International Journal of Scientific Research & Engineering Trends
Volume 12, Issue 4, July-Aug-2026, ISSN (Online): 2395-566X

Breathability Characteristics of Graphene-Coated Sheep Wool, Goat Wool and Their Composite Fabrics

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Abstract — The development of breathable and thermal comfortable textile materials is of increasing significance for personal thermal comfort products. In this study, graphene-coated sheep wool, goat wool, and sheep wool/goat wool composite fabrics were developed and their moisture management properties were evaluated according to ISO 11092. Water vapor permeability (PWVP) and water vapor resistance (Ret) were measured to assess the breathability performance of the fabrics. The results revealed that the graphene-coated sheep wool fabric exhibited the highest water vapor permeability (36.60%) and the lowest water vapor resistance (5.96 Pa·m²/W), indicating superior moisture transport capability. The graphene-coated goat hair fabric showed the lowest permeability (28.43%) and the highest Ret value (9.80 Pa·m²/W), while still remaining within the "good breathability" category. The graphene-coated sheep wool/goat hair composite fabric demonstrated intermediate behavior with a PWVP of 35.10% and a Ret value of 7.80 Pa·m²/W. According to ISO 11092 comfort classification, all investigated fabrics can be considered breathable materials.

Keywords— Graphene coating; Sheep wool; Goat hair; Composite fabric; Water vapor permeability; Water vapor resistance; Thermophysiological comfort; Wearable technologies.

I. INTRODUCTION

The perception of comfort that textile materials provide to the user is not limited solely to aesthetic aspects but is directly related to thermophysiological parameters such as breathability, moisture management, and thermal insulation. Thermophysiological comfort is defined as the balanced transfer of heat and moisture between the human skin and the environment and is considered one of the key determinants of garment performance. In this context, it has been clearly demonstrated in the literature that structural factors—such as fiber composition, yarn properties, and weaving parameters—play a critical role in comfort performance - -.

Thermophysiological comfort has become a critical requirement for advanced textile materials, particularly in wearable heating applications. The transport of moisture vapor through a fabric plays a vital role in maintaining thermal comfort and preventing excessive perspiration accumulation. Therefore, evaluating water vapor resistance and permeability is essential for assessing the comfort performance of functional textile systems -.

Water vapor permeability of fabrics is generally evaluated using several standardized methods, such as the sweating guarded hot plate, cup test, and inverted cup test. These methods - - differ considerably in terms of testing environment, heat and moisture transfer mechanisms, and evaluation criteria.

In this study, the Water vapor resistance (RET) of composite coated fabrics was evaluated using the sweating guarded hot plate method (ISO 11092). This method is widely accepted as one of the most reliable techniques for assessing thermophysiological comfort because it simulates the coupled heat and moisture transfer processes occurring between human skin, clothing, and the surrounding environment under steady-state conditions.

Although the significant interest in graphene-based functional textiles, limited studies have investigated the combined effects of graphene coating and natural wool fibers on moisture management and thermal comfort. In particular, comparative studies involving sheep wool, goat hair, and their composite structures remain scarce in the literature.

Therefore, the purpose of this study is to evaluate the water vapor transport and comfort-related properties of graphene-coated sheep wool, goat hair, and sheep wool/goat hair composite fabrics. Water vapor permeability (PWVP) and water vapor resistance (Ret) were determined using the ISO 11092 sweating guarded hot plate method. The obtained results were analyzed in terms of breathability performance and wearer comfort. Furthermore, the moisture management characteristics of the fabrics were discussed with respect to their potential use in wearable heating and personal thermal management applications.

II. EXPERIMENTAL STUDY

1. Materials

In this letter sheep and goat wool were used as the raw materials for fabric development. These natural fibers were mixed in equal proportions, consisting of 50% sheep wool and 50% goat wool by weight.

Before weaving, the sheep wool and goat wool were cleaned and prepared through standard carding and spinning processes to obtain uniform yarns suitable for weaving. The blended yarns were then produced and used in a traditional double-layer weaving machine.

2. Graphene coating by dip coating

Experimental studies on graphene nanoplatelet (GNP) coating have been initiated in the project, and preliminary tests were conducted in the first phase using ready-made white wool fabrics. First,it is prepared the coating solution, 5 g of polyvinylpyrrolidone (PVP) was completely dissolved in 500 mL of isopropyl alcohol (IPA). Approximately 0.3 g of graphene nanoparticles was added to the resulting PVP solution, and a homogeneous dispersion was obtained using a magnetic stirrer.

