# Quantitative Research on Thermal Performance of Ready-To-Wear Apparel Based on Analytic Hierarchy Process Model

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**Abstract.** This work primarily focuses on quantifying the thermal insulation ability of fibers through modeling. The study establishes a comprehensive insulation evaluation index (CWI) with six variables derived from three dimensions: thermal conductivity, air content and structural properties, humidity, and permeability. The normalized weights of each variable are calculated using the Analytic Hierarchy Process model. The consistency ratio (CR) of pairwise comparison matrices is significantly less than 1, indicating good consistency in the pairwise comparison model. Additionally, the relationship between the thermal insulation performance of polyester fibers and their average length and diameter is considered. By analyzing how the parameters in the model are influenced by fiber length and diameter, adjustments are made to the model parameters. The conclusion is drawn that fibers with shorter average length and smaller diameter tend to have stronger thermal insulation performance. Finally, the microstructure of cotton and down feathers is studied to further refine the model parameters, and it is determined that down feathers exhibit the best thermal insulation performance, followed by polyester and cotton, with no significant difference between the latter two. The aim of this paper is to address the gap in previous research regarding the quantitative analysis of fiber thermal insulation capabilities. By accurately assessing the thermal insulation effects of fibers filled within garments, this study provides a scientific basis for clothing design and material selection.

**Keywords:** Analytic Hierarchy Process, Thermal Insulation Capability, Quantitative Analysis.

## 1. Introduction

In recent years, the issue of winter warmth has gradually become a focus of attention, along with concerns about potential harm to animals. With advances in technology and the development of fiber materials, synthetic insulation fibers have received increasing attention as alternatives to down.

Muthukumar et al. compared the thermal conductivity and thermal resistance of six combination fiber composites to find suitable insulation materials [1]. Yang et al. prepared nine double-layer knitted samples and evaluated their thermal comfort properties through assessments of breathability, water transfer properties, thermo-physiological properties, and dynamic cooling performance, and statistically analyzed their relationship with fabric knitting structures and yarn compositions [2]. Veerasimman et al. summarized the thermal properties of hybrid sisal fiber composites [3]. Pasayev et al. analyzed the thermal performance of samples made from chicken feather fibers to assess the feasibility of using fibers obtained from chicken feathers as filling material in winter outerwear [4]. Abbasi et al. investigated the thermal comfort properties of fabrics produced with different widths of diamond patterns, different filling yarn linear densities, and different material types [5]. Yang et al. studied the effect of structural parameters on the thermal properties of polyester nonwoven fiber materials [6]. Vasanth Kumar et al. studied the thermal comfort properties of socks made from virgin cotton, recycled polyester fibers, and their blends, based on thermal conductivity, thermal resistance, air permeability, and relative water vapor permeability [7]. Hassan et al. found that fiber composition has a significant effect on the moisture and thermal properties of sportswear knitted fabrics [8].

In previous studies, there has been limited focus on quantitatively researching the thermal insulation ability of fibers. This paper selects six different parameter variables and, through the Analytic Hierarchy Process model, determines the weight parameters of each variable. Subsequently, it establishes a comprehensive evaluation system for the thermal performance of ready-to-wear apparel. This system quantifies the thermal insulation ability of insulation fibers filled inside clothing and provides a quantitative calculation of the thermal insulation abilities of polyester, cotton, and down feathers.

## 2. Parameter Weight Determination and Quantitative Evaluation of Warmth Performance

### 2.1. Establishment of Metrics

To establish a more reasonable metric system, this paper selects the following indicators as model parameters:

(1) Thermal conductivity (k) is a physical quantity describing the thermal conductivity of a substance, with lower thermal conductivity often indicating better insulation.

(2) Thermal resistance (R) is a physical quantity describing the hindrance factors in the process of heat conduction, with its value assumed to be the ratio of material thickness to thermal conductivity.

(3) Air content (α) has a significant impact on the warmth of clothing, as it can block the loss of heat.

(4) Fiber structure (S) can affect the insulation performance, breathability, and moisture handling capacity of clothing, thereby influencing the wearer's comfort in different environmental conditions.

