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# Thermo-Moisture Comfort Performance Testing and Optimization of Functional Textile Sportswear for Ethnic Traditional Sports

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## Article

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## ABSTRACT

*High-intensity ethnic traditional sports generate substantial metabolic heat and perspiration, requiring garments with efficient thermo-moisture regulation. This study comparatively evaluated three knitted sportswear fabrics differing in structure and composition. Air permeability, thermal resistance ( $R_{ct}$ ), water vapor resistance ( $R_{et}$ ), and overall moisture management capacity (OMMC) were assessed using standardized methods (ASTM D737, ISO 11092, AATCC 195). Statistically significant differences were identified among the fabrics ( $p < 0.001$ ). The mesh-knit polyester/spandex fabric exhibited the highest air permeability ( $839.0 \pm 44.9$  mm/s), the lowest thermal resistance ( $0.0354 \pm 0.0027$  m<sup>2</sup>·K/W), the lowest water vapor resistance ( $3.67 \pm 0.38$  m<sup>2</sup>·Pa/W), and the highest OMMC value ( $0.761 \pm 0.019$ ). Fabrics with reduced thickness and areal density were associated with enhanced airflow and improved convective and evaporative heat dissipation. Based on the comparative experimental results, the performance characteristics observed in the tested fabrics are reported as exploratory observations for fabric selection and thermo-moisture functional design in sportswear for high-intensity ethnic traditional sports. These results provide comparative performance data and preliminary insights for the development of thermo-moisture functional sportswear.*

## KEYWORDS

*ethnic traditional sports, thermo-moisture comfort, knitted fabrics, air permeability, water vapor resistance*

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## INTRODUCTION

Thermo-moisture comfort is a critical functional requirement for modern sportswear, particularly under high-intensity physical activities. During exercise, metabolic heat production and perspiration increase substantially, requiring garments to effectively dissipate heat and facilitate moisture evaporation in order to maintain physiological stability and wearer comfort [1,2]. The thermal and evaporative behavior of clothing

systems has been widely investigated using standardized laboratory methods such as ISO 11092 and ASTM D737 [3,4].

Previous studies have demonstrated that fabric structural parameters, including thickness, areal density, fiber composition, and knit configuration, are closely associated with air permeability, thermal resistance, and moisture vapor transport [5,6]. Knitted fabrics with open structures have been reported to enhance ventilation and reduce evaporative resistance compared to denser constructions [7,8]. Similarly, moisture management properties, often evaluated using AATCC 195, are closely related to fiber hydrophilicity and capillary transport mechanisms [9,10].

In addition, thermo-physiological comfort has been analyzed in various sportswear contexts, such as football jerseys and active sports garments in hot and humid climates [11]. These studies highlight the importance of low thermal resistance ( $R_{ct}$ ), low water vapor resistance ( $R_{et}$ ), and high air permeability for high-intensity activities. However, most existing research focuses on general sports apparel or protective clothing systems [12,13], with limited attention given to fabrics specifically intended for ethnic traditional sports.

Ethnic traditional sports, such as traditional wrestling, martial arts, and other explosive movement-based cultural athletic activities, often involve rapid directional changes, repetitive high-intensity actions, and intermittent bursts of exertion, generating significant metabolic heat and perspiration. In addition to thermal stress caused by high metabolic heat production, some ethnic traditional sports may also involve close body contact, repeated gripping or pulling actions, and rapid body movements, which can impose additional mechanical and comfort requirements on sportswear. Although thermal comfort theory has been extensively developed in environmental engineering contexts [14], systematic evaluation of thermo-moisture properties for ethnic traditional sportswear remains insufficient.

Therefore, this study aims to experimentally investigate the thermo-moisture comfort performance of functional knitted fabrics for high-intensity ethnic traditional sports. Standardized laboratory tests were conducted to evaluate air permeability, thermal resistance, water vapor resistance, and moisture management properties. Based on comparative analysis, practical selection and preliminary design insights are discussed.

This research aims to provide a scientific basis for the selection and structural design considerations, contributing to improved comfort and performance in ethnic traditional athletic activities.

## MATERIALS AND METHODS

### Materials

Three commercially available functional knitted fabrics commonly used in sportswear applications were selected for this study. The fabrics differed simultaneously in fiber composition and knit structure to provide a comparative evaluation of thermo-moisture comfort performance for high-intensity ethnic traditional sportswear. Because these parameters varied concurrently among the samples, the present study focuses on comparative observations rather than isolating the independent effects of fiber composition or knit structure. The samples were obtained from commercial sportswear fabric suppliers in China and represent typical structural categories in performance apparel, reflecting variations in knit openness, mass distribution, and elastomeric content. Although proprietary manufacturing details were not disclosed, key structural parameters relevant to thermo-moisture performance, including thickness, areal density, and fiber composition, were experimentally measured and reported to ensure reproducibility and comparability. The characteristics of the tested fabrics are summarized in Table 1.

