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# Optimization of Knitted Fabrics for better Thermo-Physiological Comfort by using Taguchi-based Principal Component Analysis

# *Optimizacija toplotnega udobja pletiv z analizo glavnih komponent temelječo na Taguchijevi metodi*

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## Abstract
The water, air permeability and thermal resistance of fabrics are important attributes that have a significant impact on the thermal comfort properties of sportswear fabrics in different environmental conditions. In this work, terry and fleece fabrics were developed by varying the fibre content and mass per unit area of fabrics. Moreover, the thermo-physical properties of the developed fabrics, including air permeability, water vapor permeability and thermal resistance, were analysed before and after washing. The multi-response optimization of the thermal comfort properties of knitted fabrics was performed using principal component analysis (PCA) and the Taguchi signal-to-noise ratio (PCA-S/N ratio) to achieve optimal properties. It was determined that the selected parameters (fabric type, finishing, fibre content and fabric mass per unit area) had a significant effect on the thermal comfort properties of knitted fabrics. The PCA analysis showed that 100% cotton terry fabric before washing with an aerial weight of 220 g/m$^2$ had higher air and water vapor permeability value, but a lower thermal resistance value.
Keywords: fibre blends, fabric construction, heat and transmission properties of fabric, statistical analysis

## *Izvleček*
*Prepustnost za vodo, zračna prepustnost in toplotni upor pletiv pomembno vplivajo na toplotno udobje športnih oblačil v različnih okoljskih razmerah. V tej raziskavi so bila izdelana frotirna in flisna pletiva s spreminjanjem razmerja bombaža in poliestrskih vlaken ter spreminjanjem ploščinske mase. Pred pranjem in po njem so bile pletivom analizirane zračna prepustnost, prepustnost vodne pare in toplotni upor. Večodzivna optimizacija lastnosti toplotnega udobja pletiv je bila izvedena s pomočjo analize glavnih komponent (AGK) in Taguchijevega razmerja signal/šum*

*(razmerje AGK-S/N) za optimalne lastnosti. Ugotovljeno je bilo, da so izbrani parametri (vrsta pletiva, plemenitenje, vsebnost vlaken in ploščinska masa pletiva) pomembno vplivali na lastnosti toplotnega udobja pletiv. Analiza glavnih komponent je pokazala, da je neoprano 100-odstotno bombažno frotirno pletivo s ploščinsko maso 220 g/m² doseglo najvišje vrednosti zračne prepustnosti in prepustnosti vodne pare in najnižji toplotni upor.*
*Ključne besede: mešanice vlaken, konstrukcija pletiva, toplota, prepustnost, statistična analiza*

## 1 Introduction

Knitted fabrics are widely acceptable textiles because of their good thermal comfort properties, availability in a wide range of products, and simple and low-cost manufacturing techniques [1]. These fabrics provide better freedom in body movements because their structure offers greater flexibility than woven fabrics. Knitted fabrics not only give the wearer a comfortable feeling during use, but also enable the designer to give a more fit look, which makes them ideal for use in sportswear, underwear and casual wear. Other characteristics that make knitted fabrics attractive are their moisture absorption and transmission ability and good handling properties.

Apart from development and advancement in the field of textiles, the rise of consumer awareness through different sources (social media, fashion shows and marketing campaigns by different brands), the dynamics of the clothing/fashion industry are changing at a rapid pace. Currently, clothing brands focus not only on new styles, but also target different aspects of clothing comfort [1]. Although comfort and aesthetics play an important role in the selection of a garment, comfort is becoming increasingly important because of different external factors (moisture, wind, temperature, and social and cultural influences) and internal factors (level of activity). In other words, clothing comfort can be defined as the absence of discomfort or displeasure. Clothing comfort can be categorized in different ways, such as thermo-physiological, sensorial, psychological and garment fit comfort [2]. Thermo-physiological comfort deals with heat and moisture transport properties through clothing, and depends on different factors such as fibre type, fibre content, shape of fibre, yarn characteristic, type of fabrication techniques and finishing treatments, as well as garment fit and size [3].

The air permeability (AP) of a fabric can be defined as the amount of air that passes through a fabric of 100 mm² in one second while maintaining a water head pressure difference of 10 mm [4]. The air permeability of fabric indicates how fabric will allow the movement of air through it [5, 6]. The air permeability of fabric relates to thermo-physiological comfort in different ways: air permeable material is likely to transmit water either in liquid or vapor form, while the thermal resistance of fabric is also closely related to the air trapped in the fabric structure. An earlier study [5] showed that increasing the porosity and stitch length of cotton fabrics resulted in an improvement in the thermal insulation properties of knitted fabrics. Thermal conductivity decreases with an increase in the loop length/stitch length of knitted fabric. It is understood that the thermal conductivity value of fibres is higher than the thermal conductivity of the entrapped air layer. The lower thermal conductivity of knitted fabrics from longer loop length or stitch length is the result of the high porosity of fabric [7, 8]. Fayala et al. further concluded that in cellulosic fabrics the surface characteristics and capillary structures of yarns have a significant effect on the thermal and air permeability of fabrics. Not only fibre content but also the fibre fineness, linear density of yarn, size and shape of pores also contribute significantly to the air permeability and thermal resistance of fabrics [9, 10]. In another study, Saha et al. [11] showed that fabric from 100% cotton demonstrated higher air permeability than other fabrics when the proportion of cotton was decreased and polyester content was increased because cotton has more amorphous regions than synthetic fibres, resulting in increased porosity.

