Fibers and Polymers (2024) 25:1137–1147
https://doi.org/10.1007/s12221-023-00460-w

Online ISSN 1875-0052
Print ISSN 1229-9197

REGULAR ARTICLE

# Thermal Comfort Properties of 100% Cashmere Knitted Fabrics

Selma Dolanbay Dogan[1] · Nurgül Kılınc[1]

Received: 25 May 2023 / Revised: 4 December 2023 / Accepted: 15 December 2023 / Published online: 28 January 2024


**Abstract**

The purpose of this research is to investigate the effects of knitting type (plain, rib, purl), knitting tightness (three different loop lengths), and plied-yarn (single-ply, two-ply and three-ply) on the thermal comfort properties of cashmere knitted fabrics. Thermal comfort properties of the sample fabrics were measured using Alambeta, Permetest, Textest 3300. Subsequently, the results were statistically evaluated with SPSS program. The findings of this research revealed that the knitting type, knitting tightness and plied-yarn usage significantly affect certain thermal comfort properties of cashmere knitted fabrics. Specifically, the plain knitted fabric exhibits the lowest thermal resistance value and the highest relative water vapor permeability value. The loose knitted fabric demonstrates the highest air permeability, while the fabric knitted with single-ply yarn has the lowest thermal conductivity and thermal resistance values, as well as the highest relative water vapor permeability and air permeability values.

**Keywords** Thermal comfort · Knitting type · Knitting tightness · Plied yarn · Cashmere

## 1 Introduction

The textile industry is highly competitive on a global scale necessitating continues improvement of products and processes to ensure success and sustainability for textile companies. Therefore, understanding consumers' needs and demands and aligning product development efforts accordingly has become crucial for these companies. The reasons customers choose clothing, or the properties they expect from clothes, have evolved due to globalization and advancements in technology. Beyond aesthetic design, customer also expect functional design to meet their requirements. Wilfling et al. [1] found that comfort and fit are the most important factors influencing the purchase of sports and exercise garments. Rahman et al. [2] revealed that Chinese young consumers consider comfort and fit as the primary criteria for evaluating apparel products. Kaplan and Okur [3] have also determined that comfort and body-fitting properties are the most important factors for consumers. Similarly, Wong and Li [4] also identified comfort and body-fitting as the two most significant factors influencing clothing choices. Comfort encompasses various dimensions and is subjectively perceived through different senses. It is typically classified into four categories: thermal comfort, sensorial comfort, ergonomic comfort and psychological comfort. The thermal comfort is defined as the condition of reaching the heat and moisture comfort by enabling the heat and moisture transfer from the fabric [5, 6]. Comfort is influenced by environmental factors, fabric/clothing properties and individual characteristics. Research in this field often focuses on fabric properties, such as fiber type, knitting type, density, yarn count, yarn twist, yarn spinning method and finishing processes to enhance the development of fabric structures with higher thermal comfort properties depending on the intended use. For instance, Kumar and Kumar [7] investigated the effect of knitting process parameters on thermal comfort properties of Eri silk knitted fabrics. Single jersey, single pique and honeycomb knitted structures were produced using Eri silk spun yarns of varying counts (25 tex, 17.78 tex, and 14.26 tex) and stitch lengths. Their findings indicated that tight-knit structures show higher stitch density, thickness, bursting strength, thermal conductivity, and low abrasion resistance compared to slack-knit structures. Honeycomb structures show higher course density, areal density, bending length, thermal resistance, thermal absorptivity, air permeability,

✉ Selma Dolanbay Dogan
selmadogan@selcuk.edu.tr

Nurgül Kılınc
nkilinc@selcuk.edu.tr

[1] Department of Fashion Design, Selcuk University, Konya, Turkey

and water vapor permeability. Gericke et al. [8] explored the effect of fibrous matter composition and fabric structural parameters on the thermal comfort properties of woven fabrics containing mohair. The findings unveiled that fabrics containing mohair or mohair/wool are consistently thicker, providing higher thermal resistance. Similarly, Mishra et al. [9] examined the relationship between the different knit structures (single jersey, single lacoste, double lacoste, single pique, double pique), different yarn linear densities (29. 5 tex, 24.6 tex and 19.7 tex) and the thermal comfort properties of 100% cotton knitted fabrics under wet and dry conditions. As a result, single jersey fabrics show the lowest airflow permeability due to their compact structures, while coarser yarns show higher thermal resistance. Oner [10] investigated the thermal comfort properties of knitted fabrics made of various fiber types, including cotton, linen, viscose, modal, bamboo, tencel, zein, polyester, polyamide. Cotton fabrics possess the highest whereas tencel and modal fabrics demonstrate the lowest thermal conductivity values. Atalie et al. [11] conducted a study on the effect of weft yarn twist levels on thermal properties of 100% cotton woven fabrics. The study revealed that an increase in twist leads to a decrease in thermal resistance. Demiryurek and Uysalturk [12] investigated the properties of violoft/polyester and violoft/cotton blended knitted fabrics in relation to heat, including thermal conductivity, thermal diffusivity, thermal absorptivity, thermal resistance, and moisture and air permeability. The research unveiled that the thermal properties of the manufactured fabrics improve with an increase in violoft ratio. It is also observed that compared to single jersey knitted fabrics, rib fabrics exhibit higher thermal conductivity, slightly higher thermal absorbance and lower thermal resistance values, while their water vapor permeability values are similar. Moreover, Yanilmaz and Kalaoglu [13] explored the relationship between the different knit structures (single jersey, $1 \times 1$ rib, $2 \times 2$ rib and interlock) of acrylic knitted fabrics and their thermal comfort properties (wetting, wicking and drying properties). The study reveals that the knit structures significantly influence the comfort parameters. In addition, loosely knitted fabrics exhibit higher transfer wicking ratios compared to tightly knitted fabrics. Majumdar et al. [14] investigated the thermal properties of cotton, cotton-bamboo and bamboo knitted fabrics. The findings demonstrated that the thermal conductivity values of the knit fabrics decrease with an increase in bamboo fibers, while the thermal absorptivity rates of fine yarn fabrics with the same fiber mixture are lower. Interlock knitted fabrics have exhibited the highest thermal absorptivity and thermal resistance values, followed by rib and plain knitted fabrics. In addition, it is observed that the water vapor and air permeability properties of the knitted fabrics increase as their bamboo fiber ratios increase. In comparison, plain knit structures demonstrate better water vapor and air permeability values than rib and interlock knit structures. Cil et al. [15] examined the effect of variables such as fiber content, yarn numbers and tightness on the comfort properties of the knitted fabrics made of cotton, acrylic and cotton-acrylic blends. The results showed that the fabrics' transfer and longitudinal wicking abilities increase with the use of thick yarns while their drying speed increase with the use of fine yarns. On the other hand, tightly knitted fabrics demonstrate significantly higher longitudinal wicking abilities. Oglakcıoglu et al. [16] conducted research on the thermal properties of knitted fabrics blended with different cotton and Angora rabbit fibers. The results indicated that an increase in Angora rabbit fiber leads to increased yarn hairiness, fabric thickness and thermal resistance, while thermal conductivity, thermal absorptivity, and relative water vapor permeability decrease. In another study by Oglakcioglu and Marmarali [17], the thermal properties of the single jersey, $1 \times 1$ rib, and interlock knit structures of the cotton and polyester fabrics were investigated. The findings of the study unveiled that interlock and rib fabrics exhibit notably high thermal conductivity and thermal resistance values. Conversely, single jersey fabrics demonstrate high relative water vapor permeability and provide a warm sensation due to their low thermal absorptivity values. Czaplicki et al. studied about thermal properies of knitted fabrics made of alpaca wool, sheep wool, cotton and acryl fibers. The results showed that knitted fabrics made of alpaca wool are positively evaluated. The analysis of the fabric variants showed that the best thermal protection is provided by two types of stitches, the plain stitch and plain tuck stitch [18]. Kumar et al. investigated thermo-physiological behavior of Eri silk, wool and bamboo knitted fabrics toward sportswear. Finally, the overall thermal comfort fabric is compared both subjective and objective manner and found that Eri silk based knitted honeycomb structure is highest rated than other samples [19]. Kaplan and Yilmaz studied about thermal comfort properties of double-face knitted fabrics with functional yarns such as Thermosoft®, Nilit Heat®, Viloft® and wool were combined with standard polyester and polypropylene. Wool/polyester can be suggested more for liquid management properties with its branched structure besides its higher thermal resistance and air permeability values [20]. Amber et al. examined the effects of fiber type (fine wool, mid-micron wool, acrylic), yarn type (hightwist, low-twist, single), and fabric structure (single jersey, half-terry, terry) on thermal comfort properties of sock fabrics. In the result of the study, fabric structure had the greatest effect on thermal resistance, water vapor resistance, water vapor permeability, liquid absorption capacity, and thermal conductance. Terry fabrics were the most thermal and water vapor resistant, most absorbent, and most conductive [21]. Erdumlu and Saricam investigated the thermal comfort properties of flat knitted acrylic fabrics differing in terms of knit structure, tightness, thickness and porosity within the perspective of its usage in winter wear products. The results indicated that rib 2 × 2 structures provide the optimum condition in terms of thermoregulation, breathability and thermo-physiological comfort, since the thickness improves thermal insulation and porosity improves breathability [22].