The prepared graphene dispersion was applied to sheep-sheep, goat-sheep, and goat-goat woven fabric samples using the dip-coating method. The fabrics were immersed in the dispersion and left for 1–2 minutes to ensure their surfaces were coated with graphene nanoparticles. Following the coating process, the fabrics were laid out on a workbench at room temperature for pre-drying to remove excess solvent. The samples were then dried in an oven at 50 °C for 12 hours. Following the drying process, a 10-minute curing process at 70 °C was applied to enhance the adhesion of the coating to the surface.

3. Water Vapor Resistance Measurements

The breathability tests were carried out by using using a Permetest instrument (Sensora Instruments, Czech Republic) according to ISO 11092:2014, that is also called sweating guarded-hotplate test.

First of all, all natural wool samples were exposed to standard atmospheric conditions (20 ± 2 °C and 65 ± 4% relative humidity) for 24 h. Then, the instrument simulated the heat and moisture transfer processes occurring between human skin and the surrounding environment.

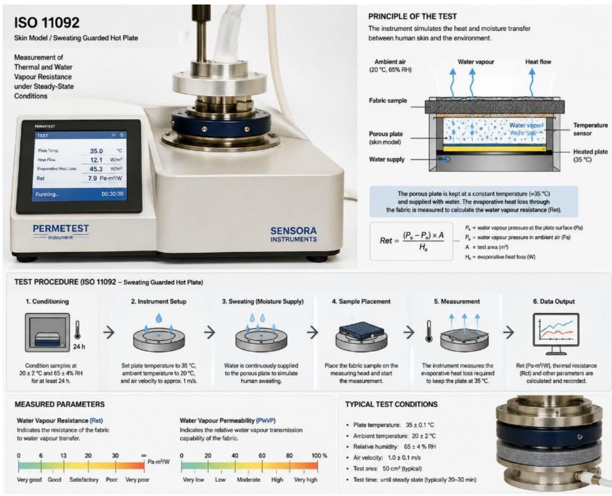

Figure1. ISO 11092 Test

The sweating guarded hot plate test assessed the resistance of the fabric structure to water vapor transport by measuring the evaporative heat loss through the fabric. The water vapor resistance (Ret) was expressed in Pa·m²/W, moreover, the percentage water vapor permeability (PWVP) was determined to show the relative vapor transmission capability of the textile.

III. RESULTS AND DISCUSSION

1. Water Vapor Permeability and Water Vapor Resistance

The water vapor permeability (PWVP) and water vapor resistance (Ret) values of the graphene-coated sheep wool, goat hair, and sheep–goat composite fabrics were evaluated according to ISO 11092. The results are presented in Table 1.

Table 1. Water vapor permeability and water vapor resistance of graphene-coated fabrics

Material	PWVP (%)	Ret ($Pa.m^2/W$)	Breathability
Graphene coated goat wool	28.43	9.80	Good
Graphene coated Sheep wool	36.60	5.96	Very good
Graphene coated Sheep and goat wool	35.10	7.80	Good

Among the investigated samples, the graphene-coated sheep wool fabric exhibited the highest water vapor permeability (36.6%) and the lowest water vapor resistance (5.96 Pa·m²/W), indicating superior breathability performance. The enhancement moisture transport behavior of sheep wool can be attributed to wool natural crimped structure, high water absorption capability that leads to water vapor diffusion through the fabric structure easily.

In contrast, the graphene-coated goat hair fabric showed the lowest water vapor permeability (28.43%) and the highest water vapor resistance (9.8 Pa·m²/W). Although goat hair fibers are known for their durability and thermal insulation properties, their relatively compact structure may have limited moisture vapor transport compared with sheep wool. Nevertheless, the measured Ret value remained below 10 Pa·m²/W, corresponding to the "good breathability" category according to ISO 11092.

The graphene-coated sheep–goat composite fabric demonstrated intermediate behavior, with a PWVP value of 35.1% and a Ret value of 7.8 Pa·m²/W. The incorporation of sheep wool into the composite structure improved moisture transport compared with pure goat hair fabric while maintaining the beneficial thermal characteristics associated with goat hair fibers. As a result, the composite fabric achieved a favorable balance between thermal insulation and breathability.