The determination of evaporative heat loss under iso-thermal conditions is known as water vapor resistance (Ret). Water vapor resistance is determined as the differentiation of water vapor pressure between the two faces of a textile substrate divided by the resultant evaporative heat flux per unit area in the direction of the gradient. This capability of fabric or clothing to transmit water vapor plays a very important role in the thermo-physiological comfort of clothing. When the body stops sweating, the textile substrate next to the skin releases water vapors in the external environment to create a dry microclimate between the skin and textile fabric [11, 12].

Thermal resistance ($R_{ct}$) can be defined as the temperature difference between the two faces of a material divided by the resultant heat flux per unit area in the direction of the gradient. The thermal resistance of fabric is directly related to fabric density and thickness. When fabric density increases, the thickness of fabric also increases due to increased air gaps in the fabric structure, which ultimately increases thermal resistance [13]. Bivainyte et al. [14] investigated the impact of a double-layer knitted structure on the thermal transmission characteristics of fabric by using different types of materials, such as cotton, polyester, polyamide and polypropylene, and found that thermal resistance in double-layered knitted fabrics increases with an increase in the thickness of fabric. Due to the thicker fabric structure, more air is trapped, so the pores present within the fabric structure decrease, which ultimately increases thermal insulation. In another study, Saha et al. [11] used 100% cotton, 80% cotton/20% polyester and 60% cotton/40% polyester fibres content in fleece fabric, and found that the maximum thermal insulation was achieved by using 80% cotton/20% polyester because the polyester content made the fabric structure compact due to the presence of more crystalline regions than in 100% cotton fabric. Havenith [15] explained that heat insulation and water vapor resistance were increased with an increase in material thickness because of more air trapped in the thick fabric structure. A similar increase in the thermal resistance of fabric was found after washing, which resulted in more air trapping because the structure of fabrics became more compact after washing [16].

Jamshaid et al. investigated thermal comfort properties such as air permeability, thermal resistance and moisture management for both knitted and woven denim fabric. It was determined that knitted denim fabric demonstrated better thermal resistance, moisture management and air permeability values than woven knitted fabric [17]. Akbar et al. [18] studied the comfort properties of knitted denim. The samples of flax and polyester blends exhibited superior results in terms of air permeability and moisture management compared to samples made from polypropylene and cotton blends. Das et al. [19, 20] conducted a study on the development of advanced knitted structures for the base layer clothing of glacier regions. It was determined that the knitted structure developed from a blend of polyester/elastane (Lycra) and polypropylene/elastane (Lycra) has better thermal properties than pure polypropylene multifilament knitted fabric.

However, there is still a gap in current literature regarding the thermo-physiological comfort properties of different fibre content in the knitted structure of terry and fleece. Moreover, there is no such research available in which the effect of thermo-physiological properties for washed terry and fleece fabric has been explained. The objective of this study was to analyse the effect of knitted fabric type (terry and fleece) on thermo-physiological comfort properties such as air permeability, water vapor resistance and thermal resistance. Also analysed was the effect of different fibre content (cotton and polyester) and areal densities on thermo-physiological comfort properties of fabric before and after washing.

## 2 Materials and methodology

### 2.1 Materials

Used in this work were yarns differing in terms of the proportion of cotton (CO) and polyester (PES), which were provided by Masood Textile Mills Limited, Faisalabad, Pakistan. The details of these yarns are presented in Table 1. The chemicals and reagents used in the study were produced by Archroma, Pakistan. All the chemicals and reagents used were of analytical grade.

*Table 1: Fibre content and yarn count used for developing knitted fabrics*

| Seq. no. | Yarn count (tex) | Fibre content |
|---|---|---|
| 1 | 29.5 | 100% CO |
| 2 | 29.5 | 80% CO/20% PES |
| 3 | 29.5 | 60% CO/40% PES |

### 2.2 Methodology

#### 2.2.1 Fabric preparation

In this work, a total of 36 samples of terry and fleece fabrics were developed according to the combination of selected factor levels [fabric type: (terry and fleece), finishing: (before and after), fibre content: (100% CO, 80% CO/20% PES and 60% CO/40% PES) and fabric mass per unit area: (220, 240, 260)], and are presented in Tables 4 and 5 respectively. All samples were developed using a Mayer & Cie Relanit 4.0 circular knitting machine from Germany. Different machine settings, such as number of needles, diameter and needle gauge, were optimized to achieve the required areal densities (220, 240 & 260) of fabric samples (Table 2).

*Table 2: Machine settings for developing different mass per unit area of fabrics*

| Seq. no. | No. of needles | Diameter of the cylinder (cm) | Needle gauge |
|---|---|---|---|
| 1 | 1680 | 76.2 | 18 |
| 2 | 1872 | 76.2 | 20 |
| 3 | 2074 | 76.2 | 22 |

It is evident from Table 2 that as the fabric mass per unit area was increased from 220 g/m$^2$ to 260 g/m$^2$, the number of needles was increased to obtain more yarns to cover the required area in order to achieve the required values. The developed terry fabrics were converted into fleece fabric by abrading the surface of the fabric on a Gessner Napper Unipro 2006 raising machine. The thickness, stitch length and stitch density of terry and fleece fabrics, as well as mass per unit area are presented in Table 3.

