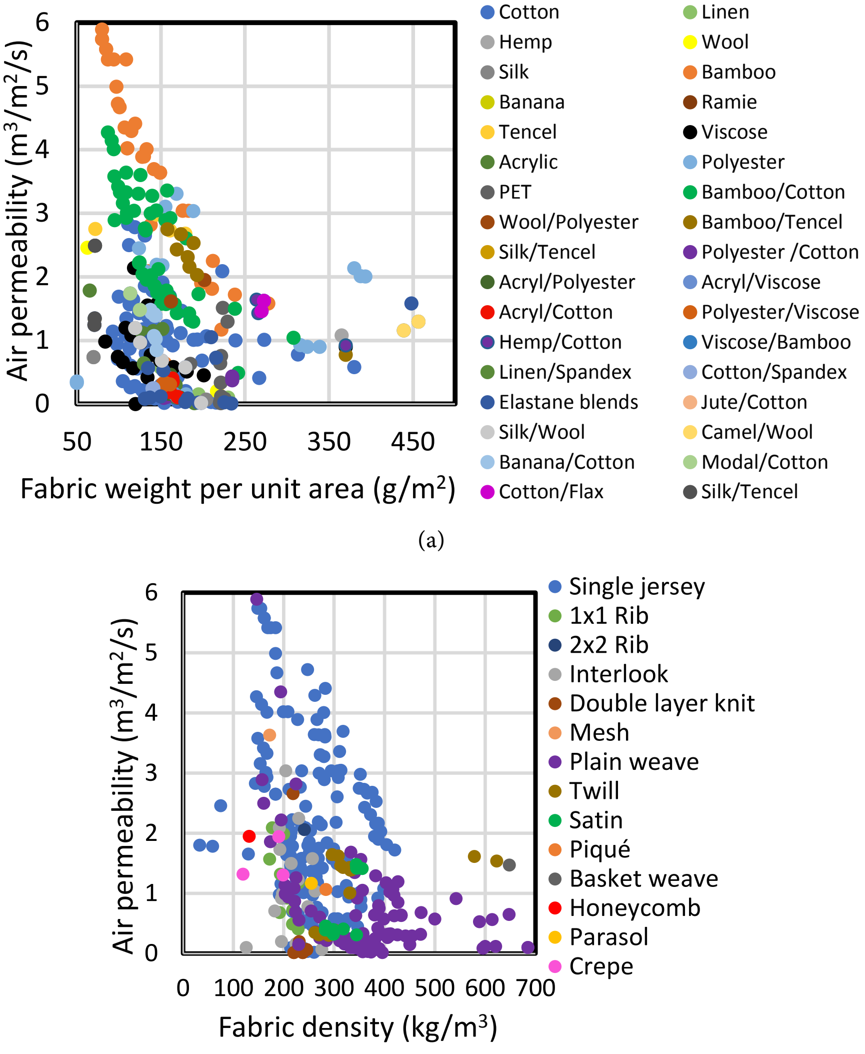
Fabric blend	Blend ratio impacts on fabric thickness and thermal resistance			
	Equation of best fit for h	R^2 (h)	Equation of best fit for R_T	R^2 (R_T)
Wool/Camel	$-5 \times 10^{-7}x^3 + 0.0001x^2 - 0.0157x + 2.58$	100	$-7 \times 10^{-8}x^3 + 10^{-5}x^2 - 0.0008x + 0.2372$	100
Wool/Acrylic	$-7 \times 10^{-6}x^2 + 0.0007x + 0.031$	100	$-0.0003x2 + 0.0242x + 1.116$	100
Cotton/Angora	$-5 \times 10^{-5}x^3 + 0.0122x^2 - 1.0821x + 33.06$	100	$-10^{-6}x^3 + 0.0003x^2 - 0.0239x + 0.7387$	100
Cotton/Bamboo	$-9 \times 10^{-8}x^3 + 2 \times 10^{-5}x^2 + 0.0011x + 0.54$	100	$-10^{-8}x^3 + 2 \times 10^{-6}x^2 - 2 \times 10^{-5}x + 0.017$	100
Acrylic/Viscose	$0.0008x + 0.4$	100	$4 \times 10^{-7}x^2 - 3 \times 10^{-5}x + 0.012$	100
Acrylic/Cotton	$2 \times 10^{-5}x^2 - 0.002x + 0.55$	100	$10^{-6}x^2 - 0.0001x + 0.0136$	100
Acrylic/PES	$-2 \times 10^{-5}x^2 + 0.0024x + 0.4$	100	$8 \times 10^{-7}x^2 - 0.0001x + 0.015$	100
Bamboo/Tencel	$-3 \times 10^{-8}x^3 + 9 \times 10^{-6}x^2 + 0.0003x + 0.477$	99	$10^{-9}x^3 + 2 \times 10^{-8}x^2 - 7 \times 10^{-5}x + 0.0211$	100
Silk/Tencel	-.-	-.-	$2 \times 10^{-9}x^4 - 4 \times 10^{-7}x^3 + 2 \times 10^{-5}x^2 - 0.0004x + 0.014$	100
Cotton/Flax	$-3 \times 10^{-5}x^2 + 0.0034x + 0.7909$	100	$-5 \times 10^{-5}x + 0.0194$	99
Cotton/Hemp	$0.0001x^2 - 0.0211x + 1.8467$	100	$10^{-6}x^2 - 0.0002x + 0.0283$	100