Table 1. Structural characteristics of tested fabrics

Fabric code	Fiber composition	Fabric structure	Areal density (g/m <sup>2</sup> )	Thickness (mm)
F1	100% Polyester	Plain knit	150.3 ± 3.4	0.546 ± 0.027
F2	65% Polyester / 35% Cotton	Plain knit	168.9 ± 2.9	0.619 ± 0.024
F3	90% Polyester / 10% Spandex	Mesh knit	140.0 ± 4.0	0.504 ± 0.018

All fabrics were tested in their commercially finished state. No additional post-finishing treatments were applied in this study.

Prior to testing, all specimens were conditioned for 24 h under standard atmospheric conditions (20 ± 2 °C and 65 ± 4% relative humidity) in accordance with ISO 139.

### Physical Property Measurements

#### *Areal Density*

Fabric areal density was determined in accordance with ISO 3801. Circular specimens were cut using a standardized cutting template with a defined area and weighed using a calibrated analytical balance with an accuracy of ±0.001 g. Five specimens were tested for each fabric, and the results were expressed as mean ± standard deviation (SD).

### *Fabric Thickness*

Fabric thickness was measured according to ISO 5084 using a digital thickness gauge under a pressure of 1 kPa. Ten measurements were taken at different locations of each specimen to account for potential structural variability, and the average value was reported as the representative thickness.

### **Thermo-Moisture Comfort Testing**

All fabric specimens were conditioned for at least 24 h under standard atmospheric conditions ( $20 \pm 2$  °C,  $65 \pm 4\%$  relative humidity) in accordance with ISO 139 prior to testing.

Standardized steady-state laboratory methods were adopted to evaluate the intrinsic thermo-moisture performance of the fabrics under controlled and reproducible conditions. Although ethnic traditional sports involve dynamic and intermittent movements, steady-state measurements provide fundamental material performance indicators that are widely used in textile engineering research to compare fabric thermo-physiological properties.

### *Air Permeability*

Air permeability was measured in accordance with ASTM D737 using a standard air permeability tester under a pressure differential of 100 Pa with a test area of 20 cm<sup>2</sup>. Ten measurements were performed at different positions for each fabric, and results were expressed in mm/s as mean  $\pm$  standard deviation.

### *Thermal Resistance (Rct)*

Thermal resistance (Rct) was determined using a sweating guarded hot plate in accordance with ISO 11092. The hot plate surface temperature was maintained at  $35 \pm 0.1$  °C to simulate human skin temperature. The ambient laboratory conditions were controlled at  $20 \pm 2$  °C and  $65 \pm 4\%$  relative humidity. Air velocity over the specimen surface complied with ISO 11092 requirements.

Steady-state conditions were confirmed when the heat flux variation remained within  $\pm 2\%$  for at least 10 min before data recording. Rct values were expressed in m<sup>2</sup>·K/W. Five replicate measurements were performed for each fabric sample.

### *Water Vapor Resistance (Ret)*

Water vapor resistance (Ret) was measured using the same sweating guarded hot plate system following ISO 11092 procedures.

During Ret testing, distilled water was supplied to the porous plate to simulate sweating conditions under steady-state airflow and environmental control. Ret values were expressed in  $\text{m}^2\cdot\text{Pa}/\text{W}$ . Five replicate measurements were conducted for each sample.

### *MMT*

Moisture management properties were evaluated using a Moisture Management Tester according to AATCC 195. Five replicate measurements were performed for each fabric sample.

### **Statistical Analysis**

All experimental results were expressed as mean  $\pm$  standard deviation (SD). Statistical analysis was conducted using SPSS 26.0 (IBM Corp., USA). Normality of data distribution was assessed using the Shapiro–Wilk test, and homogeneity of variance was evaluated using Levene’s test.

One-way analysis of variance (ANOVA) was applied to determine statistically significant differences among the three fabrics. When significant differences were detected, post-hoc comparisons were performed using Tukey’s honestly significant difference (HSD) test. Effect sizes  $\eta^2$  were estimated using partial eta squared ( $\eta^2$ ). Differences were considered statistically significant at  $p < 0.05$  and highly significant at  $p < 0.001$ .

## **RESULTS AND DISCUSSION**

### **Structural and Physical Characteristics**

The structural parameters of the tested fabrics are presented in Table 1. As illustrated in Figures 1 and 2, Fabric F2 exhibited the highest areal density and thickness, whereas Fabric F3 showed the lowest values among the three samples. These differences reflect variations in knit structure and mass distribution.