### *2.2.2 Fabric processing*

After fabric preparation, the samples were moved to the textile processing department of Masood Textile Mills Limited, Faisalabad, Pakistan for further processing:

– *semi-bleaching process*

This process was carried out to increase absorbency in the developed fabric samples. Knitted fabrics were semi-bleached at 110 °C for 55 minutes using Imacol C3G plus (1.5 g/L), Felosan RG-N detergent (0.6 g/L), RUCO-STAB OKP (0.33 g/L), Polipan conc. (0.50 g/L), NaOH flakes (2.50 g/L), and $H_2O_2$ 50% (2.0 g/L).

– *neutralizing*

After the semi-bleaching process, neutralization was carried out to eliminate the presence of hydrogen, which can cause shade variations in the samples. All of the semi-bleached fabrics were neutralized at 55 °C for 42 minutes using $CH_3COOH$ (2.0 g/L) and BT-88 catalase (0.2 g/L).

*Table 3: Planned parameters and physical properties of knitted fabrics*

| Fibre content | Fabric type | Mass per unit area (g/m$^2$) | Thickness (mm) | Stitch length (cm) | Stitch density (cm$^{-2}$) |
|---|---|---|---|---|---|
| 100% CO | Terry | 220 | 0.76 | 0.31 | 1364 |
| 100% CO | Terry | 240 | 0.85 | 0.325 | 900 |
| 100 % CO | Terry | 260 | 0.86 | 0.34 | 1080 |
| 80% CO 20% PES | Terry | 220 | 0.71 | 0.305 | 1364 |
| 80% CO 20% PES | Terry | 240 | 0.75 | 0.325 | 900 |
| 80% CO 20% PES | Terry | 260 | 0.80 | 0.35 | 1080 |
| 60% CO 40% PES | Terry | 220 | 0.72 | 0.305 | 1364 |
| 60% CO 40% PES | Terry | 240 | 0.77 | 0.325 | 900 |
| 60% CO 40% PES | Terry | 260 | 0.78 | 0.34 | 1080 |
| 100% CO | Fleece | 220 | 0.74 | 0.31 | 1452 |
| 100% CO | Fleece | 240 | 0.90 | 0.325 | 972 |
| 100% CO | Fleece | 260 | 1.01 | 0.34 | 1160 |
| 80% CO 20% PES | Fleece | 220 | 0.83 | 0.305 | 1452 |
| 80% CO 20% PES | Fleece | 240 | 0.93 | 0.325 | 972 |
| 80% CO 20% PES | Fleece | 260 | 0.97 | 0.35 | 1160 |
| 60% CO 40% PES | Fleece | 220 | 0.84 | 0.305 | 1452 |
| 60% CO 40% PES | Fleece | 240 | 0.87 | 0.325 | 972 |
| 60% CO 40% PES | Fleece | 260 | 0.95 | 0.34 | 1160 |

– *dyeing*

Cotton/polyester (PES/CO) blended knitted fabrics were dyed using reactive dyes. First, the cotton fibres were dyed in a jet machine using reactive dyes. After the completion of the dyeing process, the unfixed dye was removed in a soaping process.

– *finishing process*

After dyeing, the samples were dried and stabilized through the finishing process in Monforts Stenter 6 chambers (80 m/minute, 50–250 °C, steam 2 bar) for the purpose of achieving shape-retention, crease-resistance and resilience properties.

– *washing*

Later, 18 knitted terry and 18 fleece fabric samples were washed to give them special effects. The washing was performed in a Tonello washing machine using pre-cleaning, nano-bubble technology and neutralization.

The liquor ratio of water and Felosan RGN was maintained at 1:20 (g/L) for pre-cleaning. The fabric samples were soaked in the solution at 70 °C for 5 minutes. The neutralization of knitted samples was then performed in an acidic medium.
Using nano-bubble technology, a mixture of sodium hypochlorite (NaOCl) (400ML/L) and water was used to discharge colours from the garment surface. Nano-bubble technology uses less water and chemicals. Flow rate was maintained at 16 min/L with a pressure of 2.3 bar for five minutes, not only to remove the colour but also to give a tone-down effect to fabrics This process was performed in a Tonello washing machine [21].

## 2.3 Characterizations of knitted fabrics

### 2.3.1 Mass per unit area

The mass per unit area of samples was determined according to the standard testing procedure set out in ISO 3801:1977. Fabric samples were cut using a circular cutter with an area of 100 cm$^2$. After cutting the required fabric samples, they were weighed on a scale, and the mean values of the mass per unit area of the fabrics were calculated.

### 2.3.2 Fabric thickness

The thickness of developed knitted fabrics was measured using a Kawabata Evaluation System. A 20 cm × 20 cm fabric sample was cut and positioned on a compression tester in accordance with ASTM D1777. A compression force of 50 g was applied to the samples at a compression rate of 0.0067 mm/s on a fabric area of 2 cm$^2$. Three readings of each sample at different places were recorded.

### 2.3.3 Air permeability (AP)

The air permeability of fabrics was determined using an SDL-Atlas M021A fabric air permeability tester according to the ASTM-D737 test method. Fabric samples with an area of 20 cm$^2$ were tested for air permeability at an air pressure of 100 Pa. Ten values ¸for each fabric (five from the face and five from the back) were recorded at different places to obtain average values.

### 2.3.4 Thermal resistance (Rct)

The thermal resistance of fabric samples was measured using a PERMETEST measuring device according to the ISO 11092:2014 test method. Polytetrafluoroethylene (PTFE) membrane was used to cover the measuring head of the PERMETEST device and was kept dry to determine thermal resistance under steady-state conditions.

### 2.3.5 Water vapor permeability (WVP)

The water vapor permeability index was measured according to the ISO BS 7209-1990 test method. It was calculated by expressing the water vapor permeability of the fabric as a proportion of the water vapor permeability of a reference woven fabric.