According to the ISO 11092 comfort classification, fabrics with Ret values below 6 Pa·m²/W are considered highly breathable, while those with Ret values between 6 and 13 Pa·m²/W are classified as having good breathability. Therefore, all investigated fabrics can be regarded as breathable textile materials. The sheep wool fabric exhibited the best moisture management performance, whereas the sheep–goat composite fabric provided a balanced combination of breathability and thermal comfort.

The thermophysical properties of graphene-coated and uncoated sheep, goat, and sheep-goat composites were investigated in a comparative study. The thermal conductivity values of graphene-coated fabrics were measured as 49.4, 51.3, and 50.0 mW/mK for sheep-goat, goat, and sheep samples, respectively; in the graphene-free samples, these values were 46.35, 49.35, and 46.1 mW/mK

The fact that the goat-based sample achieved the highest thermal conductivity and thermal absorption values indicates that this material is particularly advantageous in applications where rapid heat transfer is critical (e.g., thermal balancing, heat dissipation, and energy-efficient systems). These results clearly demonstrate the effect of graphene addition on the heat transfer mechanisms of the composite material. In particular, the high thermal diffusion and thermal absorption values observed in the goat-based composite indicate that the material can both conduct heat rapidly and respond more effectively to sudden temperature changes. This result suggests that the goat fiber structure interacts more compatibly with graphene, thereby creating a positive effect on heat transfer.

Table 2. Thermal properties of fabrics produced by graphene-coated wool fibers

Material	La, Thermal Conductivity (mW/mK)	Heat Resistance, r, mK.m2/W	Termal Absorbtion, b, W.s1/2/m2.K
Graphene coated Sheep and goat wool	49.4	62.1	145.4
Graphene coated goat wool	51.3	64.3	160
Graphene coated Sheep wool	50.0	49.2	150.6

These results make significant effect on for thermal wearable heating technologies. In common thermal applications improvements in heat efficiencies are often provided by reduced moisture vapor transmission. In contrast, the graphene-coated sheep–goat composite fabric maintained a relatively low water vapor resistance (7.8 Pa·m²/W) while previously demonstrating superior thermal insulation characteristics. This indicates that the developed composite structure successfully combines thermal protection with efficient moisture management, making it a promising candidate for smart thermal garments, heated belts, and other wearable heating systems.

Overall, the results demonstrate that the developed graphene-coated natural fiber fabrics possess satisfactory moisture vapor transport properties and can provide thermal comfort during prolonged wear. The sheep–goat composite fabric, in particular, offers an optimal compromise between thermal insulation and breathability, which is highly desirable for advanced wearable heating technologies.

IV. CONCLUSION

The natural composite fabric exhibited a favorable balance between thermal insulation and breathability, combining relatively low water vapor resistance with enhanced thermal performance. This synergistic behavior is particularly advantageous for wearable heating applications, where both heat retention and efficient moisture transport are required to maintain thermal comfort.

The results indicated that the graphene-coated natural fiber fabrics showed enhanced moisture vapor transport properties and can provide thermal comfort for consumer. The graphene coated composite fabric, in particular, offers an optimal compromise between thermal insulation and breathability, which is highly preferable for wearable technologies.

The graphene coated composite fabric showed superior thermal advantages of a double-layer woven structure with satisfactory moisture management performance. The measured Ret value of 7.8 Pa·m²/W indicates that the improved thermal insulation provided by the double-layer architecture did not significantly hinder water vapor transport. This remarkable balance between thermal resistance and breathability is significantly attractive for personal thermal management applications.

The developed graphene-coated double-layer woven fabrics successfully achieved a significant balance between thermal insulation and breathability. Though increased thermal insulation is generally accompanied by mitigated moisture vapor transport, the improved fabrics maintained good water vapor permeability while providing enhanced thermal resistance, demonstrating their potential for thermophysiologically comfortable wearable heating applications.

The findings suggest that graphene-coated natural fiber composites, particularly sheep wool/goat hair hybrid structures, offer significant potential for advanced wearable textiles, heated garments, and energy-efficient personal heating systems.

Acknowledgment
This study was supported by the TÜBİTAK SME R&D Support Program under project number 7250196. The authors gratefully acknowledge the financial support provided by TÜBİTAK.

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