A variety of natural and synthetic fiber types are utilized within the textile industry, each characterized by unique mechanical and chemical properties [23]. They present a constellation of strengths and weaknesses contingent upon their intended uses and purposes [10]. Amongst these, cashmere fibers standout as one of the most valuable natural fibers harvested primarily from the underbelly fur of the Cashmere goats inhabiting Central Asia, including, but not limited to, Himalayans, Mongolia, Iran and Afghanistan [24]. Due to their low production volumes and the complexities associated with their manufacture, cashmere fibers are deemed luxurious. Their unique softness, luminosity, and lightness render them preferable in the fashion industry, used widely in producing an array of luxurious woolen items, such as shawls, scarves, sweaters and cardigans [25]. In a review of literature concerning the comfort properties of cashmere fibers, Çelik and Kaynak [23] studied the effects of cashmere/cotton ratio (95% cotton–5% cashmere, 90% cotton–10% cashmere and 85% cotton–15% cashmere) in yarn and fabrics density on permeability properties of knitted fabrics. Their findings showed that that a high cashmere ratio in yarn structure results in higher air permeability and lower water vapor permeability values. Ayakta and Oner [26] investigated the effects of weft yarn blending ratios (80% wool–20% cashmere, 90% wool–10% cashmere, 95% wool–5%cashmere, 97.5% wool–2.5%cashmere, 100% wool) on the thermal comfort properties of worsted fabrics. The research unveiled that a minimum of 10% cashmere fiber significantly improves the comfort properties of the worsted fabric. Several studies [27–32] have been dedicated to exploring the tactile properties of cashmere. This gap in the research on thermal comfort properties of cashmere justifies the present study. The purpose of this research is to investigate the effects of knitting type (plain, rib, purl), knitting tightness (three different loop lengths), and plied-yarn (single-ply, two-ply and three-ply) on the thermal comfort properties of cashmere knitted fabrics.

## 2 Materials and Methods

### 2.1 Materials

This research employed seven different types of cashmere knitted fabric to examine the effect of knitting type (plain, 1 × 1 rib and purl), knitting tightness (loose, medium, and tight loop lengths) and plied yarn usage (26/1, 26/2 and 26/3) on the fabrics' thermal comfort properties. To ascertain the effects of various factors, different sets of fabric codes were compared: fabrics 1, 2 and 3 to study knitting type impact; fabrics 1, 4 and 5 to determine knitting tightness influence, and fabrics 1, 6, and 7 to investigate plied yarn usage effect. All employed fabrics were composed of 100% cashmere. The origin of cashmere was Chinese. Scanning electron microscope (SEM) images of cashmere fibers can be seen in Fig. 1. The knitting process for the fabrics was made on a 12 gauge flat knitting machine, subsequently washing took place at 30 °C without the incorporation of any chemicals or additive substances. The structural properties of the fabrics are listed in Table 1.