(5) Moisture absorption (G) refers to the ability of fabrics to absorb moisture.

(6) Breathability (T) refers to the ability of air to circulate inside and outside the clothing.

### 2.2. Principle of Analytic Hierarchy Process Model.

The Analytic Hierarchy Process (AHP) is a mathematical method for multi-criteria decision-making, introduced by Thomas L. Saaty in the 1970s. It is a systematic approach used to address complex decision problems.

In AHP, decision-makers need to make pairwise comparisons of the items within each level to determine their relative importance. Comparisons are made by constructing a pairwise comparison matrix. Assuming there are n items to compare, a square n*n comparison matrix A is constructed, where $a_{ij}$ represents the comparison result of the i-th item relative to the j-th item. Typically, the values of $a_{ij}$ range from 1 to 9, indicating the relative importance of the i-th item compared to the j-th item, while $a_{ji}$ is the reciprocal of $a_{ij}$.

Next, the Eigenvector method or the Principal Eigenvector method is used to calculate the maximum eigenvalue of the comparison matrix A and its corresponding eigenvector ω. Then, the eigenvector ω is normalized to obtain the weights for each item. These weights represent the relative importance of each item to the objective. The mathematical formulas are as follows:

$$\mathrm{A} * \omega = \lambda_{\max} * \omega \tag{1}$$

$$\omega_{\mathrm{i}} = \frac{\nu_{\mathrm{i}}}{\sum_{\mathrm{j}=1}^{\mathrm{n}} \nu_{\mathrm{j}}} \tag{2}$$

Additionally, AHP includes consistency checks to ensure the consistency of the comparisons made by the decision-maker. The consistency index (CI) and consistency ratio (CR) are calculated to test the consistency of the comparison matrix. The formulas for calculation are as follows:

$$\mathrm{CI} = \frac{\lambda_{\max} - \mathrm{n}}{\mathrm{n} - 1} \tag{3}$$

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{4}$$

Here, RI is the Random Index, which is a random consistency index determined based on the order of the comparison matrix and is typically obtained from a table based on the order of the comparison matrix. If the CR value is less than a pre-defined threshold, such as 0.1, the comparison matrix is considered acceptable.

Finally, the weights of each item are combined with the other items within their respective levels to derive the overall evaluation. This process can be recursive until the final decision solution is obtained.

## 2.3. Quantitative Calculation of Polyester Insulation Performance

In this paper, thermal conductivity and fiber structure are identified as crucial factors in assessing the warmth performance of garments, followed by thickness and air content, with moisture absorption and breathability having the least influence. Based on this, pairwise comparison matrices are constructed as shown in Table 1.

**Table 1.** Pairwise comparison matrix

| | Thermal conductivity | Fiber structure | Air content | Moisture absorption | Breathability | Thickness |
|---|---|---|---|---|---|---|
| Thermal conductivity | 1 | 1 | 2 | 3 | 3 | 2 |
| Fiber structure | 1 | 1 | 2 | 3 | 3 | 2 |
| Air content | 1/2 | 1/2 | 1 | 2 | 2 | 1 |
| Moisture absorption | 1/3 | 1/3 | 1/2 | 1 | 1 | 1/2 |
| Breathability | 1/3 | 1/3 | 1/2 | 1 | 1 | 1/2 |
| Thickness | 1/2 | 1/2 | 1 | 2 | 2 | 1 |

Next, the maximum eigenvalue of the comparison matrix and its corresponding eigenvector real parts were computed. The weight vector was then divided by the total sum of all weights to obtain a normalized weight vector ranging between 0 and 1, as shown in Figure 1.