## 2.4 Experiment design

### 2.4.1 Taguchi technique

The Taguchi technique was used for the optimization of the air permeability, thermal resistance and water vapor permeability of fabrics. The different factors and their levels used in this study are presented in Table 4.

*Table 4: Factors and levels used in this study*

| Factors | Level 1 | Level 2 | Level 3 |
|---|---|---|---|
| A: Fabric type | A1-terry | A2-fleece | |
| B: Finishing | B1-before | B2-after | |
| C: Fibre content | C1-100% CO | C2-80% CO 20% PES | C3-60% CO: 40% PES |
| D: Fabric mass per unit area | D1-220 | D2-240 | D3-260 |

In this study, three responses (AP, $R_{ct}$, WVP) were taken for simultaneous optimization using Taguchi-based principal component analysis (PCA). The detailed experiment design with the corresponding mean values of responses can be seen in Table 5.

A Taguchi orthogonal design is a highly fractional orthogonal design that was used to reduce the number of experiment runs. Four factors, two with two levels each and the other two with three levels each, were taken into consideration in our study. An L36 ($2^2$ x $3^2$) orthogonal array was constructed for these factors using Minitab 19 software. To meet the property of orthogonality, every pair of columns, each of possible pairs of elements, appears the same number of times. Each combination was repeated three times as shown in Table 5.

*Table 5: Taguchi-based experiment design with mean experimental results*

| Seq. no. | Coded | | | | Actual | | | | Responses | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | Fabric type | Finishing | Blend % CO/% PES | Mass per unit area (g/m²) | Y1: AP (mm/s) | Y2: WVP (g/m² day) | Y3: $R_{ct}$ (m²K/W) |
| 1 | 1 | 1 | 1 | 1 | Terry | Before | 100/0 | 220 | 1660 | 86 | 0.0089 |
| 2 | 1 | 1 | 2 | 2 | Terry | Before | 80/20 | 240 | 403 | 90 | 0.021 |
| 3 | 1 | 1 | 3 | 3 | Terry | Before | 60/40 | 260 | 324 | 95 | 0.028 |
| 4 | 1 | 1 | 1 | 1 | Terry | Before | 100/0 | 220 | 1660 | 86 | 0.0089 |
| 5 | 1 | 1 | 2 | 2 | Terry | Before | 80/20 | 240 | 403 | 90 | 0.021 |
| 6 | 1 | 1 | 3 | 3 | Terry | Before | 60/40 | 260 | 324 | 95 | 0.028 |
| 7 | 1 | 1 | 1 | 1 | Terry | Before | 100/0 | 220 | 1660 | 86 | 0.0089 |
| 8 | 1 | 1 | 2 | 2 | Terry | Before | 80/20 | 240 | 403 | 90 | 0.021 |
| 9 | 1 | 1 | 3 | 3 | Terry | Before | 60/40 | 260 | 324 | 95 | 0.028 |
| 10 | 1 | 2 | 1 | 1 | Terry | After | 100/0 | 220 | 673 | 86 | 0.01 |
| 11 | 1 | 2 | 2 | 2 | Terry | After | 80/20 | 240 | 303 | 85 | 0.024 |
| 12 | 1 | 2 | 3 | 3 | Terry | After | 60/40 | 260 | 303 | 94 | 0.0335 |
| 13 | 1 | 2 | 1 | 2 | Terry | After | 100/0 | 240 | 661 | 85 | 0.012 |
| 14 | 1 | 2 | 2 | 3 | Terry | After | 80/20 | 260 | 300 | 85 | 0.027 |
| 15 | 1 | 2 | 3 | 1 | Terry | After | 60/40 | 220 | 323 | 94 | 0.028 |
| 16 | 1 | 2 | 1 | 2 | Terry | After | 100/0 | 240 | 661 | 85 | 0.012 |
| 17 | 1 | 2 | 2 | 3 | Terry | After | 80/20 | 260 | 300 | 85 | 0.027 |
| 18 | 1 | 2 | 3 | 1 | Terry | After | 60/40 | 220 | 323 | 94 | 0.028 |
| 19 | 2 | 1 | 1 | 2 | Fleece | Before | 100/0 | 240 | 533 | 84 | 0.022 |
| 20 | 2 | 1 | 2 | 3 | Fleece | Before | 80/20 | 260 | 293 | 85 | 0.0317 |
| 21 | 2 | 1 | 3 | 1 | Fleece | Before | 60/40 | 220 | 304 | 92 | 0.031 |
| 22 | 2 | 1 | 1 | 2 | Fleece | Before | 100/0 | 240 | 533 | 84 | 0.022 |
| 23 | 2 | 1 | 2 | 3 | Fleece | Before | 80/20 | 260 | 293 | 85 | 0.0317 |
| 24 | 2 | 1 | 3 | 1 | Fleece | Before | 60/40 | 220 | 304 | 92 | 0.031 |
| 25 | 2 | 1 | 1 | 3 | Fleece | Before | 100/0 | 260 | 344 | 83 | 0.026 |
| 26 | 2 | 1 | 2 | 1 | Fleece | Before | 80/20 | 220 | 303 | 88 | 0.027 |
| 27 | 2 | 1 | 3 | 2 | Fleece | Before | 60/40 | 240 | 290 | 91 | 0.0317 |
| 28 | 2 | 2 | 1 | 3 | Fleece | After | 100/0 | 260 | 242 | 82 | 0.0303 |
| 29 | 2 | 2 | 2 | 1 | Fleece | After | 80/20 | 220 | 240 | 84 | 0.0266 |
| 30 | 2 | 2 | 3 | 2 | Fleece | After | 60/40 | 240 | 267 | 87 | 0.034 |
| 31 | 2 | 2 | 1 | 3 | Fleece | After | 100/0 | 260 | 242 | 82 | 0.0303 |
| 32 | 2 | 2 | 2 | 1 | Fleece | After | 80/20 | 220 | 240 | 84 | 0.0266 |
| 33 | 2 | 2 | 3 | 2 | Fleece | After | 60/40 | 240 | 267 | 87 | 0.034 |
| 34 | 2 | 2 | 1 | 3 | Fleece | After | 100/0 | 260 | 242 | 82 | 0.0303 |
| 35 | 2 | 2 | 2 | 1 | Fleece | After | 80/20 | 220 | 240 | 84 | 0.0266 |
| 36 | 2 | 2 | 3 | 2 | Fleece | After | 60/40 | 240 | 267 | 87 | 0.034 |