Obviously, thermal conductivity of acrylic blended with cotton, viscose, or polyester fibers increases strongly with increasing porosity (**Figure 3**). On the contrary, porosity marginally affects thermal conductivity of pure cotton, pure viscose, and pure bamboo.

Air permeability can be expressed as the speed with which dry air travels thru a fabric at a given pressure difference. Obviously, air permeability seems to be less dependent on fabric thickness than on fabric unit area weight or fabric density (**Figure 4**). Typically, air permeability seems to decrease with increasing fabric weight. Because air permeability depends on inter-yarn and inter-fiber porosity, air permeability decreases with increasing fabric density (**Figure 4(b)**). The steepness of decrease of air permeability with increasing fabric density and weight differs among fabric materials and, if applicable blends (**Figure 4(a)**), and consequently also varies among fabric structure types.

3.2. Water-Vapor Resistance, Water-Vapor and Moisture Permeability

Water-vapor resistance describes the fabric's resistance to the flow of water vapor.



(a)

(b)

Figure 4. Relationship between air permeability and (a) fabric weight per unit area for various fabric materials and blends, (b) fabric density of various fabric structure types. In (a) and (b), only data for materials/blends and fabric structure with more than one value-pair for these parameters are shown for readability. Data from: [5] [7] [8] [10] [12] [13] [15] [17] [20] [23] [25] [27] [28] [30] [31] [33] [35] [36] [40] [42]-[62].

It is defined as the water-vapor pressure difference between the two sides of the fabric divided by the resultant evaporative heat flux per fabric unit area in the direction of the water-vapor pressure gradient.

Like in case of air permeability, we can express water-vapor or moisture permeability as the speed of water-vapor or sweat passing thru a fabric under a prescribed pressure difference between the two sides of the fabric. However, in contrast to air permeability, the fabric material influences water-vapor- and moisture permeability. This difference is because air permeability occurs by diffusion only. However, in case of water vapor or moisture, the fibers can absorb, and transmit water along the fiber surfaces, and then desorb water vapor. Furthermore, forced convection can reduce water-vapor transfer because, at the same temperature and pressure, water vapor is lighter than dry air. Consequently, a person's perception of moisture comfort depends on water-vapor and water permeability, porosity, and wettability.