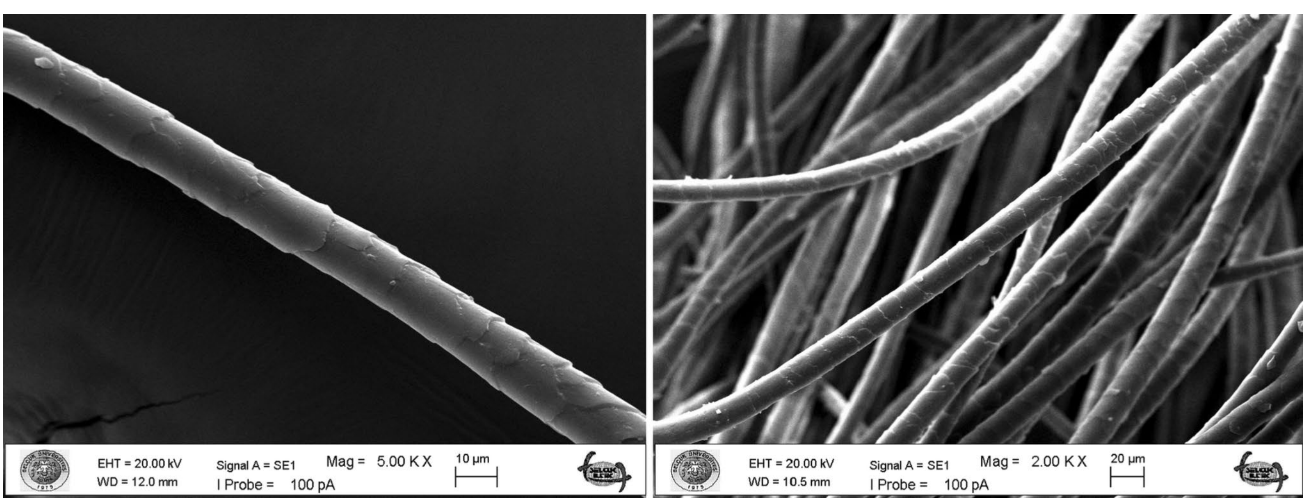


**Fig. 1** Sem images of cashmere fibers (obtained from 26/1 cashmere yarn)

**Table 1** Structural properties of the fabrics

| Sample code | Content/origin of cashmere | Knitting type | Yarn number (Nm) | Course density (course/cm) | Wale density (course/cm) | Loop length (mm) |
|---|---|---|---|---|---|---|
| 1 | 100% Cashmere/Chinese | Plain | 26/1 | 10.5 | 14.6 | 2.8 |
| 2 | 100% Cashmere/Chinese | 1 × 1 Rib | 26/1 | 8.60 | 9.00 | 2.8 |
| 3 | 100% Cashmere/Chinese | Purl | 26/1 | 8.50 | 9.90 | 2.8 |
| 4 | 100% Cashmere/Chinese | Plain | 26/1 | 10.5 | 13.88 | 3.0 |
| 5 | 100% Cashmere/Chinese | Plain | 26/1 | 12 | 16 | 2.6 |
| 6 | 100% Cashmere/Chinese | Plain | 26/2 | 9.00 | 11.25 | 3.5 |
| 7 | 100% Cashmere/Chinese | Plain | 26/3 | 7.70 | 9.5 | 4.1 |

### 2.2 Methods

To put forth the thermal comfort properties of the cashmere knitted fabrics in the study sample, their thermal properties (thermal conductivity and thermal resistance), relative water vapor permeability and air permeability properties were measured. The measuring devices and their standards are provided in Table 2.

The weight and thickness measurements implemented in this study according to TS 251: Method 6 standards and the ISO 5084–1996 standards, respectively. All the tests are conducted in standardized atmospheric conditions (20 ± 2 ℃temperature and 65% ± 5 relative humidity). Thermal conductivity, as defined by ASTM, represents the quantity of heat transferred over time from a unit area, at a unit temperature difference between the parallel surfaces within a unit distance in a stable condition [33]. Thermal resistance, conversely, refers to a material's resilience against heat flow and can be calculated by the following formula: thickness/thermal conductivity [34]. The water vapor permeability is the fabric's ability to allow water vapor through it, while the air permeability can be defined as the passing air amount between the fabric's two surfaces, from a specific area, at a specific time and under a specific pressure.

Statistical evaluations of the test results utilize the SPSS 15 program, employing non-parametric tests (Kruskal–Wallis *H* and Mann–Whitney *U*) due to limited data. With the non-parametric tests, levels of the groups are used to test whether or not the groups differ from each other. The Kruskal–Wallis *H* test was used for group comparison and the Mann–Whitney *U* test was administered for the pair comparisons. In the results, $p$ value of $p \leq 0.05$ was interpreted as a statistically significant difference between the groups. The standard deviations of the test results are calculated and displayed in Figs. 2, 3, and 4 as error bars.

## 3 Results and Discussion

The thermal comfort values of the cashmere knitted fabrics in the study sample are outlined in Table 3, whereas Tables 4 and 5 encompass the results of the statistical analyses.

The results obtained within the scope of the research are categorized into three main parts: related to knitting types, related to knitting tightness, and related to plied yarns.

### 3.1 Results Related to Different Knitting Types

The analysis of thermal properties in cashmere knitted fabrics (samples 1, 2, and 3) across different knitting types in the research sample reveal a statistically significant impact of knitting type on thermal resistance (refer to Table 4). As illustrated in Fig. 2a, variations in thermal resistance values coincide with alterations in knitting type, with the plain knitted fabric (sample 1) demonstrating the lowest thermal resistance value. Statistically significant differences exist between the plain knitted fabric and the other knitting types (samples 2 and 3). Samples 2 and 3, representing 1 × 1 rib and purl knitted fabrics, respectively, exhibit the highest thermal resistance values, with no statistically significant difference between them. Such an outcome can be attributed to the lower thickness (Table 3) of the plain

**Table 2** Properties measured in the experimental study

| Measured properties | Measuring device and standards |
|---|---|
| Thermal transfer properties (Thermal Conductivity (W/mK), Thermal resistance ($m^2$/KW)) | Alambeta |
| Relative water vapor permeability (%) | Permetest (ISO 31092) |
| Air permeability (lt/$m^2$s) | Textest FX 3300 (TS 391 EN ISO 9237) |

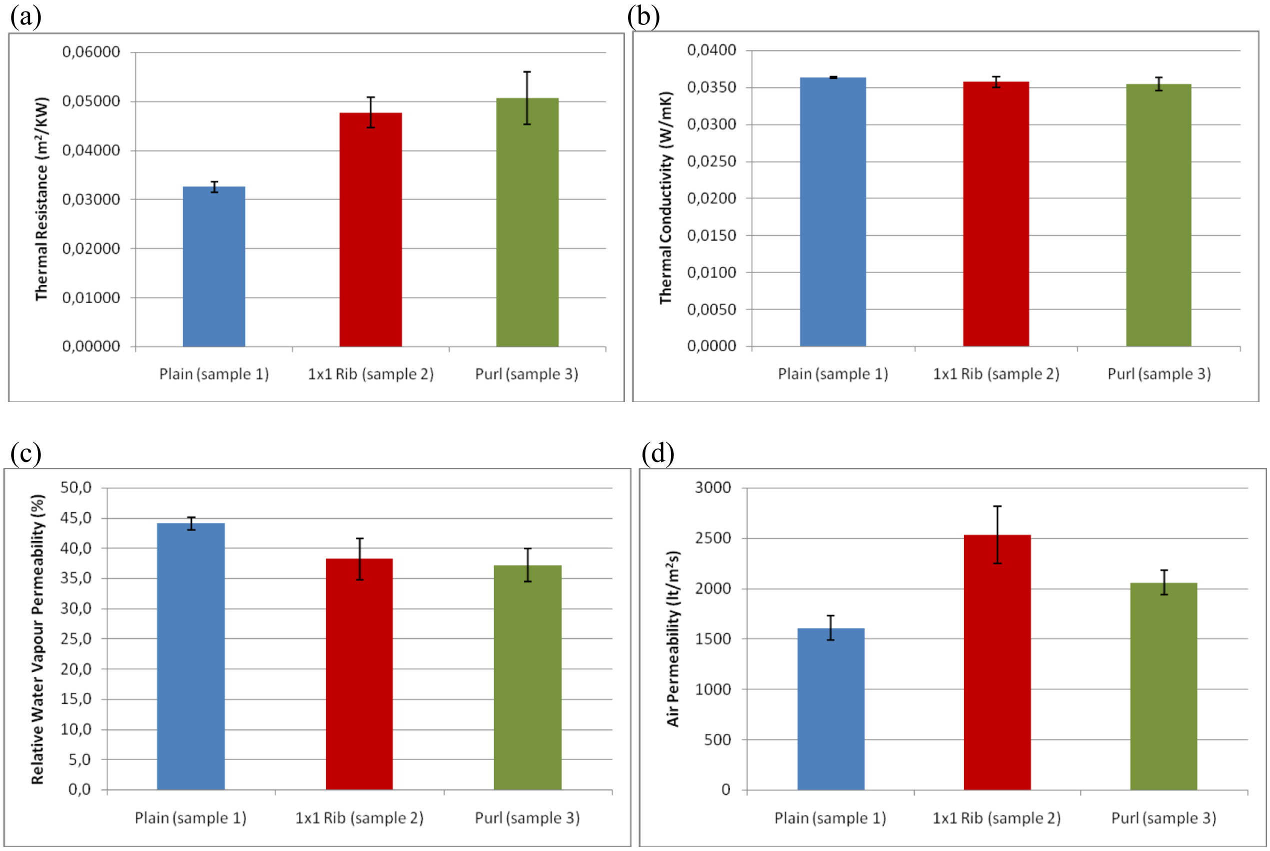


**Fig. 2** Results of different knitting types. **a** Thermal resistance. **b** Thermal conductivity. **c** Relative water vapour permeability. **d** Air permeability