Fabric thickness and areal density are recognized as key structural parameters influencing thermo-moisture behavior. Increased thickness generally promotes greater air entrapment within the textile matrix, which enhances resistance to conductive heat transfer and thus increases thermal insulation [1,6]. Similarly, higher areal density is often associated with reduced structural openness, potentially limiting airflow through the fabric.

In contrast, fabrics with lower mass and more open knit architectures tend to facilitate air circulation and reduce resistance to heat transfer. Such structural characteristics are particularly advantageous for garments designed for high-intensity physical activities, where efficient heat dissipation and ventilation are required to maintain thermal balance [2].

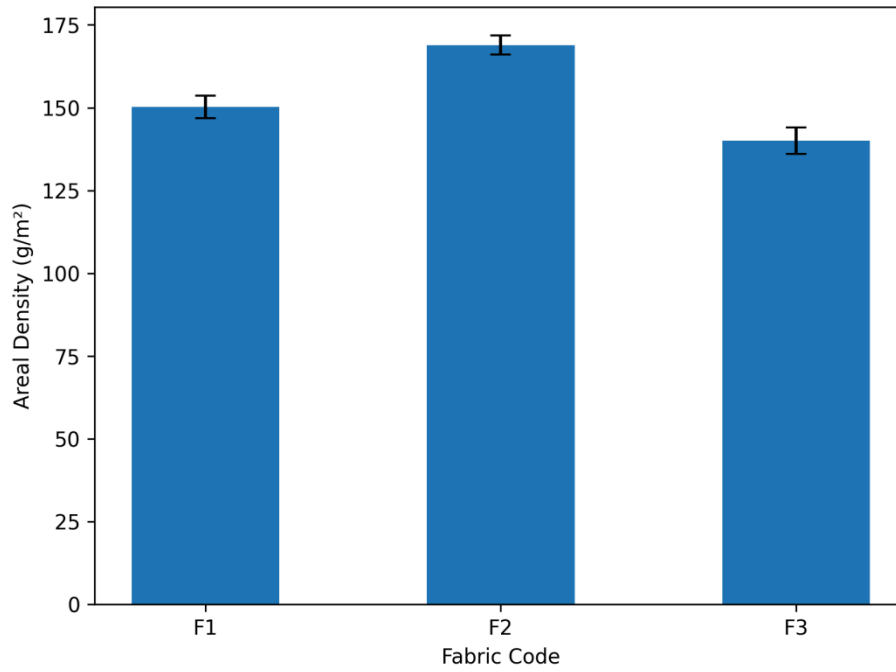


Figure 1. Areal density of tested fabrics (mean ± SD).

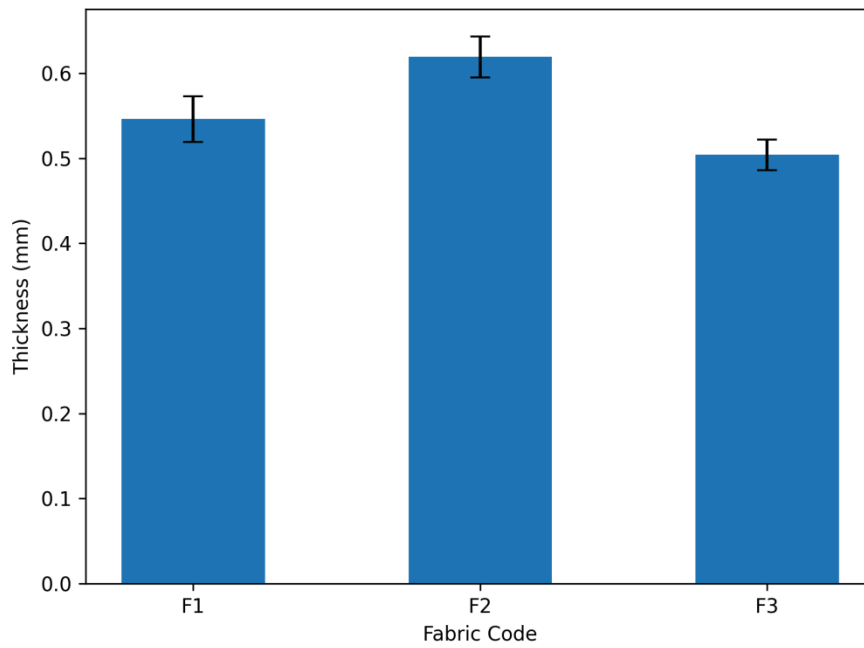


Figure 2. Thickness of tested fabrics (mean ± SD).