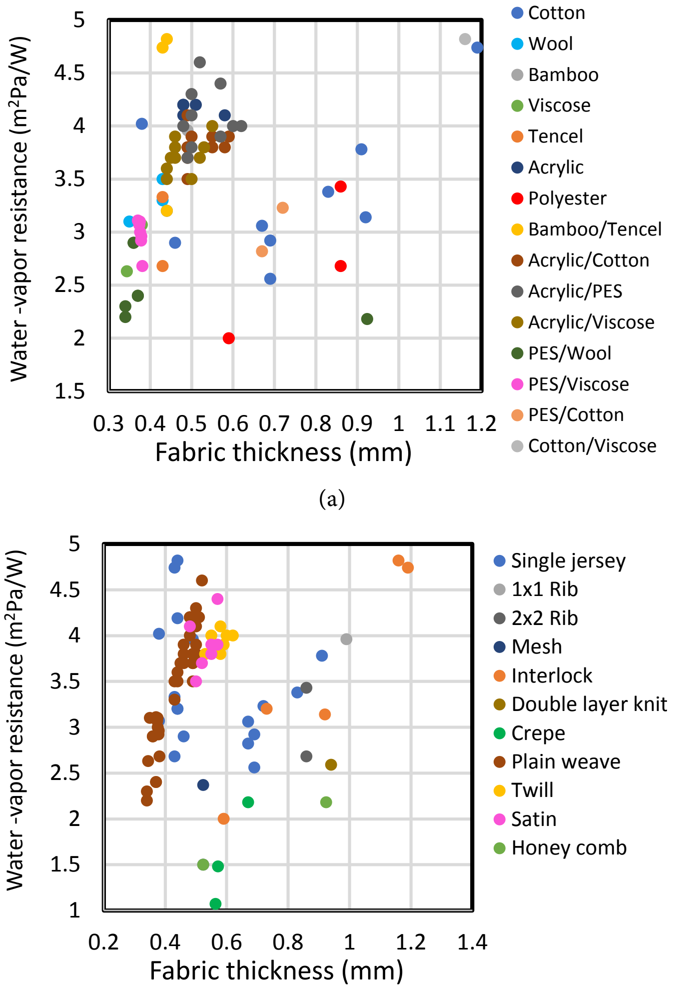
Obviously, water-vapor resistance is independent of fabric structure at the same fabric thickness (**Figure 5**). Water-vapor resistance increases with increasing fabric thickness, air entrapment, and fabric weight for all fabric materials. Herein, the magnitude of increases depends on the fabric material and blend ratio, if applicable (**Figure 4**). Tencel and viscose have low water-vapor resistance due to their high moisture regain. The same is true for hydrophilic polyester (red dot at 0.6 mm, 2 m^2·Pa/W) and wool. Furthermore, water-vapor resistance is lower for fabrics made of fine than thick yarns [63].

WVTR decreases with increasing fabric thickness (**Figure 6(a)**). At the same thickness, WVTR differs more than a factor of 100 among fabrics of different materials and blends. WVTR of cotton fabric, for instance, is much lower than WVTR of cotton/bamboo fabrics having the same fabric thickness.

Due to the low sensitivity of water-vapor resistance to fabric-structure type, fabric structure also only marginally affects WVTR as compared to fabric thickness or fabric material. This finding is supported by the high variability of WVTR for plain weaves despite similar fabric thickness. Comparison of **Figure 6(a)** and **Figure 6(b)** reveals that the high variability is related to fabric material.

Nevertheless, fabric structure has an indirect impact on WVTR because fabric structure can affect fabric thickness. For instance, plain weave polyester fabric is relatively thin with high WVTR, while double-layer knit polyester fabric is much thicker with low WVTR (cf. **Figure 6(a)**, **Figure 6(b)**). Other examples of the indirect effect of fabric structure on WVTR due to increased fabric thickness are 1 × 1 rib and interlock cotton or polyester fabrics as compared to cotton or polyester single-jersey fabrics, respectively [11] (cf. **Figure 6(a)**, **Figure 6(b)**).

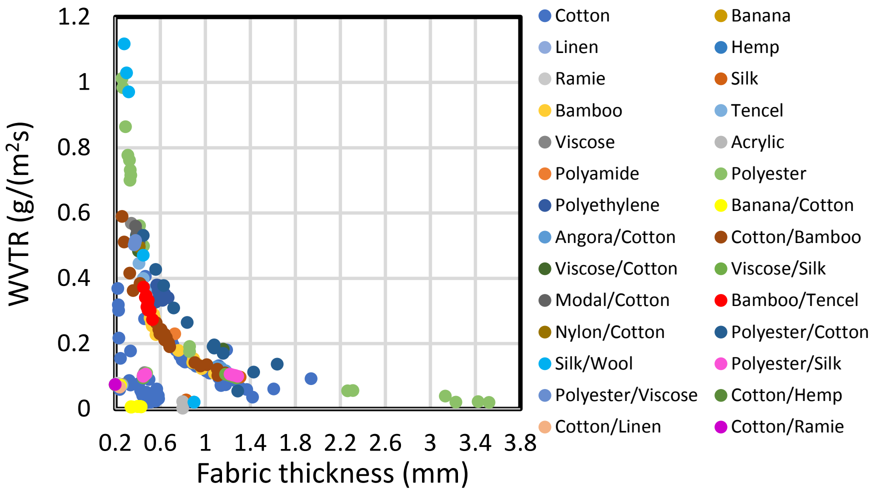
Blending low hydrophile fibers/yarns with high hydrophile fibers/yarns increases the WVTR as compared to the fabric consisting only of the low hydrophile material (cp. e.g. cotton and cotton/bamboo blends in **Figure 6(a)**). In case of blends with highly hydrophilic fibers, WVTR is directly related to the blend ratio (e.g. **Figure 7**). Of all fabrics of same thickness, silk/wool blends have the highest WVTR (**Figure 6(a)**).