knitted fabric (sample 1) compared to the other knitting types (samples 2 and 3), aligning with the expected results. It can be inferred that rib and purl knitting types are suitable for winter applications due to their superior warmth retention. In this regard, previous research by Majumdar et al. indicated that the plain knitting type exhibits lower thermal resistance value compared to rib and interlock knitting types of cotton, bamboo, and cotton-bamboo blend fabrics [14]. Similarly, Oglakcioglu and Marmarali also reported lower thermal resistance values for the single jersey knitting type of cotton and pes-knit fabrics compared to rib and interlock knitting types [17]. Amber et al. reported single jersey fabrics are the thinnest, lightest, and are the least thermal and most permeable to water vapor of sock fabrics made of fine wool, mid-micron wool and acrylic. İn addition, fiber had a much smaller effect than fabric structure on the properties investigated [21]. Czaplicki et al. revealed that both the unit of thickness and the surface density exert an influence on the thermal resistance concerning the type of knitting. Rib knitted fabrics showcase the highest thermal resistance value among various knitting types. İn addition, the knitted fabrics made from alpaca wool have highest thermal resistance values due to cotton, wool and acryl knitted fabrics [18]. Kumar et al. additionally noted that wool fabrics exhibit superior thermal resistance compared to Eri silk and bamboo fabrics. Within wool, Eri silk, and bamboo knitted fabrics, honeycomb knitted structures have the highest thermal resistance value when contrasted with single jersey and single pique structures [19]. However, in the research conducted by Demiryurek and Uysalturk, it was reported that the thick fabrics showing high thermal resistance is expected, but contrary to the expectations of their study, the thermal resistance levels of the rib knit type are lower than the single jersey knit type and that this condition might be related to the measurement method and the surface of the fabric [12]. Ayakta and Oner ascertained that the inclusion of cashmere fiber in the fabric structure notably augments the thermal resistance value, rendering it suitable for clothing designed for cold protection [26]. According to Gericke et al., mohair/wool/nylon knitted fabric showcases a 20% higher thermal resistance compared to mohair/wool/nylon/bamboo knitted fabric, despite having a similar construction but differing fiber content. Moreover, the thermal resistance of samples containing mohair and wool fibers is higher than acrylic, cotton, pes and bamboo fibers for woven fabrics [8]. Kaplan and Yilmaz determined that wool/polyester double-face knitted fabrics have higher thermal resistance and air permeability values than double-face knitted fabrics made of

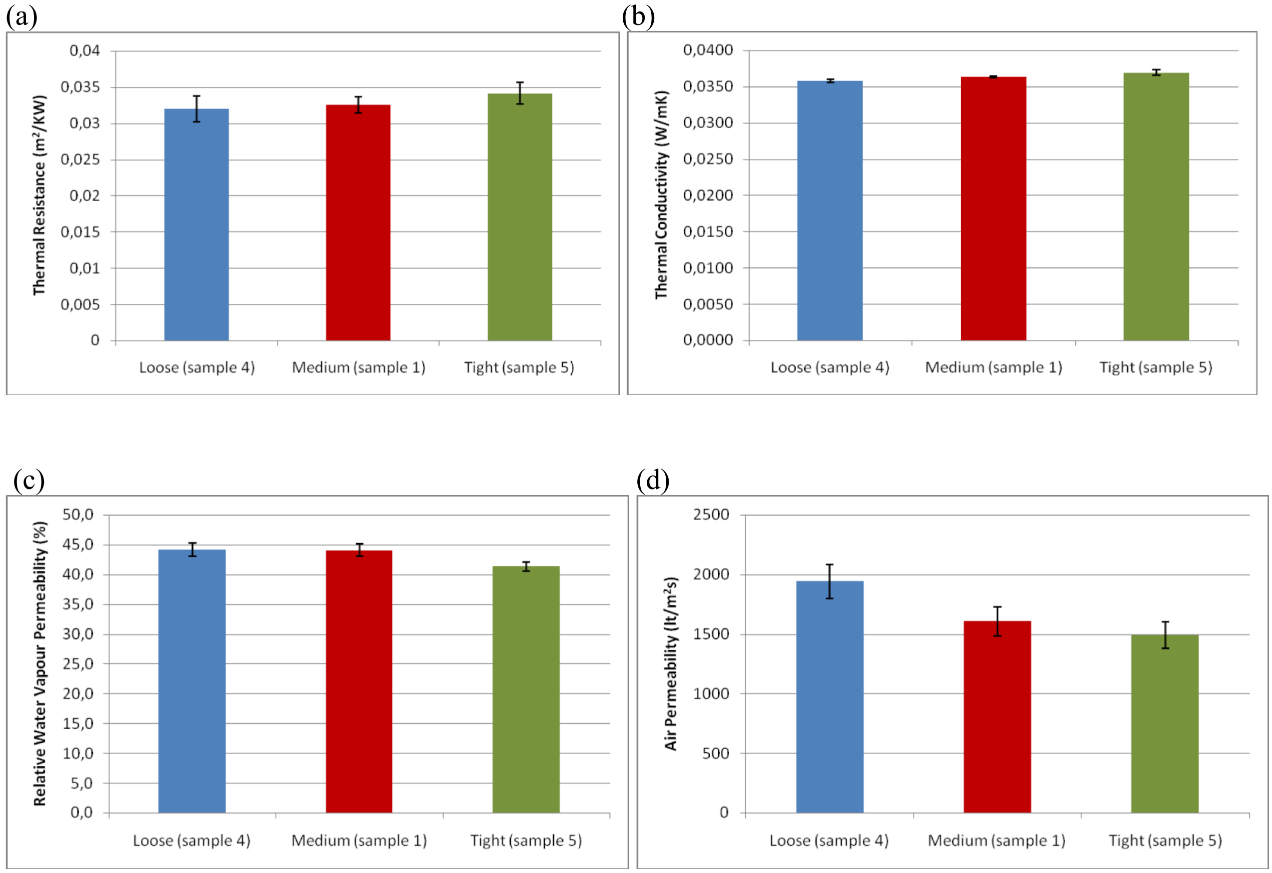


**Fig. 3** Results for different knitting tightness. **a** Thermal resistance. **b** Thermal conductivity. **c** Relative water vapour permeability. **d** Air permeability