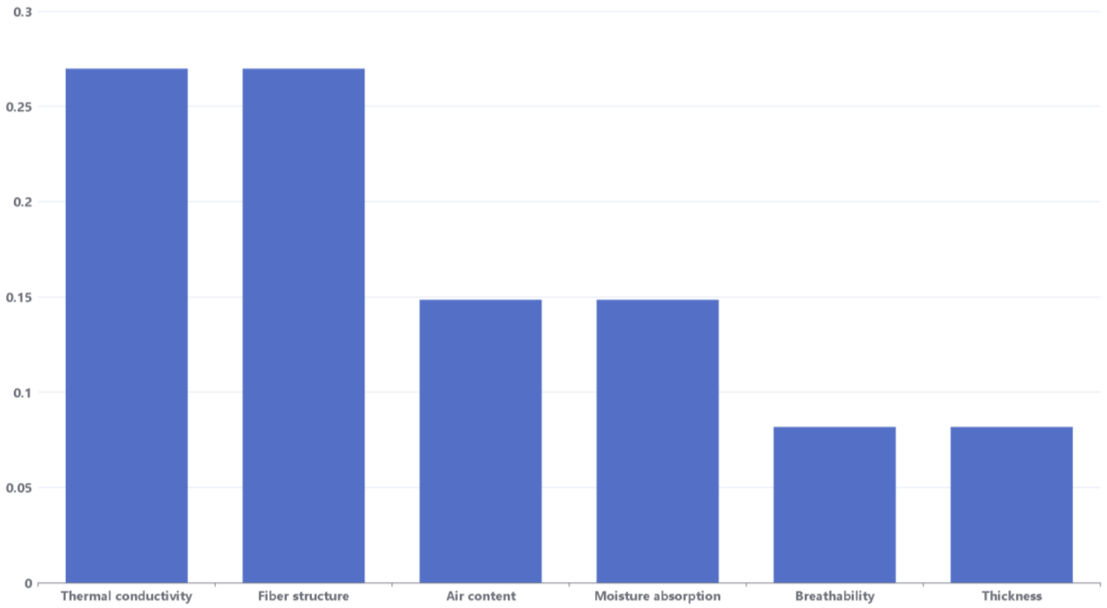

**Figure 1.** Normalized weight bar chart distribution.

The paper then computed the consistency index and consistency ratio of the matrix, finding a consistency ratio CR of 0.00297, significantly below 0.1, indicating good consistency of the pairwise comparison matrix.

Subsequently, the paper defined the calculation method for the Comprehensive Warmth Assessment Index (CWI) as follows:

$$\mathrm{CWI} = a * R - b * k + c * \alpha - d * G + e * T + f * S \tag{5}$$

where a, b, c, d, e, f are the weight coefficients.

The paper specifies the thermal conductivity of polyester as 0.04 W/(m*K), thickness as 3 mm, air content ratio as 0.7, moisture absorption as 0.08, breathability as 0.4 m^3/m^2/s, and structural parameter as 7. Substituting the above weights into the formula, the CWI is calculated to be 2.0083.