## Air Permeability

Air permeability results are summarized in Table 2 and illustrated in Figure 3. One-way ANOVA revealed statistically significant differences among the fabrics ( $p < 0.001$ ). Post-hoc Tukey tests confirmed that Fabric F3 exhibited significantly higher air permeability than both F1 and F2 ( $p < 0.01$ ), while F1 also differed significantly from F2 ( $p < 0.05$ ).

Fabric F3 showed the highest air permeability ( $839.0 \pm 44.9$  mm/s), followed by F1 ( $594.5 \pm 43.5$  mm/s), whereas Fabric F2 presented the lowest value ( $492.6 \pm 41.2$  mm/s).

The higher air permeability observed in F3 is consistent with its mesh-knit architecture, which provides increased structural openness and interconnected pore channels. In contrast, the denser plain-knit construction of F2 likely restricts airflow due to reduced pore size and greater mass per unit area.

Air permeability plays a critical role in convective heat exchange between the clothing microclimate and the surrounding environment [1]. Enhanced airflow facilitates heat dissipation and reduces thermal accumulation within the clothing system. For high-intensity ethnic traditional sports characterized by elevated metabolic heat production and intermittent bursts of activity, efficient ventilation is particularly important for maintaining thermal balance and minimizing heat strain [2,11].

Within the scope of the present comparative evaluation, these findings suggest that knit structure and mass distribution are factors associated with airflow performance in thermo-moisture functional sportswear fabrics.

Table 2. Thermo-moisture comfort properties of tested fabrics (mean  $\pm$  SD)

Fabric code	Air permeability (mm/s) (n=10)	Rct ( $m^2 \cdot K/W$ ) (n=5)	Ret ( $m^2 \cdot Pa/W$ ) (n=5)	OMMC (n=5)
F1	$594.5 \pm 43.5$	$0.0423 \pm 0.0016$	$4.48 \pm 0.42$	$0.546 \pm 0.022$
F2	$492.6 \pm 41.2$	$0.0548 \pm 0.0046$	$5.94 \pm 0.44$	$0.649 \pm 0.014$
F3	$839.0 \pm 44.9$	$0.0354 \pm 0.0027$	$3.67 \pm 0.38$	$0.761 \pm 0.019$

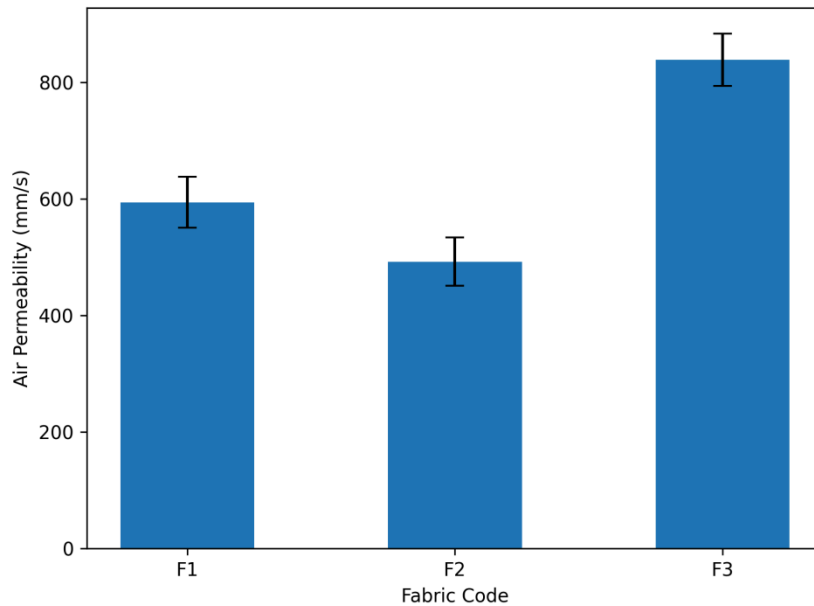


Figure 3. Air permeability of tested fabrics (mean  $\pm$  SD).

### Thermal Resistance

Thermal resistance ( $R_{ct}$ ) values are presented in Table 2 and illustrated in Figure 4. One-way ANOVA revealed statistically significant differences among the fabrics ( $p < 0.001$ ). Post-hoc Tukey tests indicated that Fabric F2 exhibited significantly higher  $R_{ct}$  values than both F1 and F3 ( $p < 0.01$ ), while F1 also differed significantly from F3 ( $p < 0.05$ ).