#### 2.4.2 Principal component analysis and signal-to-noise ratio (PCA-S/N ratio)

An approach combining principal component analysis (weighed by their eigenvalues) and Taguchi signal-to-noise ratio was used to systematize the goals of the novel responses and eliminate the correlation between the many responses. A six-step process for applying the combined PCA-S/N ratio is specified in reference material [22].

**Step 1:** Convert the original data from the Taguchi experiment into signal-to-noise ratio for responses using the appropriate equation, depending on characteristics that differ according to the nature of the problem under study and that may be categorized as larger-the-better, lower-the-better or nominal-the-best. The mathematical equations (1–3) for S/N ratios are presented below:

Larger-the-better

$$\frac{S}{N}(ratio) = -10\ log\ (\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_{ij^2}}) \tag{1}$$

where

$y_{ij}$ represents the $i_{th}$ duplicate of $j_{th}$ response and n represents S, i.e. the number of repetitions.

Lower-the-better

$$\frac{S}{N}(ratio) = -10\ log\ (\frac{1}{n}\sum_{i=1}^{n} y_{ij^2}) \tag{2}$$

Nominal-the-best

$$\frac{S}{N}(ratio) = 10\ log(\frac{\overline{y}^2}{s^2}) \tag{3}$$

where

$$\overline{y} = \frac{y_1 + y_2 + y_3 +, \dots \dots \dots \dots \dots \dots, y_n}{n}$$

$$s^2 = \frac{\sum_{i=1}^{n}(y_i - \overline{y})^2}{n-1}$$

Taguchi's signal-to-noise ratio was applied for air and water vapor permeability responses according to equation (1) and for thermal resistance according to equation (2).

**Step 2:** Normalize the signal-to-noise ratios:

$$Y_{ij} = \frac{y_{ij} - \min(y_{ij})}{\max\ (y_{ij}) - \min\ (y_{ij})} \tag{4}$$

**Step 3:** Perform factor analysis using MINITAB 18 statistical software according to the principal component method (PCA) to determine the number of factors to extract in a factor analytic study.

**Step 4:** Compute MRPI (Multi-Response Performance Index) using the principal component achieved via factor analysis (equations 5–7).

$$X_1 = P_1Y_1 + P_1Y_2 \tag{5}$$

$$X_2 = P_2Y_1 + P_2Y_2 \tag{6}$$

$$MRPI = W_1\,X_1 + W_2\,X_2 + W_3\,X_3 + \cdots \tag{7}$$

where

$W_1$ and $W_2$ represent the weights of particular principal components. $P_1$ and $P_2$ represent the principal components of factors 1 and 2 respectively.

**Step 5:** Describe the optimum factor and the combination of its level.

Improved product features are obtained via a higher performance index. The factor's effect and optimum level of each controlled factor can be assessed on the basis of the performance index. The factor's effect (FE) can be determined as (equation 8):

$$FE = \max(MRPI) - \min(MRPI) \tag{8}$$

**Step 6:** Perform an analysis of variance (ANOVA) to determine significant factors.

## 3 Results and discussion

### 3.1 Air permeability

The air permeability of terry and fleece fabrics with different fibre proportions and areal densities was investigated before and after the washing process. It is evident from Figure 1 that all the values of air permeability showed that all fabric samples allow the flow/passage of air through them. However, a significant difference in air permeability was identified between terry and fleece fabrics. It was determined that the fabric structure has a significant effect on the air flow rate through the fabric. The results also indicated that fleece fabrics offered higher resistance to air movement through the fabric than terry fabrics because the fleece fabrics have pile or plush on their surface, which offered more resistance to air while passing through the fabrics.

Hady and Baky found that fleece fabrics showed higher air resistance due to the more random arrangement of raised fibres from the surface of fabric [23]. Similar results were also reported by Badr and Nahrawv who determined that the raising of fibres on the surface of fabric helped provide an effective barrier against the flow of air [24].