## 3. Study on the Insulation Performance of Polyester and Its Average Length and Diameter

### 3.1. Parameter Adjustment

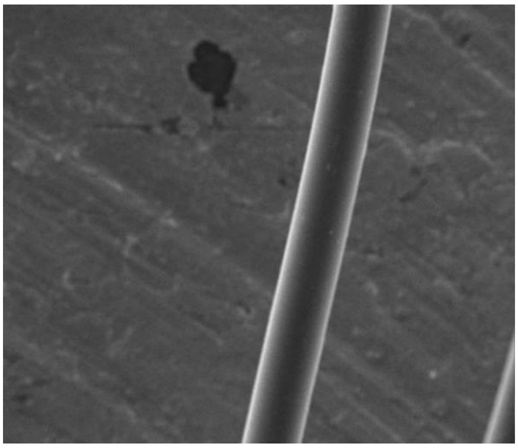

**Figure 2.** Polyester Cross-Section Diagram

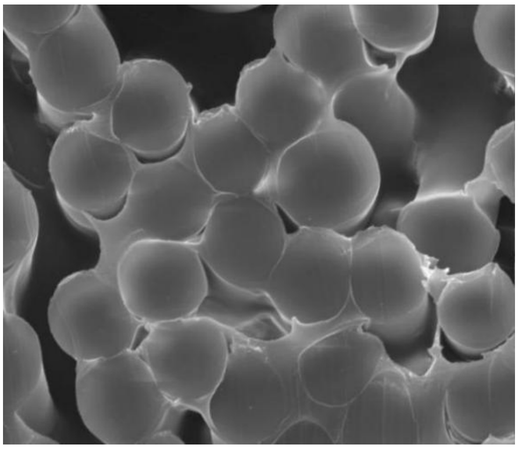

**Figure 3.** Polyester Horizontal Section Diagram

Based on the microstructure of polyester illustrated in Figures 2 and 3, this study assumes that the cross-section of polyester fibers is circular, and the fiber filling is uniformly distributed. Furthermore, the thermal performance of the fibers is primarily determined by the geometric shape of the fibers and the inherent properties of the material. In theory, the geometric dimensions of the fibers will affect the density of the filling material and the air content, thereby influencing the thermal resistance. Additionally, longer and finer fibers can increase the air content, and their geometric dimensions will also affect the fiber structural parameters. Therefore, this study makes the following adjustments to the parameters:

(1) The formula for thermal resistance $R(L, D)$ is redefined as $R(L, D) = \frac{L}{kA}$, where $A = \pi(\frac{D}{2})^2$ is the cross-sectional area of the fiber.

(2) It is assumed that the air content $\alpha(D)$ and breathability T(D) are inversely proportional to the fiber diameter, i.e., $\alpha \propto \frac{1}{D}$ $T(D) \propto \frac{1}{D}$ .

(3) It is assumed that the fiber structural parameter $S(L, D)$ is related to the fiber length and diameter according to the following equation:

$$S(L, D) = \frac{L}{D} \tag{6}$$

Because the thermal conductivity and hygroscopicity are determined solely by the material properties of the fibers and are independent of the geometric dimensions, and thickness is a design parameter considered constant, they are not adjusted. The revised method for calculating the Comprehensive Warmth Index (CWI) is as follows:

$$CWI = a * R(L, D) - b * k + c * \alpha(D) - d * G + e * T(D) + f * S(L, D) \tag{7}$$

### 3.2. Calculation of CWI Values for Polyester of Different Lengths and Diameters

The CWI values for fibers with lengths ranging from 0.01m to 0.1m and diameters ranging from 0.00005m to 0.0002m were calculated separately. The calculated results are shown in Figure 4.

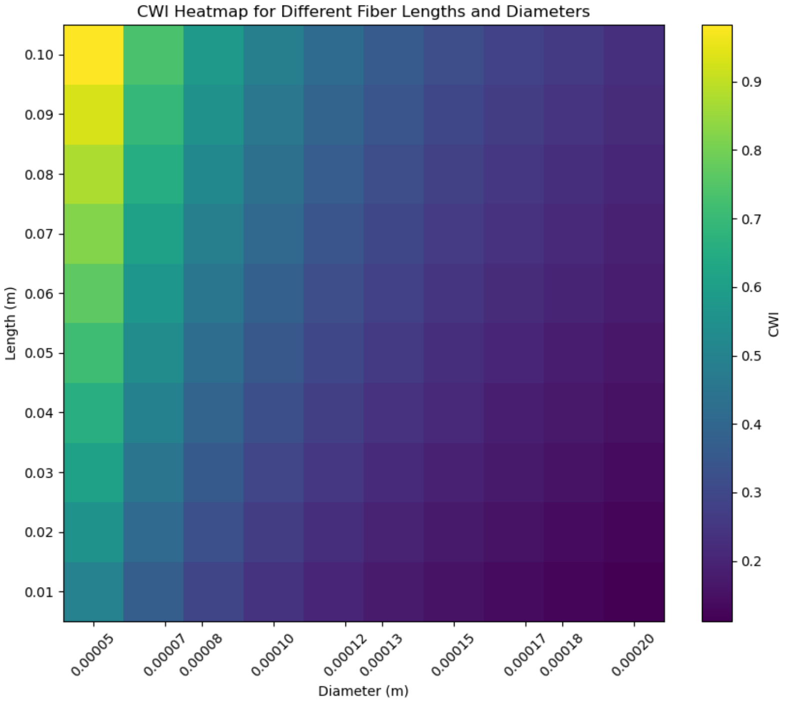

**Figure 4.** Heat map of CWI values for different fiber lengths and diameters

As observed from Figure 4, with the decrease in fiber diameter and increase in length, CWI tends to increase, indicating an enhancement in thermal insulation performance. This result aligns with the assumption made in this study, where shorter average lengths and smaller diameters of fibers generally exhibit stronger thermal insulation performance, attributed to higher air content and fiber structural complexity in the resulting garments.