Fabric F2 showed the highest  $R_{ct}$  value ( $0.0548 \pm 0.0046 \text{ m}^2 \cdot \text{K}/\text{W}$ ), followed by F1 ( $0.0423 \pm 0.0016 \text{ m}^2 \cdot \text{K}/\text{W}$ ), whereas Fabric F3 demonstrated the lowest thermal resistance ( $0.0354 \pm 0.0027 \text{ m}^2 \cdot \text{K}/\text{W}$ ).

$R_{ct}$  represents resistance to dry conductive heat transfer through the fabric layer, as defined by ISO 11092 [8]. The higher  $R_{ct}$  observed in F2 is consistent with its greater thickness and areal density, which may promote increased still-air entrapment within the textile structure. Since stagnant air acts as an effective thermal insulator, thicker and denser fabrics generally exhibit enhanced resistance to heat transfer [1,6].

In contrast, the lower  $R_{ct}$  value of the mesh-knit F3 fabric is consistent with its more open structure and reduced mass per unit area. For garments intended for vigorous physical exertion, particularly in high-intensity ethnic traditional sports, lower thermal resistance is advantageous as it facilitates heat dissipation and may help reduce thermal strain [11].

Within the scope of the present comparative study, these findings suggest that structural parameters such as thickness and knit openness are associated with conductive heat transfer in performance-oriented sportswear fabrics.

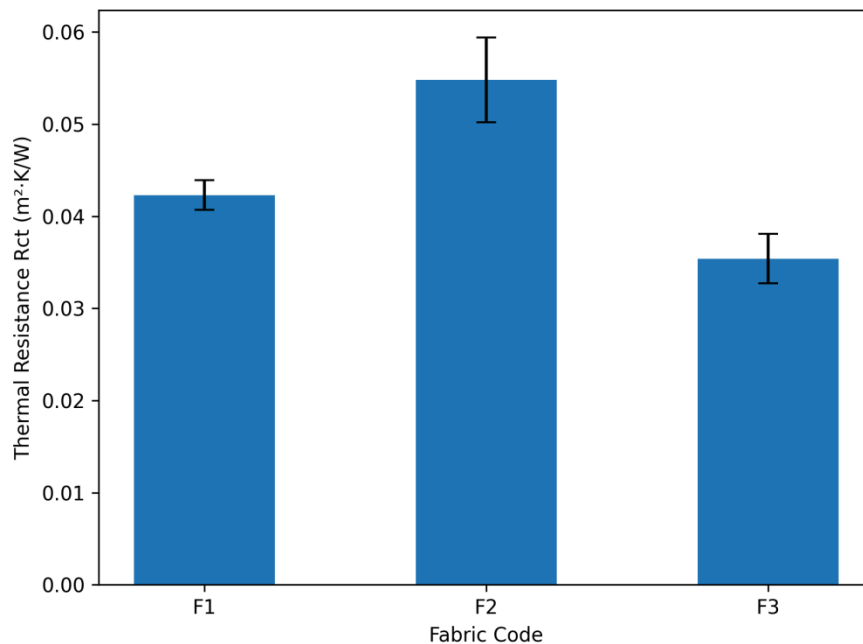


Figure 4. Thermal resistance (Rct) of tested fabrics (mean  $\pm$  SD).

### Water Vapor Resistance

Water vapor resistance (Ret), representing resistance to evaporative heat transfer, showed statistically significant differences among the fabrics ( $p < 0.001$ ). Post-hoc Tukey tests indicated that Fabric F2 exhibited significantly higher Ret values than both F1 and F3 ( $p < 0.01$ ), while F1 also differed significantly from F3 ( $p < 0.05$ ).

As presented in Table 2 and illustrated in Figure 5, Fabric F3 exhibited the lowest Ret value ( $3.67 \pm 0.38$  m<sup>2</sup>·Pa/W), followed by F1 ( $4.48 \pm 0.42$  m<sup>2</sup>·Pa/W), whereas Fabric F2 showed the highest resistance ( $5.94 \pm 0.44$  m<sup>2</sup>·Pa/W).

Ret reflects the fabric's resistance to moisture vapor diffusion under steady-state conditions, as defined in ISO 11092 [4]. Although real sports activities involve dynamic and transient physiological conditions, standardized steady-state measurements provide a consistent basis for comparing the intrinsic evaporative performance of textile materials. The higher Ret observed in F2 is consistent with its greater thickness and mass per unit

area, which may reduce vapor permeability by limiting pore connectivity and increasing diffusion path length. In contrast, the open mesh structure of F3 is associated with enhanced vapor transport due to interconnected air channels that facilitate moisture diffusion.