(a)

(b)

Figure 5. Relationship between water-vapor resistance and fabric thickness for fabrics of various (a) raw materials, and (b) structures. PES is polyester. In (a) and (b), only data for materials/blends and fabric structure with more than one value-pair for these parameters are shown for readability. Data from: [13] [23] [34] [36] [49] [50] [63] [64].



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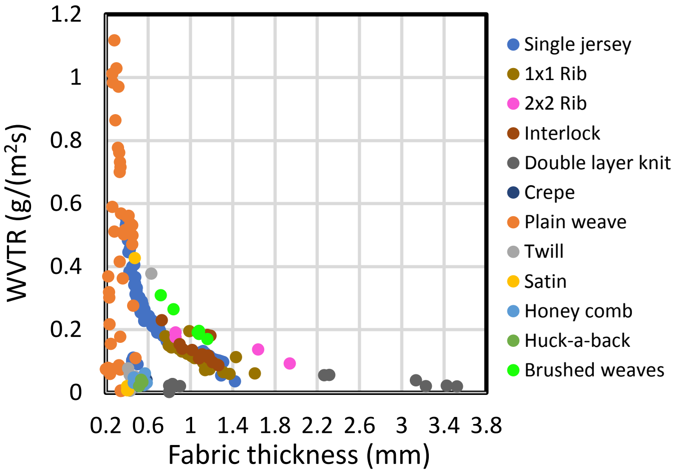
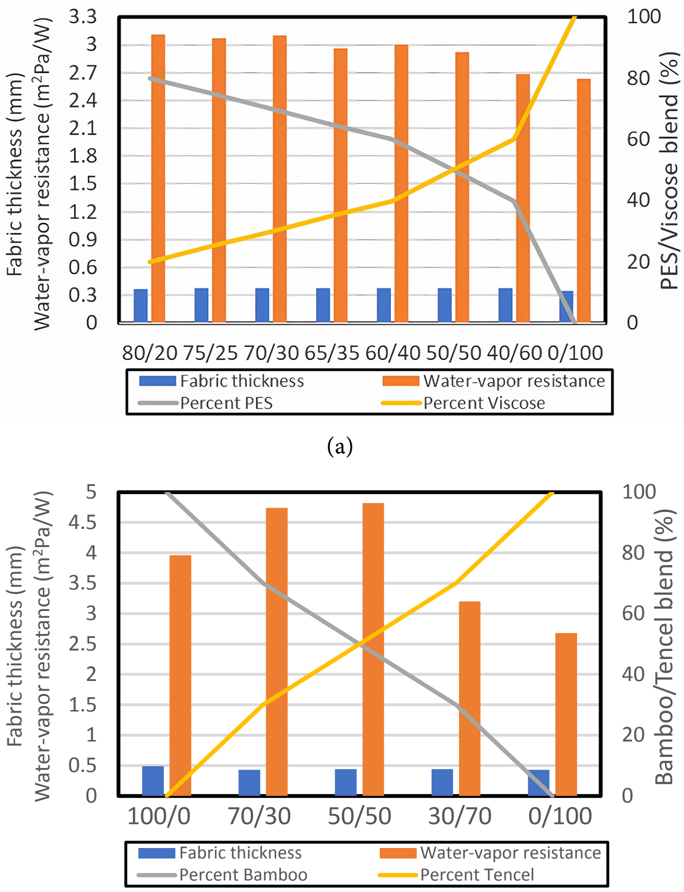


(b)

Figure 6. Relationship between WVTR and fabric thickness for various fabric (a) materials or blends, and (b) structure types. Data from: [5] [10] [12] [13] [15] [23] [24] [27] [29] [30] [31] [37] [38] [40] [41] [42] [46] [48] [50] [51] [52] [55] [57] [58] [60] [63] [65] [66] [67] [68].



(a)

(b)

Figure 7. Relation between fabric thickness and water-vapor resistance for various blend ratios of (a) polyester (PES), PES/viscose and viscose fabrics. Data from: [51], and (b) bamboo, bamboo/Tencel and Tencel fabrics. Data from: [13].