## 4. The calculation of WPI for cotton and down

### 4.1. Parameter Adjustment

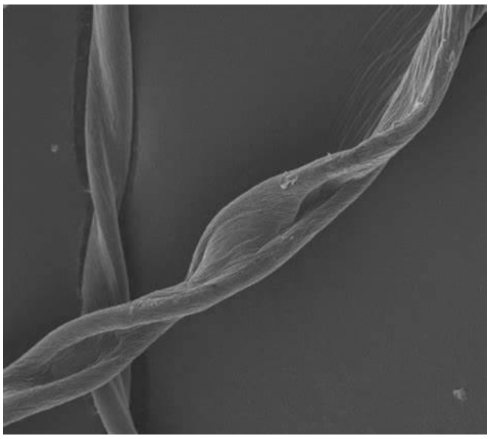

**Figure 5.** Microstructure of cotton

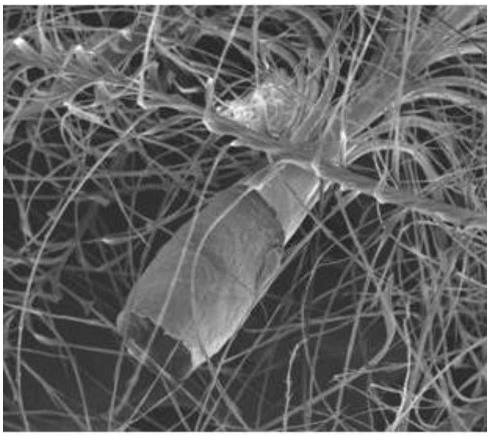

**Figure 6.** Microstructure of down

From Figure 5 and Figure 6, it can be observed that the fiber structure of cotton is relatively loose, with many voids between the fibers. These voids can store a large amount of air, making cotton a good insulating material. Additionally, the loose structure of cotton enables good breathability, facilitating the dissipation of body heat and preventing overheating. In contrast, the down feathers in Figure 6 exhibit a three-dimensional structure with many small air pockets. These small air pockets effectively trap heat and enhance the insulation properties of down. Furthermore, the resilience of the air pockets in down allows them to quickly regain their shape after compression, maintaining the fluffiness of the down and thereby preserving its insulation efficiency. Based on these observations, the following adjustments are made to the parameters:

(1) The loose structure of cotton reduces its ability to trap air, resulting in higher thermal conductivity, whereas the unique three-dimensional structure of down allows it to trap a significant amount of air, leading to lower thermal conductivity. Therefore, the thermal conductivity of cotton is adjusted to 0.06 W/(m*K), while that of down is adjusted to 0.023 W/(m*K).

(2) The microstructure of cotton is relatively simple compared to down, resulting in a lower air content proportion. Therefore, the air content of cotton is set to 0.7, and the structural parameter is set to 7. In contrast, the complex three-dimensional structure of down significantly increases its air content, thus the air content of down is set to 0.9, and the structural parameter is set to 10.

Since the breathability and moisture absorption of materials are primarily determined by their material properties rather than their microstructure, they are not considered as primary distinguishing factors.

### 4.2. Comparison of Results

Using the adjusted parameters, this study calculated the CWI for cotton as 1.969 and for down as 2.818. As shown in Figure 7, down exhibits the best insulation performance, followed by polyester and cotton, with no significant difference between the latter two.

