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# Innovative Outdoor Jacket Design Featuring Honeycomb Thermal Layers with Graphene/Silver Integration for Enhanced Thermal Conductivity

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## Abstract

Outdoor jackets are engineered to protect against extreme weather while ensuring comfort and safety. Key to this protection is the thermal properties, achieved through insulation materials like down feathers and synthetic fibers, which trap heat and minimize heat loss. Resistance to wind, rain, and snow is provided by waterproof and windproof fabrics, while breathability allows moisture to escape, maintaining a comfortable microclimate. Air permeability and water resistance are essential for achieving this balance. This study examines two outdoor jacket prototypes with six material layers each. The outer layer (Layer 1) consists of 100% polyester coated with polyurethane for waterproofing. Inner layers (Layers 2, 3, and 6) use wool/cotton and wool/polyamide blends, offering insulation and moisture-wicking properties. Down feathers are used as the filling material, providing excellent warmth. Advanced materials like graphene and silver honeycomb fabrics were included to enhance thermal conductivity and regulate heat transfer. Performance testing focused on thermal conductivity, comfort (water and air permeability), and mechanical properties like tensile strength and tear resistance. Tests also assessed spray application and fastness to evaluate durability under environmental exposure. Results showed that jackets with silver-infused honeycomb fabrics had superior thermal conductivity, enabling better heat regulation and comfort in harsh conditions. The findings highlight the advantages of integrating silver honeycomb fabrics into outdoor jackets. These materials enhance insulation, thermal regulation, and overall comfort, making them ideal for high-performance designs. Incorporating such fabrics ensures functionality, durability, and user protection in extreme environments.

**Keywords**

Honeycomb Thermal Fabric, Outdoor Jacket Design, Silver, Graphane

## 1. Introduction

Outdoor clothing plays a crucial role in protecting individuals engaged in outdoor activities from various environmental conditions. Whether hiking, camping, skiing, or mountaineering, outdoor garments are designed not only to shield users from the elements but also to offer comfort, functionality, and protection. These garments must be capable of withstanding harsh weather, including rain, wind, snow, and extreme temperatures, while maintaining breathability and providing necessary insulation to keep the body warm in cold climates. In recent years, the development of innovative materials, such as honeycomb thermal fabrics, has further enhanced the performance of outdoor clothing, making it more effective in managing heat retention, moisture, and comfort in diverse outdoor environments [1]-[3].

In addition to protection from the elements, modern outdoor clothing has evolved to meet the growing demand for versatile performance. Beyond the basic necessity of keeping individuals warm and dry, outdoor garments today are expected to facilitate mobility, comfort, and performance during physically demanding activities. This evolution has led to the incorporation of advanced textile technologies that allow for increased insulation, enhanced moisture-wicking, and better heat retention. Layering systems have also become a standard design feature, optimizing the functionality of the garments by providing users with the flexibility to adapt to changing weather conditions [4]. With the growing popularity of outdoor activities, such as trekking, climbing, and winter sports, outdoor clothing must continue to meet the needs of a diverse and active user base.

The use of multi-layered fabrics and specialized insulation materials has become a hallmark of outdoor garment design. Typically, these garments consist of three layers: an inner breathable layer that sits close to the skin to manage moisture, a middle insulating layer to retain body heat, and an outer layer designed to provide protection from the elements, such as rain or wind. Among the various innovative materials used, honeycomb thermal fabrics are gaining attention for their unique design and ability to offer superior thermal insulation while remaining lightweight and breathable. By mimicking the natural hexagonal structure of a honeycomb, these fabrics trap air, which improves heat retention without adding bulk, making them ideal for use in outdoor jackets and other cold-weather gear [5]-[7].