Lower Ret values correspond to improved evaporative cooling efficiency and reduced resistance to sweat vapor transfer. Efficient evaporation is particularly important for high-intensity ethnic traditional sports, where rapid metabolic heat production necessitates effective moisture dissipation to maintain thermal balance [2]. Within the scope of the present comparative evaluation, the lower Ret observed in F3 suggests superior evaporative performance relative to the other tested fabrics, highlighting the potential role of structural openness and reduced mass in moisture and heat management fabric design.

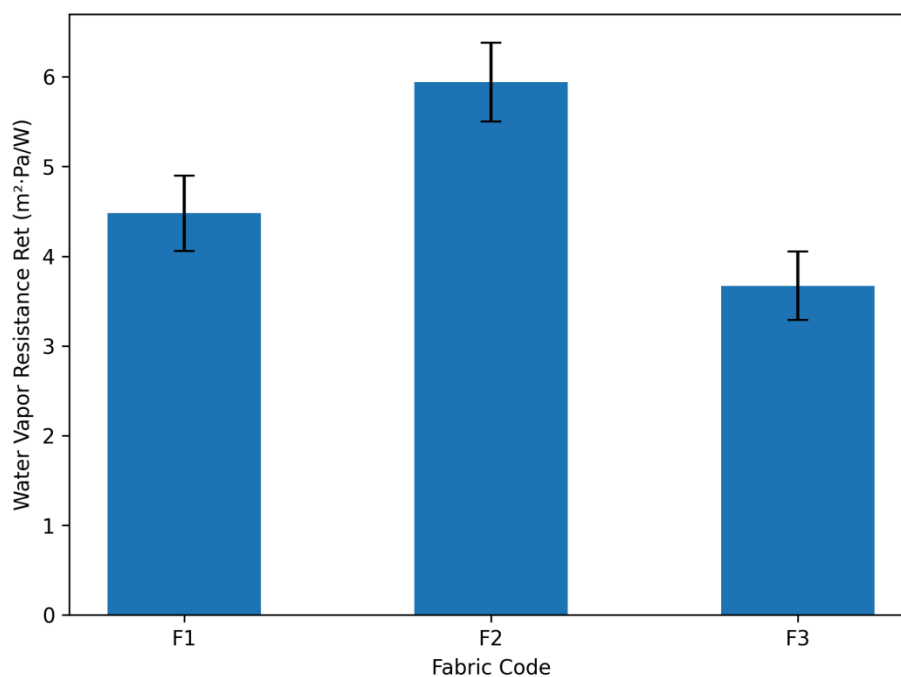


Figure 5. Water vapor resistance (Ret) of tested fabrics (mean  $\pm$  SD).

### Moisture Management Performance

Moisture management performance, expressed as overall moisture management capacity (OMMC), is summarized in Table 2 and illustrated in Figure 6. One-way ANOVA revealed statistically significant differences among the fabrics ( $p < 0.001$ ). Post-hoc Tukey tests indicated that Fabric F3 exhibited significantly higher OMMC values than both F1 and F2 ( $p < 0.01$ ), while F2 also differed significantly from F1 ( $p < 0.05$ ).

Fabric F3 achieved the highest OMMC value ( $0.761 \pm 0.019$ ), followed by F2 ( $0.649 \pm 0.014$ ) and F1 ( $0.546 \pm 0.022$ ).

OMMC is a composite index reflecting dynamic liquid moisture transport behavior, including wetting, spreading, and one-way moisture transfer. Higher OMMC values indicate more efficient liquid sweat absorption and redistribution across the fabric surface. The higher OMMC observed in F3 is consistent with its mesh-knit architecture, which may enhance capillary pathways and facilitate lateral moisture spreading.

In contrast, the lower OMMC observed in F1 and F2 may be associated with reduced structural openness and limited capillary connectivity within the knit structure. Although fiber composition can influence hydrophilicity and wetting behavior [5,8], the present comparative results indicate that structural configuration appears to play a substantial role in regulating dynamic moisture transport under the tested conditions.

For high-intensity ethnic traditional sports involving intermittent bursts of activity, efficient liquid moisture management is important for minimizing localized wetness sensation and maintaining thermal comfort. Within the scope of this controlled laboratory study, these findings suggest that integrating structural openness with optimized capillary transport pathways may enhance thermo-moisture functionality in performance-oriented sportswear fabrics.