Obviously, water-vapor resistance of blends changes non-linearly between the respective values of the materials blended (e.g. **Figure 7**). In case of the polyester/viscose blend, the linear trendline correlates 85% ($R_{et} = -0.0066x + 3.2318$, where x is the fraction of viscose in the blend). Polynomial fits of order 2 or 3 yield correlations of 89% and 95%, respectively. Looking at the related change in fabric thickness, a linear trend in fabric thickness changes with increasing viscose fraction correlates 47%, while polynomial fits of 2nd and 3rd order correlated 97% and 98%. In case of wool/polyester, bamboo/Tencel, acrylic/viscose, acrylic/cotton, and acrylic/polyester blends nonlinear fits for both water-vapor resistance and fabric thickness correlate higher than the linear fits (**Table 3**). These results may be explained by the different hydrophile behavior of the blended fibers. Potentially, differences in hairiness of the fibers might clog macro-pores of the fabric more or less effectively.

Of course, the blend ratio affects WVTR (e.g. **Figure 8**) and absorptance as well. Like for water-vapor resistance non-linear fits have higher correlation than linear fits except cotton/bamboo, polyester/silk, and bamboo/Tencel (**Table 3**). Again, changes in fabric thickness and porosity related to the blend ratio play a role. The data from [67] suggest that fabric structure marginally influences WVTR

Table 3. Equations of best fit and percent of correlation, R^2, between blend ratio, x, water-vapor resistance, R_{et}, and *WVTR* for the fabrics in **Figure 8**. PES is polyester. Blends for which no or insufficient data were available are indicated by -.-.

Fabric blend	Blend ratio impacts on fabric thickness and thermal resistance			
	Equation of best fit for R_{et}	R^2	Equation of best fit for WVTR	R^2
Bambo/Tencel	$7 \times 10^{-7}x^4 - 0.0002x^3 + 0.0103x^2 - 0.169x + 2.68$	100	$-0.0013x + 0.3681$	99
Cotton/Bamboo	-.-	-.-	$-0.0011x + 0.2692$	99
PES/Silk	-.-	-.-	$0.0001x + 0.0974$	98
Cotton/Angora	-.-	-.-	$7 \times 10^{-6}x^3 - 0.0019x^2 + 0.1707x - 4.8705$	100
Banana/Cotton thin	-.-	-.-	$2 \times 10^{-6}x^2 + 6 \times 10^{-5}x + 0.0742$	100
Banana/Cotton thick	-.-	-.-	$-3 \times 10^{-6}x^2 + 0.0003x - 0.0021$	100
Viscose/Silk	-.-	-.-	$-3 \times 10^{-8}x^3 + 6 \times 10^{-6}x^2 - 0.0002x + 0.0973$	98
Linen/Cotton	-.-	-.-	$0.0001x + 0.0594$	99
Hemp/Cotton	-.-	-.-	$-3 \times 10^{-6}x^2 + 0.0004x + 0.0594$	100
Ramie/Cotton	-.-	-.-	$-2 \times 10^{-6}x^2 + 0.0004x + 0.0594$	100
Silk/Acrylic twill	-.-	-.-	$-7 \times 10^{-10}x^4 + 2 \times 10^{-7}x^3 - 10^{-5}x^2 + 0.0002x + 0.0058$	100
Silk/Acrylic plain w.	-.-	-.-	$-10^{-10}x^4 + 3 \times 10^{-7}x^3 - 10^{-5}x^2 + 0.0002x + 0.0062$	100
Wool/Polyester	$-0.0005x^2 + 0.0805x + 0.0824$	100	-.-	-.-
Acrylic/Viscose	$0.0002x^2 - 0.022x + 4$	100	-.-	-.-
Acrylic/Cotton	$0.0002x^2 - 0.026x + 4.4$	100	-.-	-.-
Acrylic/PES	$0.0006x^2 - 0.092x + 7$	100	-.-	-.-