functional fibers such as ThermoSoft®, Viloft®, Nilit Heat® are combined with standard polyester and polypropylene filaments [20]. Oglakcioglu et al. propose that augmenting the Angora fiber ratio in the fabric amplifies the thermal resistance value in cotton and cotton/angora knitted fabrics. It is recommended to use Angora blended fabrics in winter clothing [16]. Subburaayasaran et al. reported that 85:15% wool/Eri silk double-layered knitted fabrics demonstrate the utmost thermal resistance. Conversely, 100% Eri silk exhibits inferior thermal resistance compared to other samples, including cotton and micro-denier acrylic [35]. Simultaneously, the investigation into the thermal conductivity values of different knitting types (refer to Fig. 2b) demonstrates that the plain knitted fabric (sample 1) displays the highest thermal conductivity value and the purl knitted fabric (sample 3) showcases the lowest conductivity value but the difference between them is not statistically significant. The knitting type significantly influences thermal resistance, it does not exhibit a notable effect on thermal conductivity. This observation can be rationalized by the disparities in thickness values across the fabrics, given that thermal resistance calculations rely on both thermal conductivity and thickness values. Likewise, Gericke et al. highlighted a high correlation between thermal resistance and thickness values [8].

The statistical analysis examining the relative water vapor permeability properties of cashmere knitted fabrics across different knitting types indicates a significant impact of the knitting type on relative water vapor permeability (refer to Table 4). As depicted in Fig. 2c and detailed in Table 5, the plain knitted fabric (sample 1) showcases the highest relative water vapor permeability value, differing significantly from the other knitted types (samples 2 and 3). In contrast, rib and purl knitted fabrics display the lowest relative water vapor permeability, with no significant difference observed between them. This trend can be ascribed to the thinner and lighter characteristics inherent in plain knitting compared to other knitting types (as depicted in Table 3). The conclusions were drawn by Majumdar et al. [14] and Oglakcioglu and Marmarali [17] are in harmony with the outcomes of this study, changes in the knitting type of cashmere knitted fabrics to their effects on relative water vapor permeability. An examination of air permeability values across different knitting types (as depicted in Fig. 2d) elucidates that the plain knitted fabric (sample 1) manifests the lowest

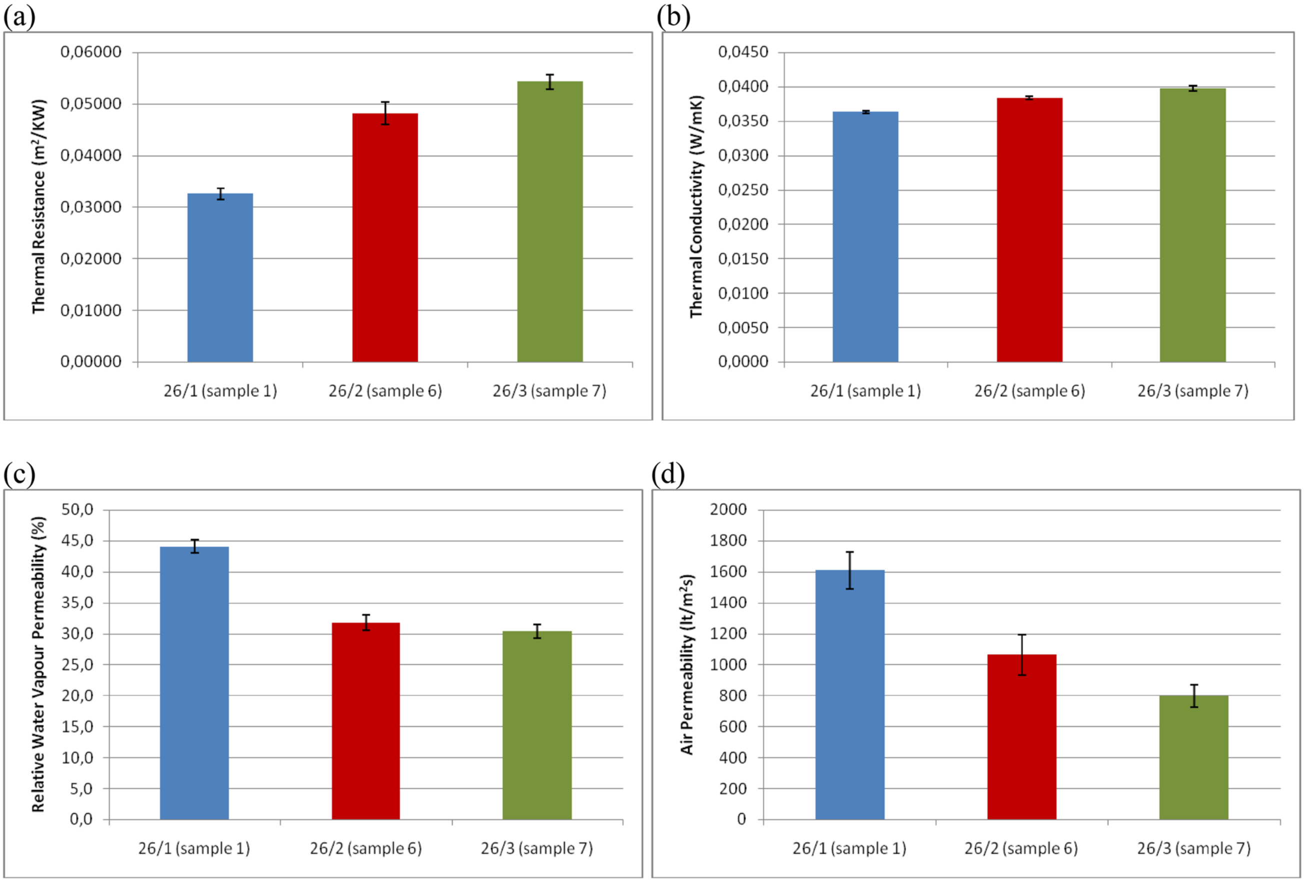


**Fig. 4** Results related to different plied yarn. **a** Thermal resistance. **b** Thermal conductivity. **c** Relative water vapour permeability. **d** Air permeability

**Table 3** Thermal comfort properties of the cashmere knitted fabrics in the study sample

| Sample code | Weight in grams (g/m$^2$) | Thickness (mm) | Thermal conductivity (W/mK) | Thermal resistance (m$^2$/KW) | Relative water vapor Permeability (%) | Air permeability (lt/m$^2$s) |
|---|---|---|---|---|---|---|
| 1 | 142.7 | 1.184 | 0.0363 | 0.03254 | 44.1 | 1608 |
| 2 | 145.3 | 1.708 | 0.0358 | 0.04771 | 38.2 | 2533 |
| 3 | 149.9 | 1.798 | 0.0355 | 0.05066 | 37.2 | 2059 |
| 4 | 140.2 | 1.147 | 0.0358 | 0.03200 | 44.2 | 1940 |
| 5 | 161.8 | 1.260 | 0.0369 | 0.03414 | 41.3 | 1492 |
| 6 | 224.8 | 1.847 | 0.0384 | 0.04815 | 31.7 | 1063 |
| 7 | 321.4 | 2.158 | 0.0398 | 0.05429 | 30.4 | 800 |

air permeability value, while the rib knitted fabric (sample 2) displays the highest air permeability values, with no statistically significant difference observed between them. This observation could be associated with the surface properties inherent in cashmere fibers. Notably, Ayakta and Oner [26] observed that fabrics with a higher cashmere content tend to exhibit increased air permeability compared to other wool and wool/cashmere fabrics. They attributed this phenomenon to the smoother and thinner structure of cashmere fibers in contrast to wool fibers.