This study focuses on exploring the potential of honeycomb thermal fabrics in outdoor garment design. Specifically, it investigates the combination of different thermal insulating materials, including down, synthetic fibers, and honeycomb structures, to create garments that not only offer excellent thermal insulation but also improve breathability and comfort. Through the development of two outdoor jackets, each incorporating a three-layer construction, different insulation types, and honeycomb thermal structures, this research aims to assess the overall performance of these materials in terms of air permeability, insulation efficiency, and wearer comfort under varying environmental conditions. This approach is intended to contribute to the ongoing advancement of functional outdoor clothing that meets the demands of modern outdoor enthusiasts.

In this article, we present two outdoor jackets designed for cold environments. While the design and material selections remain the same for both jackets, they differ in the honeycomb thermal layer used. The first jacket features a polyester/silver fabric, while the second uses a polyester/graphene fabric. Subsequently, we compare the two designs in terms of comfort, mechanical properties, and thermal performance.

## 2. Materials and Methods

In this study, two outdoor jacket designs were created using four distinct layers. The fabrics (K1, K2, K3 and K6) and filling materials used in these layers were sourced from Boyner Büyük Mağazacılık A.Ş. The fabric properties utilized in the layers are detailed in **Table 1**, while the characteristics of the conductive honeycomb fabrics are presented in **Table 2**. These materials were selected to optimize the performance of the jackets in cold environments, focusing on insulation, comfort, and durability. (K4, K5) The K4 and K5 fabrics are honeycomb-structured, thermally conductive textiles purchased from Shaoxing Yewang Textile Co., Ltd. Both fabrics come with the necessary certifications, ensuring their quality and compliance with industry standards [8]. Additionally, the properties of the filling materials are outlined in **Table 3**. The fabric K1 has been coated with a water-based, polyester-based polyurethane coating material as the polymer. The properties of the polymer used in the coating of fabric K1 are presented in **Table 4**.

**Table 1.** Layer and fabric properties used in outdoor jacket design.

| Sample codes | Layers | Composition of Fibers | Composition of Fibers, Blend Ratio % | Yarn Count Ne | | Thickness (mm) | Fabric Construction | Fabric unit weight (g/m$^2$) |
|---|---|---|---|---|---|---|---|---|
| | | | | Warp | Weft | | | |
| K1 | 1st Layer | Polyester | 100 | 22 | 20 | 0.20 | Weave/Plain | 361 |
| K2 | 2nd Layer | Wool/Cotton | 58.8/41.2 | 20 | 20 | 0.36 | Weave/Plain | 220 |
| K3 | 3rd Layer | Wool/Polyamide | 67.7/32.3 | 20 | 20 | 0.28 | Weave/Plain | 180 |

**Table 2.** Properties of honeycomb thermal fabrics [8].

| Sample codes | Layers | Composition of Fibers | Composition of Fibers, Blend Ratio % | Yarn Count Ne | | Thickness (mm) | Fabric Construction | Fabric unit weight (g/m$^2$) |
|---|---|---|---|---|---|---|---|---|
| | | | | Warp | Weft | | | |
| K4 | 4th Layer | Polyester/ Silver | 95/5 | 22 | 20 | 0.30 | Weave/Plain | 210 |
| K5 | 4th Layer | Polyester/Graphen | 95/5 | 20 | 20 | 0.30 | Weave/Plain | 210 |

**Table 3.** Properties of filler materials.

| Sample codes | Layers | Fiber | Composition of Fibers, Blend Ratio % | Fiber Diameter (μm) | Thickness (mm) | Fabric Construction | Fabric unit weight ($g/m^2$) |
|---|---|---|---|---|---|---|---|
| K6 | 3rd Layer | Goose down | 100 | 3 | 0.75 | Filler | 340 |

**Table 4.** Properties of coating polymers applied to K1 layer fabric.

| Polymer Type | Polyester Type PU (W) |
|---|---|
| Appearance | White emulsion |
| Ionic Structure | Anionic |
| pH | 7 - 9 |
| Density (25˚C) | 1.06 $g/cm^3$ |
| Viscosity (25˚C) | 40 - 450 cP (centipoise) |

In the polyester-based polyurethane coating, an anionic, blocked isocyanate-type crosslinking agent has been used as an auxiliary material. At 25˚C, the cross-linker has a density of 1.1 $g/cm^3$ and a pH of 7 - 10. As a thickening agent, an anionic acrylic polymer dispersion has been used. At 20˚C, the thickener has a density of 1.1 $g/cm^3$ and a pH of 6.