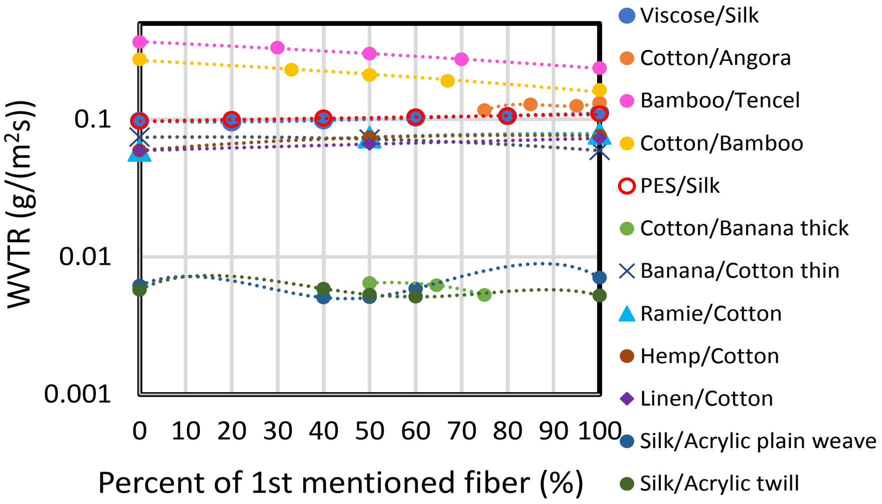


Figure 8. Relationship between blend ratio and WVTR for selected fabric blends. Data from: [13] [37] [40] [51] [57] [60] [67].

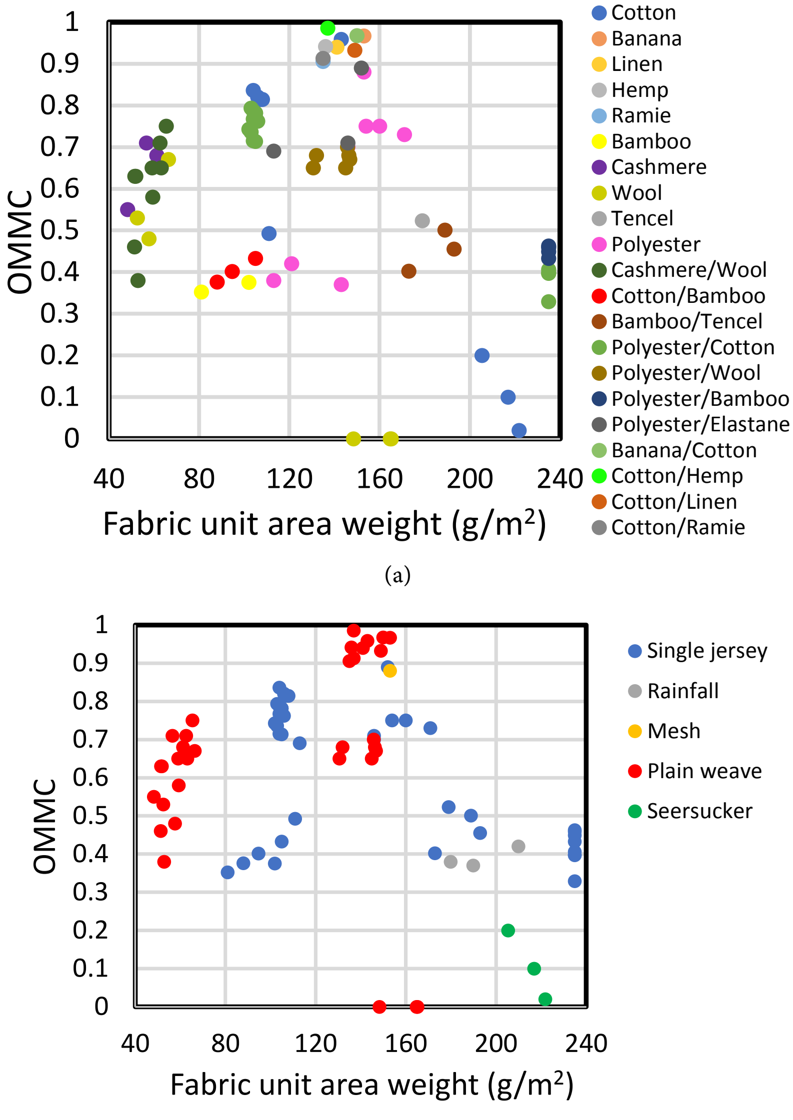
too. Often only three different blend ratios were tested, for which the equations in **Table 2** and **Table 3** may only give a glimpse on whether or not linear relations might exist. This means too few data exist for a more qualitative assessment of blend-ratio impacts on fabric thickness, water-vapor resistance, WVTR and other moisture comfort affecting properties and processes.