It is evident from Figure 1 that air permeability was decreased both in terry and fleece fabrics after washing. Similar results were also reported by Mavruz and Ogulata [25] who found that air permeability was decreased in knitted fabrics after washing because the structure of fabric becomes tighter. In another study, S. Vasile et al. [26] showed that air permeability decreased with an increase in the number of washes. Increasing the mass per unit area of the fabrics also resulted in a decrease in the air permeability of fabrics, as shown in Figure 1. Published literature [27–28] shows that increasing the mass per unit area of a fabric resulted in a reduction in the air permeability of fabrics because fabric thickness increases with an increase in mass per unit area. This also offers higher resistance to air flow because of a reduction in porosity between the yarns in the fabric. Machine needle gauge, stitch length and material content play an important role in achieving the required mass per unit area of a fabric [29–30]. It is evident from Table 3 that as the mass per unit area of terry fabric was increased from 220 g/m$^2$ to 260 g/m$^2$, the stitch length decreased because of the higher number of needles per unit area, which resulted in an increase in the amount of yarn in a particular area. A decreased stitch length ultimately results in a more compact structure, which causes a reduction in air permeability [31]. As stitch length decreased, more yarns became closer to each other, thereby decreasing pore spacing, which facilitated a higher resistance to air flow (9). As the polyester content in the yarn was increased, a gradual reduction in air permeability of knitted fabrics was observed because of the increased packing density of fibres. Nazir et al. [32] developed a mathematical relationship between yarn packing density and yarn count, spindle speed, twist per inch, yarn diameter and yarn hairiness (yarn packing density = 0.21 - 0.000293; yarn count = 0.00000013; spindle speed = + 0.00633; twist per inch = +0.645; yarn diameter = 0.0316). Increasing the polyester content in the yarn resulted in higher yarn packing density, which resulted in a reduction in the number of pores, which in turn might cause reduced air permeability values.

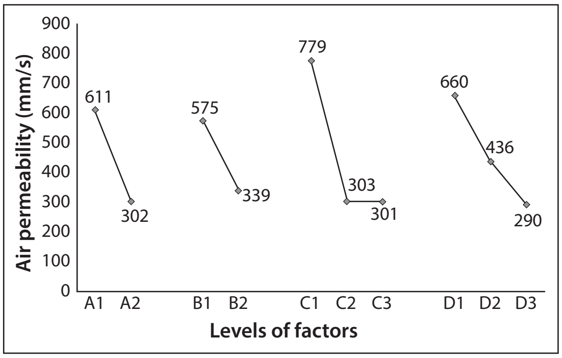


*Figure 1: Air permeability of terry and fleece with different proportions of fibre content and mass per unit area before and after the washing process*

## 3.2 Thermal resistance

The thermal resistance of terry and fleece fabrics with different proportion of fibre content and areal densities was determined before and after the washing process. It was established that different parameters, such as fibre content, yarn characteristics, fabric construction and finishing treatments, have a significant impact on the thermal characteristics of fabrics. It is evident from Figure 2 that fleece fabrics showed higher thermal resistance than terry fabrics. After washing, however, thermal resistance increased from 0.0238 m$^2$K/W to 0.0264 m$^2$K/W. A higher value of thermal resistance was found in fleece fabrics than in terry fabric because the fleece has a raised surface that resulted in the greater thickness of the fabric and trapped more air in its structure. As air is a good thermal insulator, the greater thickness of the fleece fabric resulted in higher thermal insulation than terry fabric [35]. Havenith [15] also reported similar results, as he showed that thermal resistivity increased as a fabric trapped more air in its structure.

As the mass per unit area of fabric was increased from 220 g/m$^2$ to 260 g/m$^2$, the stitch length also decreased, which resulted in a higher number of stitches in a particular area. The fabric thickness thus increased with an increase in the mass per unit area of fabric [33–35]. Afzal et al. [16] and Mitra et al. [36] also reported similar results of thermal resistance in knitted fabrics. In this study, the thermal resistance of fabrics increased slightly after the washing process. This may be due to the fact that after washing, the fabric structure became more compact, which contributed to an increase in thermal resistance. However, Holcombe showed that washing did not have any impact on the thermal resistance of polyester/cellulosic fabrics [37]. Increasing the polyester content of the yarn, however, increased the thermal resistance of fabrics.

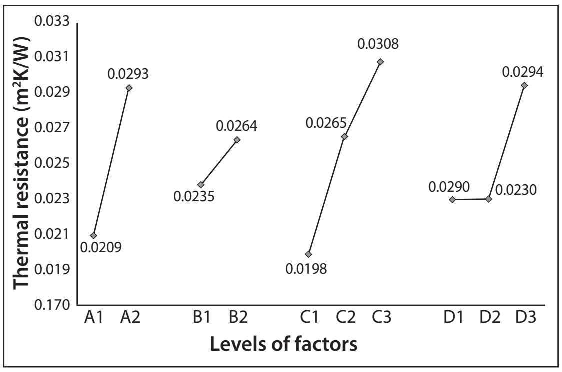


*Figure 2: Thermal resistance of terry and fleece with different proportions of fibre content and mass per unit area before and after the washing process*

## 3.3 Water vapor permeability

Water vapor permeability is a measure of how much vapor is transmitted through a material. It is evident from Figure 3 that terry fabric showed higher water vapor permeability than fleece fabrics, while both fabrics structures showed a decreasing trend of vapor permeability after the washing process.

Kandhavadivu et al. [38] reported that piled/fleece fabrics demonstrated a slower transfer of moisture than other knitted structures because of lower contact of fibre with moisture and increased thickness of material. It is evident from Figure 3 that after washing water vapor permeability decreased slightly, from 89 to 86 g/mm$^2$. This slight decrease in water vapor permeability may be attributed to an increase in fabric hairiness after washing, which offered more resistance to the flow of water vapors through the fabric thickness.