**Performance Tests**

In this study, the performance of the jackets was evaluated through the following tests:

- Water Permeability Testing: A water permeability test was conducted according to the ISO 811:2018 standard (water temperature 21.3˚C, 10 mbar/min).
- Abrasion Resistance Testing: The abrasion resistance of the swimwear fabric samples was tested under a known pressure fixed at 9 kPa, in accordance with the ISO standard EN ISO 12947-2:2016.
- Air Permeability Testing: Air permeability was measured according to ISO 9237:1995; the test pressure was 100 Pa on an area of 20 $cm^2$. The test was repeated 10 times, and their average was calculated to obtain the mean air permeability of each sample.
- Tensile Testing: In the study, tensile strength tests were conducted according to TS EN ISO 13934-1:2013, and tearing tests were performed in compliance with the ISO-EN 13937-1:2002 standards.
- Fastness Testing: The washing fastness of fabric layers was tested using the Gyrowash-James H. Heal washing fastness tester, in accordance with the ISO 105-C06 standards. The samples were placed in a solution containing 4 g/L Ece detergent at a fabric-to-water ratio of 1/100 and washed at 40˚C for 30 minutes in the Gyrowash Washing Tester. After washing, the color change was evaluated using the grayscale. The rubbing fastness was tested using the Crockmeter Test device, following the ISO 105-X12: 2016 standard. Both wet and dry staining fastness values were determined by evaluating the color transfer onto a white test cloth during rubbing, using the gray scale. The light fastness test was conducted according to the EN ISO 105-B02-1994 standard using the Atlas

Alfa 150 S light fastness tester. The color change due to light exposure was evaluated using the blue scale, determining the layers' resistance to light. These tests comprehensively analyze the fabric layers durability against various conditions such as washing, rubbing, and light exposure, assessing how stable and vibrant the colors remain when subjected to washing, rubbing, and light.

**Thermal conductivity testing**

The thermal resistance and temperature variation tests of the fabrics were conducted in accordance with the ISO EN 11092 standards. This standard provides a method for determining the thermal insulation properties of textiles, specifically designed to assess how well a fabric resists heat flow, ensuring its suitability for applications in outdoor clothing and other insulation products.

**Designs of Outdoor Jackets**

In this outdoor jacket design study, various layers were selected based on their performance and functional use (See Figure 1). The first layer (outer layer) was made from 100% polyester with a polyurethane coating to provide waterproof protection against wind, rain, and snow. For the second and third layers (lining layers), fabrics containing wool/cotton and wool/polyamide were chosen to ensure moisture management and breathability.

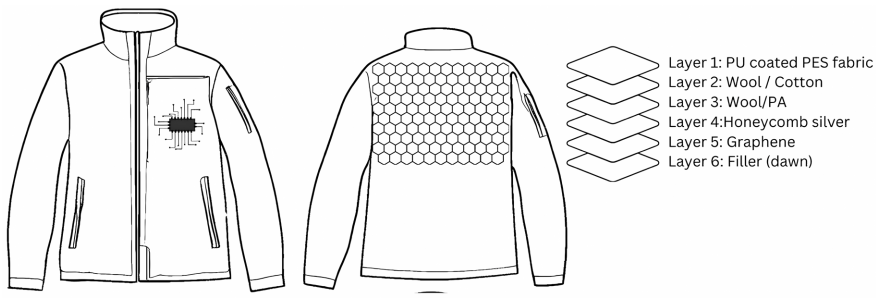


Figure 1. Outdoor jacket design.

A coating technology has been used for applying waterborne polyurethane to polyester fabric. The densities of the coating chemicals were measured using a Brookfield viscometer. The coating properties are provided in Table 5. The coating processes were carried out using a laboratory-type knife coating machine. The coated samples were cured at 140˚C for 2 minutes.