Obviously, the fabric structure plays a minor role for OMMC (**Figure 9**). Instead, fiber type, tightness, and blend ratio govern the OMMC. For instance, plain weave wool, cashmere/wool, and cashmere fabrics of about 50 g/m^2 fabric area weight have OMMC values of slightly below 0.4 to slightly above 0.6. Polyester/cotton fabrics have lower OMMC than polyester/bamboo fabrics because bamboo absorbs more water than it spreads it. Of all fabrics, cotton seersucker and heavy wool fabric have the worst moisture management. Nevertheless, seersucker is a favorite in hot humid climate due to its thermal comfort. Wool fabric with low density for its thickness is basically waterproof and a favorite in wet, humid weather.

3.3. Thermo-Physiological Comfort Relationships

The thermo-physiological comfort requirements of a garment depend on the typical weather of a person's living environment and activities. People in climate zones with muggy summers, for instance, need clothes that are moisture wicking and have low thermal resistance. On the contrary, people involved in cross-country skiing under cold, dry weather conditions require clothes with high thermal resistance and low water-vapor resistance.

Analysis of the correlations of the various thermo-physiological characteristics revealed the following. Absorbency is significantly correlated with the overall moisture management capacity (**Table 1**) at the 95% confidence level (R^2 = 81%, R = 0.901). Therefore, it could be used as a good proxy for OMMC that requires a more complex set of measurements. Absorbency and thermal resistance also



(a)

(b)

Figure 9. Relationship between OMMC and fabric unit area weight for (a) various fiber types, and (b) fabric structures. Data from: [3] [4] [12] [13] [23] [60] [64] [69] [70] [71].

showed a very strong correlation, but only at the 90% confidence level (**Table 1**). As expected, water-vapor resistance and absorbency show a very strong negative correlation; The same is true for thermal absorptivity and thermal resistance. Furthermore, strong negative correlations exist between thermal resistance and thermal conductivity, thermal absorptivity and thermal resistance, absorbency and air permeability, absorbency and porosity, water-vapor resistance and OMMC, water-vapor resistance and WVTR, WVTR and wicking, as well as thermal conductivity and wicking. On the contrary, strong positive correlation exists between WVTR and absorbency, thermal conductivity and thermal absorptivity, thermal conductivity and water-vapor resistance.

OMMC correlates weakly with fabric thickness, even though statistically significant at the 90% confidence level (**Table 1**).

3.4. Next Generation Fabrics

Obviously, traditional fabrics (e.g. wool, silk, cotton, nylon, polyester) have several shortcomings. Most traditional fabrics lack the ability to emit the thermal radiation from the body [72]. Therefore, recent research aims to develop self-adaptive materials for thermo-physiological comfort for athletes, construction workers, firefighters, law-enforcement officers, soldiers, and even to stabilize the health condition of patients with health disorders. These inventions include, among other things, ways to enhance thermal conduction and convection from the skin to the environment to keep the body cool under hot conditions.

Indoors, nano-porous polyethylene-based fabrics, for instance, provide radiative cooling because they are mid-infrared transparent. These fabrics can decrease skin temperature by 2.7 K. The nanopores scatter visible light, for which they are opaque in the visible range, while transmitting mid-infrared radiation. Nano-porous polyethylene microfiber fabrics can keep body temperature up to 2.3 K lower than cotton fabrics of same thickness [72].

The developments to increase the heat transfer via thermal convection aim at maximizing the airflow rate for fast evaporation of sweat. Metallic fibers with high thermal reflectivity can reduce significantly the absorption of the incoming solar radiation.

Another approach is tetra-channel polyester fabric. Herein the large surface area of the tetra-channel fiber wicks sweat away from the skin to the outer fabric layer for fast evaporation. Fabrics from this yarn are highly breathable and suitable for apparel, sports accessories, medical wraps, braces, and pads [24].

Another way to create thermophysiological comfort is so-called functional knit that has “suction channels”. They consist of a hydrophobic and hydrophilic layer. The porosity at the hydrophobic-hydrophilic material interface significantly affects the thermo-physiological comfort achieved with structured knitted fabric. The number of suction channels namely shows a quadratic relationship with both thermal absorptivity and thermal resistance. For instance, bi-layer knitted structures with polyester yarn as an inner layer and modal/bamboo yarn as an outer layer improve water-vapor permeability with decreasing thickness, and openness in the fabric [73]. The moisture absorbency of such bi-layer knitted structures increases with increasing stitch density, and tightness.