## 3.2 Results Related to Different Knitting Tightness

The investigation of thermal resistance values among the fabrics (samples 1, 4, and 5) in the research sample, as depicted in Fig. 3a, indicates that the loose knitted fabric

**Table 4** Statistical evaluation of the thermal comfort properties of the cashmere knitted fabrics in the study sample—the results of the Kruskal–Wallis *H* test

| Thermal comfort property | Fabric property | *p* value |
|---|---|---|
| Thermal conductivity | Knitting type | 0.329 |
| | Knitting tightness | 0.079 |
| | Plied yarn | **0.027** |
| Thermal resistance | Knitting type | **0.050** |
| | Knitting tightness | 0.288 |
| | Plied yarn | **0.027** |
| Relative water vapor permeability | Knitting type | **0.050** |
| | Knitting tightness | 0.177 |
| | Plied yarn | **0.050** |
| Air permability | Knitting type | 0.109 |
| | Knitting tightness | **0.000** |
| | Plied yarn | **0.000** |

Bold values indicate statistical difference $p \leq 0.005$

(sample 4) demonstrates the lowest thermal resistance value, whereas the tight knitted fabric (sample 5) displays the highest thermal resistance value. However, there is no statistically significant difference between them. A similar trend is evident in the thermal conductivity results (Fig. 3b). Ozdil et al. emphasized that fabric tightness does not exert a significant influence on thermal resistance and thermal conductivity concerning cotton fabrics [36]. Shobanasree et al. observed a trend of elevated thermal resistance values corresponding to an increase in loop length for tencel/elastane knitted fabrics, albeit this increase did not achieve statistical significance at a 95% confidence level [37]. In addition, findings from Marmarali et al. indicated that fabric tightness significantly influences the thermal conductivity and thermal resistance values of knitted fabrics produced from pes, patented natural, and synthetic fibers [38]. This situation can be attributed to the inherent structure of cashmere fibers and the amount of changes in loop length noted in the cashmere fabrics studied. Due to thickness of fabrics in the study sample as a result of the cashmere fiber structure and used yarn count, small changes in the loop length might lead to minor differences in the thermal resistance and conductivity values.

Regarding water vapor permeability values across different knitting tightness (as depicted in Fig. 3c), the loose knitted fabric (sample 4) exhibits the highest value, while the tight knitted fabric (sample 5) shows the lowest value, yet the difference lacks statistical significance. Analyzing air permeability properties of fabrics with distinct knitting tightness (detailed in Table 4) indicates a statistically significant influence of knitting tightness on air permeability. As ıllustrated in Fig. 3d, the air permeability value decreases as the fabric tightens, with the loose knitted fabric (sample 4) presenting the highest air permeability value. Furthermore, Table 5

**Table 5** Statistical evaluation of the thermal comfort properties of the cashmere fabrics in the study sample—the results of the Mann–Whitney *U* test

| Thermal comfort property | Fabric property | Fabric property | *p* value |
|---|---|---|---|
| Thermal conductivity | Plied yarn | 26/1 ve 26/2 | **0.050** |
| | | 26/1 ve 26/3 | **0.050** |
| | | 26/2 ve 26/3 | **0.050** |
| Thermal resistance | Knitting type<br>Plied yarn | Plain and 1 × 1 rib | **0.050** |
| | | Plain and purl | **0.050** |
| | | 1 × 1 rib and purl | 0.275 |
| | | 26/1 and 26/2 | **0.050** |
| | | 26/1 and 26/3 | **0.050** |
| | | 26/2 and 26/3 | **0.050** |
| Relative water vapor permeability | Knitting type<br>Plied yarn | Plain and 1 × 1 rib | **0.050** |
| | | Plain and purl | **0.050** |
| | | 1 × 1 rib ve purl | 0.275 |
| | | 26/1 ve 26/2 | **0.050** |
| | | 26/1 ve 26/3 | **0.050** |
| | | 26/2 ve 26/3 | 0.275 |
| Air permability | Knitting tightness<br>Plied yarn | Loose and medium | **0.034** |
| | | Loose and tight | **0.000** |
| | | Medium and tight | **0.000** |
| | | 26/1 ve 26/2 | **0.000** |
| | | 26/1 ve 26/3 | **0.000** |
| | | 26/2 ve 26/3 | **0.001** |

Bold values indicate statistical difference $p \leq 0.005$

highlights a statistically significant distinction among loose, medium, and tight knittings. Consistently, Marmarali et al. unveiled that looser fabrics exhibit increased air permeability values in knitted fabrics produced with diverse yarns [38]. Similarly, Erdumlu ve Saricam found that tightness of the knitted structures has an influence on air permeability, while it had no significant impact on water vapor permeability [22]. The findings by Coruh suggested that an increase in loop length augments air permeability, whereas enhanced thickness decreases air permeability for cotton, viscose, and polyester blended knitted fabrics [39]. Celik and Kaynak observed that the air permeability of cotton/cashmere knitted fabrics increases as the cashmere ratio of the sample increases and the air permeability increases from the tight density to loose density [23].

### 3.3 Results Related to Different Plied Yarn

The analysis of thermal properties among cashmere knitted fabrics (samples 1, 6, and 7) utilizing different plied yarns, as depicted in Table 4, indicates a statistically significant impact of plied yarns on both thermal resistance and thermal conductivity. Illustrated in Fig. 4 a, b, an increase in the number of yarn plies lead to an increase in the thermal resistance and conductivity values. Specifically, the single-ply yarn fabric (sample 1) displays the lowest thermal resistance and thermal conductivity values. Furthermore, Table 5 underscores a statistically significant distinction among these fabrics. This situation can be explained as the reduction in heat transfer through the fabric, attributed to increased space within the fabric resulting from the thinning of the thread, namely, the reduction in the number of thread plies. However, while an inverse relationship between the thermal conductivity values and the thermal resistance values are expected when they are evaluated together, there is a linear relationship between the thermal conductivity and thermal resistance values in this sample group (as depicted Fig. 4 a, b). This observation can be interpreted as an instance where the increase in fabric thickness (as outlined in Table 3) surpasses the elevation in thermal conductivity value. This interpretation aligns with the thermal conductivity formula (Thermal Resistance = Fabric Thickness/Thermal Conductivity). A linear relationship between thermal resistance and thermal conductivity values is also evident in fabrics exhibiting different knitting tightness (as shown in Fig. 3 a, b). In line with the findings of this study, Ozdil et al. also determined a decrease in both thermal conductivity and thermal values of cotton fabrics as the yarn becomes thinner [36]. Furthermore, Majumdar et al. highlighted a reduction in heat conductivity associated with the usage of thinner threads [14]. Moreover, Kumar and Kumar indicated that with the finer yarn count and slack fabric structure, the amount of fiber per unit area decreases, and the amount of entrapped air increases, which attributes to low thermal conductivity for eri-silk knitted fabrics [7].