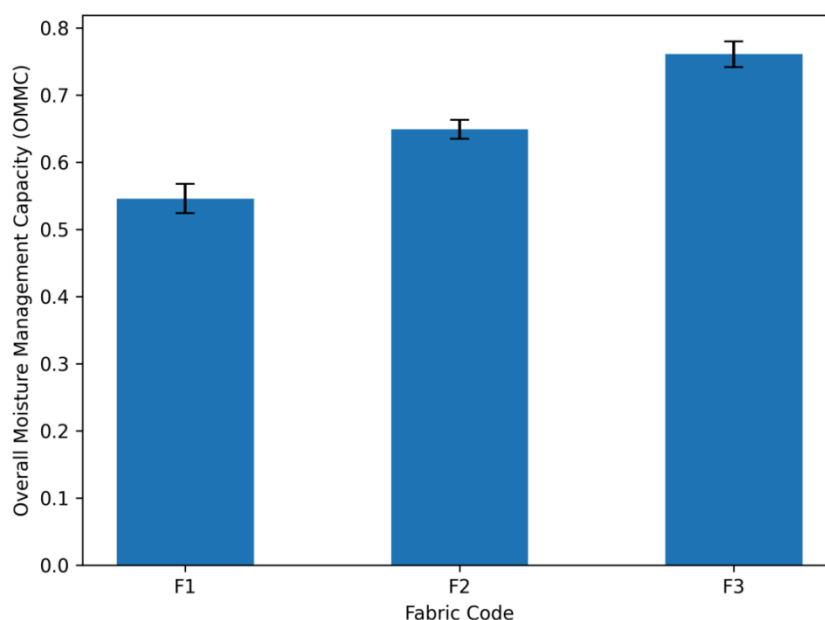


Figure 6. Overall moisture management capacity (OMMC) of tested fabrics (mean  $\pm$  SD).

### **Structural–Performance Tendency Analysis**

Based on the comparative results obtained in this study, comparative structural–performance patterns can be observed among the tested fabrics. Fabrics with lower thickness and reduced areal density were associated with higher air permeability and lower thermal ( $R_{ct}$ ) and evaporative ( $R_{et}$ ) resistance values.

The mesh-knit polyester fabric (F3), characterized by its open-loop geometry and lower mass per unit area, exhibited the highest air permeability and the lowest  $R_{ct}$  and  $R_{et}$  values among the three samples.

These observations indicate that increased structural openness and reduced material volume may enhance convective airflow and facilitate vapor transport under high-intensity activity conditions. However, because multiple structural and compositional parameters varied simultaneously among the fabrics, the findings should be interpreted as comparative observations rather than evidence of isolated causal relationships.

### **Structural–Performance Observations for High-Intensity Ethnic Traditional Sportswear**

Based on the comparative experimental findings of the present study, several structural–performance observations are discussed to provide preliminary insights for the design of thermo-moisture functional sportswear intended for high-intensity ethnic traditional sports.

#### *Performance Requirement Definition*

High-intensity ethnic traditional sports are often characterized by intermittent explosive movements, rapid directional transitions, and elevated metabolic heat production. Such activity patterns typically result in increased perspiration rates and significant microclimate heat accumulation.

Under these conditions, garments are expected to promote rapid heat dissipation and efficient moisture transport in order to reduce thermal strain and localized wetness sensation.

Based on the performance differences observed among the tested fabrics, thermo-moisture design priorities for high-intensity scenarios may include:

- High air permeability to enhance convective heat exchange
- Low thermal resistance ( $R_{ct}$ ) to reduce dry heat insulation
- Low water vapor resistance ( $R_{et}$ ) to improve evaporative cooling efficiency
- High overall moisture management capacity (OMMC) to support rapid liquid sweat redistribution

Within this functional context, excessive insulation may hinder thermal regulation, and ventilation-driven cooling becomes a primary structural consideration.

### *Structural–Performance Relationship Analysis*

The present comparative results indicate that fabric thickness and areal density are structural parameters associated with thermo-moisture behavior. Fabrics with greater thickness and mass per unit area exhibited higher  $R_{ct}$  and  $R_{et}$  values, corresponding to increased resistance to both conductive and evaporative heat transfer. Conversely, the mesh-knit fabric (F3), characterized by lower thickness and enhanced structural openness, showed improved airflow and moisture transport performance relative to the other tested fabrics. A comparative trend observed among the three samples suggests that higher air permeability coincided with lower  $R_{et}$  values. However, given the limited number of fabric types evaluated, this observation should be interpreted as an exploratory comparative observation rather than a statistically established relationship. Such simultaneous enhancement of ventilation and evaporative transport may be advantageous for garments designed for high-intensity activities requiring rapid heat and moisture dissipation.

Within the scope of the present laboratory-based evaluation, knit architecture appears to be associated with thermo-moisture performance among the tested fabrics. However, because both structural parameters and fiber composition varied simultaneously among the samples, further controlled single-factor experiments would be required to isolate and quantify the independent contribution of each factor. Therefore, the present results should be interpreted as comparative observations rather than definitive causal relationships.