Table 5. Materials and processes used in coating process.

| Items | Polyester-based Polyurethane Coating Material | Curing Temperature (˚C) | Sample Code |
|---|---|---|---|
| Polyurethane (PU) | 100 | 140 | K1 Layer |
| Crosslinker | 10 | | |
| Thinner | 0.7 | | |
| Viscosity (cps) | 30,000 | | |

For insulation, the first jacket design and the second jacket design used goose down as a filler material to retain heat and trap air. The innovative honeycomb structure was incorporated for superior insulation and thermal regulation, designed to trap air and enhance warmth. The first design included silver, while the second incorporated graphene in the honeycomb layers. These materials reflect body heat, maintaining optimal temperature and preventing excessive overheating during physical activity.

The thermal features of the outdoor jackets include a heating system that allows temperature adjustment via a controller. The jackets use silver and graphene fabrics with thin, flexible conductive properties. The heating elements, designed with honeycomb features, are integrated into the shoulder area of the jacket.

The heating elements are selected based on the IP68 standard, ensuring waterproofing with polyurethane-based materials sealed with silicone. The ends of the cables, which are equipped with leak-proof connectors, are fitted with special rubber seals and tight connections to prevent water ingress at the connection points. The cables are placed inside the jacket's inner layers (K2, K3) as curved, hidden channels, in harmony with the user's movements. Each heat level was indicated by color-coded thermoregulation labels for easy adjustments.

A wired control mechanism (button-operated) is used to adjust the temperature levels of the jacket, which can range between 30˚C - 50˚C. The power source consists of rechargeable and replaceable lithium-ion batteries (10,000 mAh), which are discreetly integrated into the pocket area of the jacket. The battery is protected by waterproof casings.

For stitching, the multi-layered fabrics were sewn using specialized needles to prevent perforation. The outer layer's waterproof feature was preserved through ultrasonic stitching using the Pfaff 8310 ultrasonic machine (30 kHz frequency, with a source speed of 6 to 136 dm/min at a pressure of 6 bar). The outer material was made from water-repellent 100% PES polyester (yarn linear density: 40 tex, number of strands: 2), with 3 cm spacing between 13 needles.

## 3. Results

- **Results of Mechanical Properties**

Figure 2 shows the tensile strength measurements of the fabrics in both warp and weft directions show varying levels of durability:

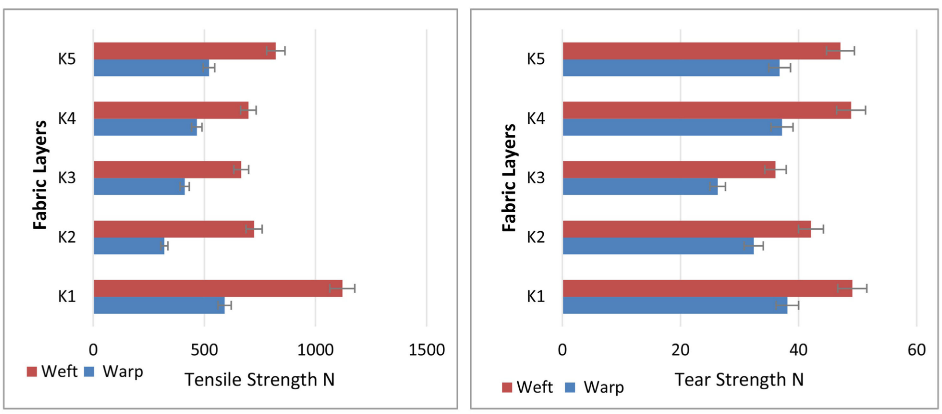


**Figure 2.** Tensile strength and tear strength results of fabric layers.

The tensile strength measurements of the fabrics in both warp and weft directions show varying levels of durability; K1 shows the highest strength, particularly in the weft direction, making it a robust fabric for both directions. K2, has the lowest strength values, especially in the warp direction, indicating it is a relatively weaker fabric. K3, exhibits moderate strength, with the weft being stronger than the warp. K4 displays a balanced strength in both directions, with the weft and warp showing similar resistance. K5, offers decent strength in both directions, especially in the weft, indicating a durable option for various applications. Overall, fabrics K1 and K5 show the highest durability, with K1 excelling in both warp and weft directions, while K2 is the least durable [9].