As mentioned earlier, the packing density of yarn increases with an increase in polyester content in the cotton/polyester blend, which resulted in a reduction in the inter-fibre spacing. Water vapor permeability is inversely proportional to the thickness of fabric; increasing the value of needle gauge decreases the stitch length of fabric. As a result, the GSM of fabric increases and the water vapor permeability of the fabric decreases [39, 40]. A decreasing trend in moisture vapor permeability was observed with an increase in the mass per unit area of fabrics as shown in Figure 3. Reducing the gaps in the fabric structure caused an increase in material thickness, which offered more resistance in moisture transportation from one side of fabric to the other.

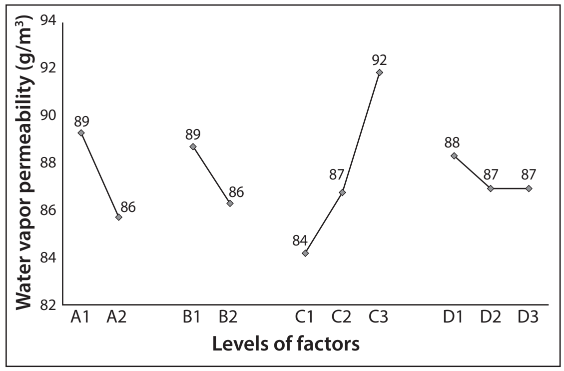


*Figure 3: Water vapor permeability of terry and fleece with different proportions of fibre content and mass per unit area before and after the washing process*

## 3.4 Optimization using principal component analysis combined with the signal-to-noise ratio (PCA-S/N ratio) method

The multi-response optimization of AP, WVP and $R_{ct}$ was performed using principal component analysis (PCA). Initially, the S/N ratio values for the responses were determined as shown in Table 6. The S/N ratios were computed as larger-the-better for AP and WVP according to equation 1 and lower-the-better for $R_{ct}$ according to equation 2. In the second step, normalized S/N ratios were calculated according to equation 4 for all the output variables to eliminate the probabilities of error and normalize several quality characteristics as presented in Table 5. In the third step, principal component analysis was performed using the results of normalized S/N ratios. The first principal component has an eigenvalue greater than one, and was considered for further analysis. The principal component analysis matrix is presented in Table 7. The data from Table 7 were used to calculate X1, X2 and MRPI according to equations 5–9, and the results are presented in Table 8.

$$\mathrm{MRPI} = 0.656(\mathrm{X}_1) + 0.323(\mathrm{X}_2) + 0.020(\mathrm{X}_3) \quad (9)$$

*Table 6: S/N ratios of experimental results*

| Seq. No. | S/N ratios | | | Normalized S/N ratio | | | MRPI |
|---|---|---|---|---|---|---|---|
| | Y1: AP (mm/s) | Y2: WVP (g/m² day) | 0.7630 | AP | WVP | $R_{ct}$ | |
| 1 | 64.402 | 38.700 | 0.3931 | 1.000 | 0.331 | 0.000 | 0.7630 |
| 2 | 52.094 | 39.076 | 0.4414 | 0.268 | 0.633 | 0.639 | 0.3931 |
| 3 | 50.186 | 39.532 | 0.7630 | 0.154 | 1.000 | 0.854 | 0.4414 |
| 4 | 64.402 | 38.700 | 0.3931 | 1.000 | 0.331 | 0.000 | 0.7630 |
| 5 | 52.094 | 39.076 | 0.4414 | 0.268 | 0.633 | 0.639 | 0.3931 |
| 6 | 50.186 | 39.532 | 0.7637 | 0.154 | 1.000 | 0.854 | 0.4414 |
| 7 | 64.402 | 38.700 | 0.3931 | 1.000 | 0.331 | 0.033 | 0.7637 |
| 8 | 52.094 | 39.076 | 0.4414 | 0.268 | 0.633 | 0.639 | 0.3931 |
| 9 | 50.186 | 39.532 | 0.4480 | 0.154 | 1.000 | 0.854 | 0.4414 |
| 10 | 56.554 | 38.660 | 0.1792 | 0.533 | 0.299 | 0.084 | 0.4480 |
| 11 | 49.603 | 38.619 | 0.4016 | 0.120 | 0.266 | 0.739 | 0.1792 |
| 12 | 49.603 | 39.456 | 0.4193 | 0.120 | 0.939 | 0.988 | 0.4016 |
| 13 | 56.402 | 38.561 | 38.396 | 0.524 | 0.220 | 0.222 | 0.4193 |
| 14 | 49.542 | 38.599 | 31.361 | 0.116 | 0.250 | 0.827 | 0.1735 |
| 15 | 50.180 | 39.504 | 31.046 | 0.154 | 0.977 | 0.854 | 0.4337 |
| 16 | 56.402 | 38.561 | 38.396 | 0.524 | 0.220 | 0.222 | 0.4193 |
| 17 | 49.542 | 38.599 | 31.361 | 0.116 | 0.250 | 0.827 | 0.1735 |
| 18 | 50.180 | 39.504 | 31.046 | 0.154 | 0.977 | 0.854 | 0.4337 |
| 19 | 54.533 | 38.508 | 33.134 | 0.413 | 0.177 | 0.675 | 0.3415 |
| 20 | 49.303 | 38.577 | 29.981 | 0.102 | 0.233 | 0.946 | 0.1609 |
| 21 | 49.589 | 39.233 | 30.170 | 0.119 | 0.760 | 0.930 | 0.3420 |
| 22 | 54.533 | 38.508 | 33.134 | 0.413 | 0.177 | 0.675 | 0.3415 |
| 23 | 49.303 | 38.577 | 29.981 | 0.102 | 0.233 | 0.946 | 0.1609 |
| 24 | 49.589 | 39.233 | 30.170 | 0.119 | 0.760 | 0.930 | 0.3420 |
| 25 | 50.696 | 38.392 | 31.688 | 0.185 | 0.084 | 0.799 | 0.1644 |
| 26 | 49.603 | 38.856 | 31.361 | 0.120 | 0.457 | 0.827 | 0.2426 |
| 27 | 49.247 | 39.192 | 29.981 | 0.099 | 0.727 | 0.946 | 0.3184 |
| 28 | 47.658 | 38.288 | 30.367 | 0.004 | 0.000 | 0.913 | 0.0209 |
| 29 | 47.589 | 38.517 | 31.487 | 0.000 | 0.185 | 0.817 | 0.0760 |
| 30 | 48.490 | 38.752 | 29.355 | 0.054 | 0.373 | 1.000 | 0.1757 |
| 31 | 47.658 | 38.288 | 30.367 | 0.004 | 0.000 | 0.913 | 0.0209 |
| 32 | 47.589 | 38.517 | 31.487 | 0.000 | 0.185 | 0.817 | 0.0760 |
| 33 | 48.490 | 38.752 | 29.355 | 0.054 | 0.373 | 1.000 | 0.1757 |
| 34 | 47.658 | 38.288 | 30.367 | 0.004 | 0.000 | 0.913 | 0.0209 |
| 35 | 47.589 | 38.517 | 31.487 | 0.000 | 0.185 | 0.817 | 0.0760 |
| 36 | 48.490 | 38.752 | 29.355 | 0.054 | 0.373 | 1.000 | 0.1757 |