Recent research on enhancing the thermal comfort properties of tri-layer knitted fabrics for active sportswear tested various combinations of cotton, micro-denier filament polyester, spun polyester yarn, and polypropylene layers. Obviously, the fiber chosen plays a major role for the thermal comfort properties of tri-layer fabrics. Tri-layer knitted fabrics with micro-denier polyester, micro-denier polyester, and cotton as inner, middle, and outer layer, respectively, have exceptionally appreciable thermal comfort properties because of their filamentous nature, lower thickness, areal weight, and bulkiness than other combinations [74].

Recently, knitted sportswear often is treated with moisture management finish

(MMF). A study on the influence of laundering on comfort characteristics of MMF micro-denier polyester knitted fabrics showed that the MMF can withstand at least 20 home laundry cycles [75].

4. Conclusions

Data of fabric thickness, fabric unit area weight, fabric density, thermal conductivity, thermal resistance, thermal absorptivity, air permeability, water-vapor permeability, moisture vapor transmittance, relative water-vapor permeability, porosity, overall moisture management capacity, absorbency, water-vapor resistance, wicking, and water-vapor transmission rate were collected from the literature, and converted to metric units. The resulting inventory encompasses fabrics of different materials, material blends, and structure types. These data were analyzed to derive over-arching concepts that cannot be seen by individual studies alone.

Analysis of the inventory data revealed the following. Air permeability decreases with increasing fabric weight as well as fabric density at different degrees depending on the fabric's material, blend ratio, and structure type (e.g. **Figure 4**). Obviously, for many fabric blends, there exists a non-linear relationship between thermal resistance and blend ratio (**Figure 2**, **Table 2**). The same is true for fabric thickness and blend ratio, WVTR and blend ratio as well as water-vapor resistance and blend ratio. Future studies should involve more blend ratios to improve the derived relations in **Table 2** and **Table 3**. This knowledge could help to optimize thermo-physiological comfort for various applications and climate zones.

The non-linear change of water-vapor resistance of fabric blends with the blend ratio (**Figure 7**) is due to differences in hydrophile behavior, and potential hairiness of the fibers that might clog macro-pores to a certain degree. Consequently, the blend ratio affects WVTR and absorptance as well. At the same fabric thickness, fabric structure only marginally affects WVTR due to the low sensitivity of water-vapor resistance to fabric-structure type (**Figure 6**). However, fabric structure indirectly affects WVTR when for fabrics of same material, the different structure yields a change in fabric thickness. Therefore, one has to conclude that generally, at the same environmental conditions, WVTR strongly depends on fabric thickness, material, and blend ratio.

Unfortunately, data on blend ratios and thermo-physiological parameters and processes exist only for few blended fabrics. These data fail to cover the full suite of potential blend ratios and raw materials, and hence blend combinations. Therefore, a complete qualitative assessment of blend-ratio influences on fabric thickness, thermal and water-vapor resistances, thermal conductivity and WVTR as well as other thermo-physiological comfort-relevant properties and processes has to be postponed to the future when more data become available.

The study also revealed that water absorptance is statistically significantly correlated with the overall moisture management capacity at the 95% confidence level (R^2 = 81%, R = 0.901; Table 1). Consequently, one could use water absorptance as a good qualitative proxy for OMMC when the more complex observations required to calculate OMMC are not available or too expensive.

Scientific research has emphasized that fiber type, yarn properties, fabric structure, finishing, and the cut of the clothing affect thermal-physiological comfort of a person. In the last decade, the customers' demand for fabrics from so-called sustainable or renewable resources is increasing. There is also an increasing demand for vegan fibers for three major reasons. Many customers are concerned about the environmental impacts from overgrazing, and fertilizer (needed to grow cotton) on water resources. Furthermore, many customers also consider shearing animals as crucial. While regenerated fibers like bamboo, birch, and other woods are from natural resources, they involve the use of chemicals that might be health-adverse to the workers and toxic [76] [77] [78]. On the other hand, there is an increased demand for thermo-physiological comfort wear.

To fulfill these demands, future research has to develop fast, inexpensive and effective methods to directly extract the natural fibers from banana stems and bamboo. Also, further investigations on extending the use of linen, hemp, banana, and ramie fibers in blends could help to create fabrics that meet the thermo-physiological comfort requirements for specific climate zones and activities. These studies should address how the blend ratio affects the wear comfort of these non-common fibers.

The growing demand for natural fibers also requires to investigate the thermo-physiological comfort properties of currently underused fibers from leaves (e.g. pineapple, date palm, abaca), stems (e.g., kenaf, corn husk, sorghum), straw (e.g. corn, wheat, rice), Furthermore, technology has to be developed to gain and process these uncommon fibers in a cost-effective way.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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