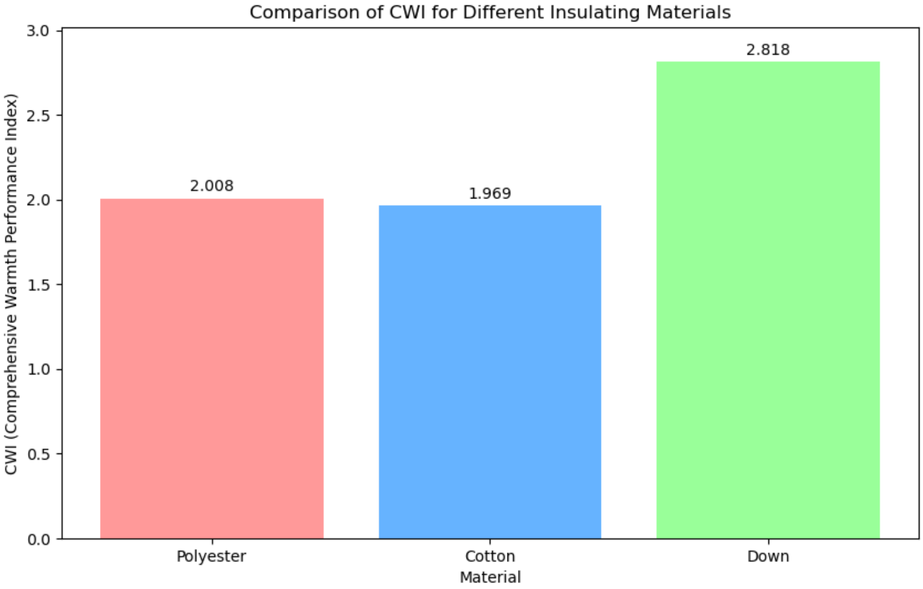

**Figure 7.** Bar chart of CWI for polyester, cotton, and down

## 5. Conclusions

The developed ready-to-wear thermal performance quantification model in this study provides a systematic approach to evaluate garment insulation performance by considering key factors such as thermal conductivity, fiber structure, air content, moisture absorption, breathability, and thickness of material fibers. Through quantitative assessments of the thermal insulation capabilities of commonly used fibers like polyester, cotton, and down feathers, this model assists industry practitioners in making informed decisions regarding material selection and garment design, thereby enhancing the warmth and comfort of clothing. Additionally, the flexibility of this model allows for customization according to different types and purposes of clothing, thereby expanding its applicability within the apparel industry. This research contributes to advancing the understanding and optimization of garment insulation performance, offering directions for improvement in clothing design and manufacturing.

# References

[1] Muthukumar K, Sabariraj R V, Kumar S D, et al. Investigation of thermal conductivity and thermal resistance analysis on different combination of natural fiber composites of banana, pineapple and jute[J]. Materials Today: Proceedings, 2020, 21: 976-980.

[2] Yang Y, Yu X, Chen L, et al. Effect of knitting structure and yarn composition on thermal comfort properties of bi-layer knitted fabrics[J]. Textile research journal, 2021, 91(1-2): 3-17.

[3] Veerasimman A, Shanmugam V, Rajendran S, et al. Thermal properties of natural fiber sisal-based hybrid composites–a brief review[J]. Journal of Natural Fibers, 2022, 19(12): 4696-4706.

[4] Pasayev N, Tekoglu O. The use of chicken feather fibers as filling material in Winter clothes for heat insulation purposes[J]. International Journal of Clothing Science and Technology, 2019, 31(2): 259-271.

[5] Abbasi S A, Marmaral A, Ertekin G. Thermal comfort properties of weft knitted quilted fabrics[J]. International Journal of Clothing Science and Technology, 2020, 32(6): 837-847.

[6] Yang T, Xiong X, Petrů M, et al. Theoretical and experimental studies on thermal properties of polyester nonwoven fibrous material[J]. Materials, 2020, 13(12): 2882.

[7] Vasanth Kumar D, Raja D. Study of thermal comfort properties on socks made from recycled polyester/virgin cotton and its blends[J]. Fibers and Polymers, 2021, 22: 841-846.

[8] Hassan M. Evaluation of the Moisture and Thermal Characteristics of Knitted Sport Wear Fabrics[J]. MEJ-Mansoura Engineering Journal, 2020, 34(2): 8-23.

[9] Thakkar J J, Thakkar J J. Analytic hierarchy process (AHP)[J]. Multi-Criteria Decision Making, 2021: 33-62.

[10] Tavana M, Soltanifar M, Santos-Arteaga F J. Analytical hierarchy process: revolution and evolution[J]. Annals of operations research, 2023, 326(2): 879-907.