The tear strength results for the fabric layers show that, K1 demonstrates the highest tear strength in both warp and weft directions, indicating strong resistance to tearing forces, suitable for heavy-duty applications. K4 closely follows with values of 37.2 N (warp) and 48.9 N (weft), making it another durable choice. K5 also shows good performance (36.8 N warp, 47.1 N weft), suitable for robust usage. K2 and K3 display comparatively lower tear strengths, with K3 having the lowest values (26.3 N warp, 36.1 N weft), making it less ideal for high-stress areas. These results highlight the suitability of K1 and K4 for outdoor jackets requiring high tear resistance [10].

- **Results of Comfort Properties**

The results of the water permeability and air permeability tests for the outdoor jacket are presented in **Figure 3**. These tests assess the fabric's performance in terms of resistance to water penetration and its ability to allow air flow, which are essential factors for ensuring comfort and functionality in various environmental conditions.

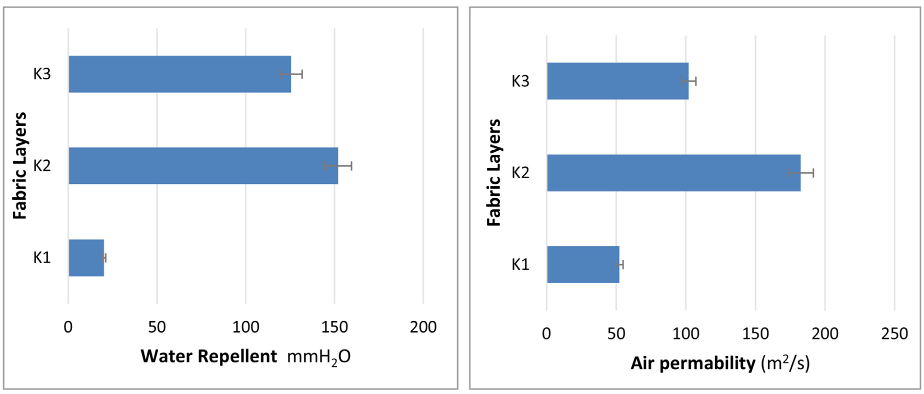


**Figure 3.** Result of water repellent and air permeability.

The water-repellent measurements for the fabric layers in the outdoor jacket design show distinct differences in performance; K1 has the lowest water resistance with 20.1 mm$H_2O$, which indicates a limited ability to repel water, making it less suitable for wet conditions. K2 exhibits the highest water resistance at 152 mm$H_2O$, offering strong protection against rain and moisture, ideal for outdoor activities. K3 provides moderate resistance with 125.5 mm$H_2O$, making it suitable for light to moderate exposure to wet conditions but less effective than K2 (**Figure 3**) [11].

The air permeability test results presented in **Figure 3** have been evaluated. The primary aim of studies on the air permeability of textile materials is to identify the relationship between the air permeability and the structure of the textiles. Porosity has a significant impact on the air permeability of untreated textiles. As pore size increases, air permeability also increases. Coated fabrics, however, exhibit very low air permeability. Fabric layer K2 consists of wool/cotton, while fabric layer K3 includes wool/polyamide. Comparing the air permeability of cotton plain weave fabric and polyamide plain weave fabric reveals notable differences in breathability and suitability for outdoor garments. Cotton, a natural fiber, typically exhibits higher air permeability, providing better ventilation and moisture management, making it ideal for comfort in hot conditions [12].

On the other hand, polyamide, a synthetic fiber, has lower air permeability, offering better protection against wind and water but potentially reducing breathability. Therefore, the choice between these fabrics depends on the specific performance requirements of the outdoor garment.