*Table 7: Principal component analysis matrix*

| Seq. no. | Principal component | Eigenvalue | Proportion | Eigenvector |
|---|---|---|---|---|
| 1 | First | 1.9689 | 0.656 | −0.687 ($y_{11}$), 0.196 ($y_{12}$), 0.700 ($y_{13}$) |
| 2 | Second | 0.9702 | 0.323 | 0.196 ($y_{21}$), 0.976 ($y_{22}$), −0.096 ($y_{23}$) |
| 3 | Third | 0.0609 | 0.020 | 0.700 ($y_{31}$), −0.071 ($y_{32}$), 0.711 ($y_{33}$) |

*Table 8: Main effects on MRPI*

| Seq. no. | Factors | Level 1 | Level 2 | Level 3 | Max – Min |
|---|---|---|---|---|---|
| 1 | Fabric type (A) | 7.8749 | 3.2319 | - | 0.5988 |
| 2 | Finishing (B) | 7.2074 | 3.8994 | - | 0.3039 |
| 3 | Blend (C) | 4.4865 | 2.4977 | 4.1226 | 0.1868 |
| 4 | GSM (D) | 4.7596 | 3.7256 | 2.6216 | 0.1905 |

*Table 9: Results of ANOVA*

| Seq. no. | Factors | SS | df | MS | F-Test | Contribution (%) |
|---|---|---|---|---|---|---|
| 1 | A | 0.5988 | 1 | 0.5988 | 64.43 | 38 |
| 2 | B | 0.3040 | 1 | 0.3040 | 32.71 | 18 |
| 3 | C | 0.1869 | 2 | 0.0934 | 10.05 | 12 |
| 4 | D | 0.1905 | 2 | 0.0953 | 10.25 | 12 |
| 5 | Error | 0.2788 | 30 | 0.0093 | 1.00 | 20 |
| 6 | Total | 1.3685 | 36 | | | |

The main effects on MRPI are presented in Table 8. The table shows that the controllable factors on MRPI value were, in the order of importance, A, B, D, C. The maximum MRPI value indicates better quality. The optimum parameters might therefore be set as A1, B1, C1 and D1.

The results of ANOVA are presented in Table 9. It was determined that fabric type was the most imperative factor, with a contribution of 38%, while finishing type was the second most important factor, with a contribution of 18%. The blend ratio and mass per unit area showed almost the same contribution, while error was determined to be 20%.

All the factors have a significant effect on the comfort properties of fabrics. However, factors A and B have a greater effect than C and D. The optimum response values might be set as A1, B1, C1 and D1, which corresponds to terry fabric, before washing, 100% cotton and 220 g/m$^2$ respectively. The results showed that this fabric had higher air and water vapor permeability values, but a lower thermal resistance value.

## 4 Conclusion

This study proposed a method for the multi-response optimization of knitted fabric thermal comfort properties for sportswear using Taguchi-based principal component analysis. Herein, terry and fleece knitted fabrics, with mass per unit area of 220 g/m$^2$, 240 g/m$^2$ and 260 g/m$^2$, were developed using a 29.5 tex (20's Ne) staple spun yarn with three blend ratios (100% cotton, 60% cotton/40 polyester and 80% cotton/20% polyester), while thermal comfort properties, including air permeability, water vapor permeability and thermal resistance, were analysed before and after fabric washing. It was observed that air permeability and water vapor permeability decreased and thermal resistance increased after washing. The multi-response optimization proposed optimum comfort properties for 100% cotton terry fabric with a mass per unit area of 220 g/m$^2$ before washing. ANOVA results showed that fabric type was the most critical factor affecting fabric comfort properties (38%), while finishing type (18%) had a comparatively smaller contribution to those properties. The blend ratio and mass per unit area (12%) were found to have a minimum effect on fabric comfort properties.

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