An examination of the relative water vapor permeability and air permeability values among cashmere knitted fabrics utilizing different plied yarns (referenced in Tables 4 and 5) highlights a statistically significant influence of plied yarn on these values. As illustrated in Fig. 4 c, d, an increase in the number of plies lead to decrease relative water vapor permeability and air permeability values. The one-ply yarn cashmere knitted fabric displays the highest values for both parameters. Hence, it is inferred that air and water transmission increase as the number of yarn plies decreases. This observation aligns with findings by Majumdar et al., who observed that fabrics produced from cotton, cotton-bamboo, and bamboo knits exhibit higher water vapor permeability and air permeability in comparison with those made from fine yarns. This phenomenon is attributed to the lower weight and thickness of these fabrics [14]. Similarly, Atmaca et al. [40] and Havlova [41] also noted a decrease in air permeability with an increase in fabric thickness for woolen and viscose fabrics, respectively. According to Ozdil et al., thinner yarns contribute to increased relative water vapor permeability of cotton fabrics due to the more porous structures in fabrics from fine yarns [36]. Oğulata and Mavruz indicated a correlation between air permeability in knitted fabrics and pore size, noting that fabrics with the lowest yarn number exhibit the highest air permeability values [42]. Öner also observed that modal and viscose fabrics display the highest air permeability values compared to cotton and linen fabrics due to their lower weight and thickness [10]. Kumar and Kumar noted a decrease in air permeability with an increase in yarn linear density for eri-silk knitted fabrics [7]. In addition, Mishra et al. indicated that finer yarns contribute to increased air permeability for 100% combed cotton knitted fabrics due to higher fabric porosity resulting from a low packing factor; conversely, coarser yarns lead to smaller spaces between the yarns, reducing airspace within the yarn and resulting in lower air permeability [9].

## 4 Conclusion

This study delves into the effect of specific production parameters—namely, knitting type, tightness, and plied yarn—on the thermal comfort properties of 100% cashmere knitted fabrics. It compares these findings with existing literature. On the basis of the results in this research that the plain knitted fabric (sample 1) displays the lowest thermal resistance value and the highest relative water vapor permeability value compared to rib and purl knitting types. Among the samples, the loose knitted fabric (sample 4) exhibits the highest air permeability value, whereas the single-ply yarn fabric showcases the lowest thermal conductivity and thermal resistance values alongside the highest relative water vapor permeability and air permeability values. In line with our findings and prior researches in the literature emphasize the influence of knitting type, knitting tightness, and the utilization of plied yarn on the thermal comfort properties of fabrics. Therefore, despite employing various fiber types and combinations, it is evident that production parameters directly shape thermal comfort properties. Moreover, this research affirms the significant influence of fabric structural parameters, such as mass per unit area and thickness, on thermal comfort attributes. İn addition, rib and purl knitted structures, tight knitted fabrics and three plied yarn used fabrics are offered for winter applications due to their superior warmth retention.

This study primarily focuses on objectively examining the effects of a limited set of production parameters on thermal comfort, exclusively utilizing 100% Chinese cashmere. Future researchers are strongly encouraged to widen the investigation by exploring the impacts of cashmere fibers derived from diverse origins, varied fiber combinations, and additional production parameters on thermal comfort. Integrating subjective tests would fortify and enhance the comprehensiveness of these findings. In addition, conducting studies that elucidate the similarities or differences between cashmere and other hair fibers would not only deepen our understanding of cashmere's functionality but also stimulate innovative advancements in this particular domain.

**Funding** Open access funding provided by the Scientific and Technological Research Council of Türkiye (TÜBİTAK). We express our deepest gratitude to Selcuk University Scientific Research Project Coordinatorship for financially supporting the graduate thesis of Selma Dolanbay Dogan, out of which this research emerged.

## Declarations

**Conflict of Interest** The authors declare no conflicts of interest.



## References

1. J. Wilfling, G. Havenith, M. Raccuglia, S. Hodder, Consumer expectations and perception of clothing comfort in sports and exercise garments. Res. J. Text. Appar. **26**(4), 293–309 (2022)
2. O. Rahman, B.C. Fung, Z. Chen, Young Chinese consumers' choice between product-related and sustainable cues—the effects of gender differences and consumer innovativeness. Sustainability. **12**(9), 3818 (2020). https://doi.org/10.3390/su12093818
3. S. Kaplan, A. Okur, The meaning and importance of clothing comfort: a case study for Turkey. J. Sens. Stud. **23**, 688–706 (2008)
4. A.S.W Wong, Y. Li. Clothing sensory comfort and brand preference. In Proceedings of the 4th IFFTI International Conference. Hong Kong, (2002), pp 1131–1135
5. R. Shishoo, *Textiles for sportswear* (Woodhead Publishing Limited, UK, 2005)
6. Y. Li, A.S. Wong, Introduction to clothing biosensory engineering, in *Clothing biosensory engineering*. (Woodhead Publishing Limited, England, 2006)
7. C.S. Kumar, S.B. Kumar, Study on thermal comfort properties of eri silk knitted fabrics for sportswear application. J. Nat. Fibers. **19**(14), 9052–9063 (2022). https://doi.org/10.1080/15440478.2021.1982110
8. A. Gericke, J. Militky, M. Venkataraman, H.J. Steyn, J. Vermaas, Investigation of thermal comfort properties of fabrics containing mohair. J. Text. Inst. **113**(4), 616–627 (2022). https://doi.org/10.1080/00405000.2021.1896158
9. R. Mishra, H. Jamshaid, S.H.S. Yosfani, Thermo physiological comfort of single jersey knitted fabric derivatives. Fash. Text. **8**, 40 (2021). https://doi.org/10.1186/s40691-021-00266-5
10. E. Oner, Mechanical and thermal properties of knitted fabrics produced from various fiber types. Fiber. Polym. **20**, 2416–2425 (2019). https://doi.org/10.1007/s12221-019-9119-1
11. D. Atalie, A.F. Tesema, G.K. Rotich, Effect of weft yarn twist level on thermal comfort of 100 per cent cotton woven fabrics. Res. J. Text. Appar. **22**(3), 180–194 (2018). https://doi.org/10.1108/RJTA-11-2017-0049
12. O. Demiryurek, D. Uysalturk, Thermal comfort properties of violoft/cotton and violoft/polyester blended knitted fabrics. Text. Res. J. **83**(16), 1740–1753 (2013)
13. M. Yanilmaz, F. Kalaoglu, Investigation of wicking, wetting and drying properties of acrylic knitted fabrics. Text. Res. J. **82**(8), 820–831 (2012)
14. A. Majumdar, S. Mukhopadhyay, R. Yadav, Thermal properties of knitted fabrics made from cotton and regenerated bamboo cellulosic fibres. Int. J. Therm. Sci. **49**, 2042–2048 (2010)
15. M.G. Cil, U.B. Nergis, C. Candan, An experimental study of some comfort-related properties of cotton-acrylic knitted fabrics. Text. Res. J. **70**(10), 917–923 (2009)
16. N. Oglakcioglu, P. Celik, B.T. Ute, A. Marmarali, H. Kadoglu, Thermal comfort properties of angora rabbit/cotton fiber blended knitted fabrics. Text. Res. J. **79**(10), 888–894 (2009)
17. N. Oglakcioglu, A. Marmarali, Thermal comfort properties of some knitted structures. Fibres Text. East. Eur. **15**(5–6 (64–65)), 94–96 (2007)
18. Z. Czaplicki, Z. Mikołajczyk, A. Prążyńska, Analysis of functional properties of knitted fabrics made of alpaca wool and other fibres. Fibres Text. East. Eur. **26**(3(129)), 52–59 (2018). https://doi.org/10.5604/01.3001.0011.7302
19. S. Kumar, S. Kumar Boominathan, D.V. Kirubakar Raj, Comparative analysis on thermo-physiological behavior of eri silk, wool and bamboo knitted fabrics toward sportswear. J. Nat. Fibers. **19**(14), 7702–7713 (2022). https://doi.org/10.1080/15440478.2021.1958406
20. S. Kaplan, B. Yilmaz, Thermal comfort performances of double-face knitted insulation fabrics. Fiber. Polym. **23**(2), 537–545 (2022)
21. R.R. Van Amber, C.A. Wilson, R.M. Laing, B.J. Lowe, B.E. Niven, Thermal and moisture transfer properties of sock fabrics differing in fiber type, yarn, and fabric structure. Text. Res. J. **85**(12), 1269–1280 (2015). https://doi.org/10.1177/0040517514561926