In this study, goose down was used as the filling material in the inner fabric layer due to its exceptional thermal properties. Goose down effectively traps heat due to its high temperature-to-weight ratio while remaining lightweight, making it ideal for cold-weather applications. Unlike synthetic alternatives, goose down is flexible, providing a compact and portable solution for outdoor use. Additionally, goose down is a natural material that aligns with sustainable practices, being biodegradable and environmentally friendly, making it an attractive choice for eco-conscious users [13].

- **Result of Thermal Conductivity**

In this study, two different jacket designs were compared based on their thermal conductivity. The thermal conductivity results are shown in **Figure 4**.

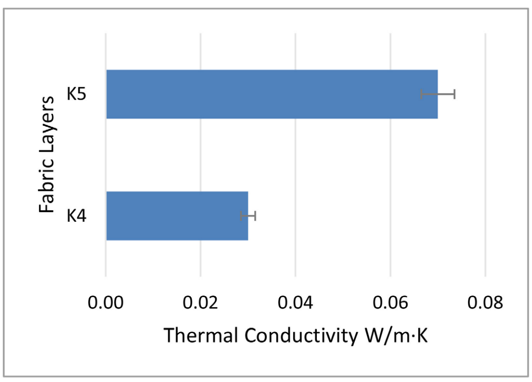


**Figure 4.** Thermal conductivity properties.

When comparing honeycomb silver fabric (0.03 W/m·K) and honeycomb graphene fabric (0.07 W/m·K) for outdoor jackets, the fabric with lower thermal conductivity (0.03 W/m·K) proves more effective in insulation and heat retention, making it ideal for colder conditions. In contrast, the graphene fabric with 0.07 W/m·K conductivity provides slightly higher thermal conductivity, which may be beneficial for jackets designed for moderate temperatures where a balance between insulation and breathability is required. Therefore, the choice of fabric depends on the specific temperature and performance requirements of the outdoor jacket [14].

In **Figure 5**, the temperature variations associated with the application of K4 and K5 fabrics on the right and left shoulders are presented. The results indicate that the thermal properties of the fabrics, specifically the silver and graphene honeycomb-structured textiles, adhere to the established standards for thermal regulation. These fabrics demonstrated consistent and reliable temperature control across both shoulders. Additionally, the findings reveal a uniform heat distribution pattern, ensuring that the fabrics are effective in maintaining thermal balance. This homogeneity in temperature distribution highlights the potential of these advanced materials in applications where consistent thermal performance is crucial, particularly in outdoor wear and protective garments. Such characteristics suggest that the fabrics not only meet functional requirements but also offer the possibility of enhanced user comfort and performance in various environmental conditions.

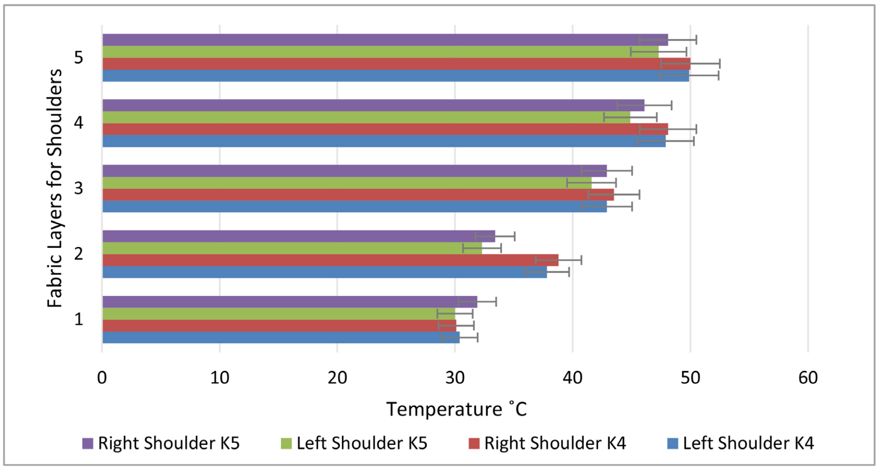


**Figure 5.** Temperature variation of the thermally conductive fabrics used on the shoulders (30°C - 50°C).

- **Spray Test, Rainfall, and Bundesmann Rain Test Results**

In the spray test (AATCC 22), based on the AATCC 22 standard rating scale, uncoated polyester fabric demonstrated a rating of 0. On the other hand, fabrics with K1 coating exhibited significantly higher values compared to uncoated fabrics. The developed coated sample reached a rating of 70, which is substantially better than the uncoated counterpart.

It was observed that the spray test results improved with the curing temperature used during the coating process. After 10 washes, the water repellency value remained optimal and unchanged. The fabric achieved optimal water repellency properties when cured at 140°C (**Table 6**) [15].

Table 6. Spray test result.

| Code | Under Normal Conditions | After 10 washes |
|---|---|---|
| Standard | 0 | 0 |
| K1 | 70 | 70 |

The liquid moisture transport properties of fabrics significantly influence the perception of moisture by humans. Moisture spreads across both surfaces of the fabric and transfers from one side to the other. To characterize the liquid moisture management properties of a fabric, ten indices have been proposed. Based on the spray test results, it was concluded that the developed K1 fabric is waterproof, and its moisture management parameters fall within the commercial evaluation limits, demonstrating positive performance (Table 6).

- **Result of Fastness Properties**

Upon evaluating Table 7, it was observed that the K1 fabric exhibited normal performance levels for coated fabrics in terms of usability properties.

Table 7. Fastness properties result.

| Material | Washing | | | | | | | Rubbing Fastness | | Light Fastness |
|---|---|---|---|---|---|---|---|---|---|---|
| | Color Change | Staining | | | | | | | | |
| | | CA | CO | PA | PET | PAN | WO | Dry | Wet | |
| K1 | 4 - 5 | 4 | 4 | 4 | 4 | 4 - 5 | 5 | 4 - 5 | 4 - 5 | 4 - 5 |
| K2 | 4 | 4 | 4 | 4 | 5 | 4 - 5 | 5 | 4 | 4 | 4 |
| K3 | 4 | 4 | 4 | 4 - 5 | 4 | 4 | 5 | 4 | 4 | 4 |
| K4 | 4 - 5 | 4 | 4 | 5 | 4 | 4 | 5 | 4 - 5 | 4 - 5 | 4 - 5 |
| K5 | 4 - 5 | 4 | 4 | 5 | 4 | 4 | 5 | 4 - 5 | 4 - 5 | 4 - 5 |

The fastness properties of K2 and K3 fabrics, which are used for inner purposes, were found to be satisfactory. Additionally, the K4 and K5 fabrics, featuring graphene and silver-infused honeycomb structures, demonstrated excellent usability properties.

## 4. Conclusions

This study evaluated outdoor jacket designs based on honeycomb silver and honeycomb graphene thermal fabrics. Mechanical and comfort test results were used to assess fabric performance. The results revealed that fabrics K1 and K5 showed the highest durability, while K2 exhibited the lowest tear strength. For water permeability, K3 demonstrated moderate resistance, making it suitable for light exposure to wet conditions. The comparison of air permeability highlighted differences between wool/cotton and wool/polyamide fabrics, influencing breathability. Based on thermal conductivity, the honeycomb silver fabric (0.03 W/m·K) was preferred for its superior insulation properties, making it ideal for colder conditions.

Based on the results of the spray test, it has been determined that the waterproof properties of the fabrics have significantly improved. Furthermore, the fastness test results indicate that the selected fabrics are suitable for outdoor jacket design in terms of end-user requirements. These findings suggest that the tested fabrics not only meet the functional demands for water resistance but also exhibit durability and performance characteristics that are essential for outdoor apparel. This highlights their potential applicability in the development of high-quality outdoor garments, ensuring both comfort and protection under various environmental conditions.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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