22. N. Erdumlu, C. Saricam, Investigating the effect of some fabric parameters on the thermal comfort properties of flat knitted acrylic fabrics for winter wear. Text. Res. J. **87**(11), 1349–1359 (2017)
23. H.I. Celik, H.K. Kaynak, Investigation of the Effects of Blend Ratio on Permeability Properties of Cashmere/Cotton Knitted Fabrics. Dokuz Eylül Üniversitesi-Mühendislik Fakültesi Fen ve Mühendislik Dergisi **19**(57), 1015–1025 (2017)
24. F. Kaya, Y. Yazıcıoğlu. Lif Teknolojisi. Ankara: Seçkin Ofset Matbaacılık. 318 sayfa (1992)
25. S.I. Ishrat, N.P. Grigg, N. Jayamaha, V. Pulakanam, Cashmere industry: value chains and sustainability, in *Sustainability in luxury fashion business*. ed. by C. Lo, J. Ha-Brookshire (Springer Series in Fashion Business Springer, Singapore, 2018)
26. D.Y. Ayakta, O. Eren, The Effect of Cashmere Fibres on the Thermal Comfort Properties of Worsted Fabrics. European J. Eng. App. Sci. **3**(1), 1–4 (2020)
27. N. Davaajav, X. Liu, S. Sukigara, Compression and surface properties of Mongolian cashmere tops related to tactile characterization. Text. Res. J. **89**(9), 1759–1769 (2019). https://doi.org/10.1177/0040517518779993
28. B.A. McGregor, M. Naebe, Fabric handle properties of superfine wool fabrics with different fibre curvature, cashmere content and knitting tightness. J. Text. Inst. **107**(5), 562–577 (2016). https://doi.org/10.1080/00405000.2015.1046310
29. M.G. Supuren, N. Özdil, L. Hes, Prickle and handle properties of fabrics produced from specialty animal fibers. Text. Res. J. **85**(20), 2155–2167 (2015). https://doi.org/10.1177/0040517515578327
30. B.A. McGregor, Variation in the softness and fibre curvature of cashmere, alpaca, mohair and other rare animal fibres. J. Text. Inst. **105**(6), 597–608 (2014). https://doi.org/10.1080/00405000.2013.828448
31. M. Naebe, B.A. McGregor, Comfort properties of superfine wool and wool/cashmere blend yarns and fabrics. J. Text. Inst. **104**(6), 634–640 (2013). https://doi.org/10.1080/00405000.2012.752560
32. B.A. McGregor, R. Postle, Mechanical properties of cashmere single jersey knitted fabrics blended with high and low crimp superfine merino wool. Text. Res. J. **78**(5), 399–411 (2008). https://doi.org/10.1177/0040517507087675
33. J.Y. Hu, Y.I. Li, K.W. Yeung, Thermal properties, in *Clothing biosensory engineering*. ed. by Y.I. Li, S.W. Anthony (Woodhead Publishing Limited, England, 2006)
34. A. Marmarali, D.S. Kretzschmar, N. Ozdil, G.N. Oglakcioglu, Giysilerde ısıl konforu etkileyen parametreler. Tekstil. Ve. Konfeksiyon. **4**, 241–246 (2006)
35. A.S. Subburaayasaran, S. Kubera Sampath Kumar, D. Vasanth Kumar, T. Ramachandran, C. Prakash, H.L. Vijaya Kumar, Comparative studies on thermal comfort properties of eri silk, wool/eri silk, cotton, and micro-denier acrylic double-layered knitted fabrics. J. Nat. Fibers. **19**(15), 11449–11457 (2022). https://doi.org/10.1080/15440478.2022.2025982
36. N. Ozdil, A. Marmarali, S.D. Kretzschmar, Effect of yarn properties on thermal comfort on knitted fabrics. Int. J. Therm. Sci. **46**, 1318–1322 (2007)
37. P.C. Shobanasree, C. Prakash, M. Ramesh Kumar, K.V. Lokesh, Effect of elastane plating on physical & thermal comfort properties of lyocell single jersey knit fabric with different loop length. J. Nat. Fibers **19**(15), 11574–11581 (2022). https://doi.org/10.1080/15440478.2022.2028215
38. A. Marmaralı, H. Kadoğlu, N. Oğlakçıoğlu, P. Çelik, M. Blaga, M. Ursache, C. Loghin, Thermal comfort properties of some new yarns generation knitted fabrics, in AUTEX 2009 World Textile Conference, Izmir, Turkey, 26–28 May 2009, pp. 75–81 (2009)
39. E. Çoruh, Optimization of comfort properties of single jersey knitted fabrics. Fibres. Text. East. Eur. **23**(4(112)), 66–72 (2015). https://doi.org/10.5604/12303666.1152728
40. M. Atmaca, V. Dal, A. Yılmaz, A.B.B. Kurtulus, Investigation of the effects of fabric parameters on air permeability of woolen fabrics. Text. Res. J. **85**(20), 2099–2107 (2015)
41. M. Havlova, Air permeability and structural parameters of single jersey knitted fabric. Fibres. Text. **28**(3), 20–27 (2021)
42. R.T. Ogulata, S. Mavruz, Investigation of porosity and air permeability values of plain knitted fabrics. Fibres. Text. East. Eur. **18**, 71–75 (2010)