### *Observed Structural Characteristics of Tested Fabrics*

Based on the comparative performance of the tested fabrics, several structural and thermo-moisture performance characteristics were observed for knitted sportswear intended for high-intensity ethnic traditional sports.

- Fabric thickness in the lower range of the tested samples (approximately 0.5 mm or below)
- Areal density in the lower range of the tested samples (approximately 150 g/m<sup>2</sup> or below)
- Mesh or structurally open knit construction
- Higher air permeability within the tested sample range
- Lower water vapor resistance ( $R_{et}$ ) within the tested sample range
- Lower thermal resistance ( $R_{ct}$ ) within the tested sample range

These observations are derived from the relative performance differences observed in this controlled study and should be interpreted as exploratory comparative findings rather than generalized engineering design

ranges. Specific optimal values may vary depending on garment construction, fiber selection, and environmental conditions.

### *Engineering Implications*

The structural–performance considerations outlined in this study highlight structural openness and reduced fabric mass as important design considerations for thermo-moisture regulation in high-intensity ethnic traditional sportswear. Rather than maximizing insulation, garment design strategies may benefit from prioritizing enhanced airflow pathways and facilitating both vapor diffusion and liquid moisture redistribution.

The comparative findings suggest that lightweight mesh-knit polyester/spandex blends or comparable open-knit constructions are associated with improved thermo-moisture performance under the tested conditions. Such structural configurations may contribute to enhanced microclimate regulation while maintaining flexibility and mechanical compliance required for dynamic movement.

Although the present study was conducted under controlled laboratory conditions, the identified structural–performance tendencies provide preliminary design insights for textile designers and manufacturers seeking to optimize thermo-moisture comfort in performance-oriented sportswear applications. Future investigations incorporating a broader range of fabric architectures and dynamic wear trials are recommended to further validate and refine the proposed engineering reference values.

## **CONCLUSIONS**

This study comparatively evaluated the thermo-moisture comfort performance of three functional knitted fabrics intended for high-intensity ethnic traditional sportswear applications. Air permeability, thermal resistance ( $R_{ct}$ ), water vapor resistance ( $R_{et}$ ), and moisture management capacity (OMMC) were assessed using standardized laboratory methods, and statistically significant differences were identified among the tested fabrics ( $p < 0.001$ ).

The results indicate that fabric structural characteristics, particularly thickness, areal density, and knit configuration, are closely associated with thermo-moisture behavior. Fabrics with greater thickness and density exhibited higher thermal insulation and evaporative resistance, whereas structurally open mesh constructions were associated with enhanced airflow and vapor transport. The mesh-knit polyester/spandex fabric (F3) showed the most favorable thermo-moisture profile among the tested samples.

A comparative pattern observed in this study suggests that higher air permeability coincided with lower  $R_{et}$  values, indicating the potential benefit of structurally open knit architectures in simultaneously supporting

convective and evaporative heat transfer. From an engineering perspective, knit architecture appears to play an important role on thermo-physiological performance under high-intensity activity conditions.

Based on the comparative experimental findings, comparative structural–performance observations for thickness, areal density, and thermo-moisture performance indicators were outlined to support application-oriented fabric selection. These values should be interpreted as engineering guidance derived from controlled laboratory evaluation rather than universal optimization standards.

Although the experiments were conducted under standardized laboratory conditions, the evaluated indices represent widely recognized indicators of thermo-physiological performance. Future research incorporating dynamic wear trials, microclimate monitoring, and broader structural variations would further validate and refine the proposed engineering framework. Overall, the present study provides comparative structural–performance insights that may support future engineering-oriented design of thermo-moisture functional sportswear for high-intensity ethnic traditional sports.

### **Study Limitations**

Several limitations should be acknowledged. First, the study was conducted under controlled laboratory conditions using standardized steady-state testing methods; dynamic wear trials under real movement conditions were not included. Although ethnic traditional sports involve dynamic and intermittent movements, steady-state measurements are widely used to evaluate the intrinsic thermo-moisture performance of textile materials and provide a consistent basis for comparing fabric properties. Second, the selected fabrics differed simultaneously in fiber composition, knit structure, thickness, and areal density, which may introduce multi-factor coupling effects. Therefore, the present findings should be interpreted as comparative observations rather than isolated single-factor investigation. Third, only three representative commercial fabrics were examined, and broader structural variations may provide additional insights in future research.

Despite these limitations, the standardized methodology and consistent statistical analysis enhance the reliability of the comparative findings, and the identified structural–performance tendencies provide meaningful guidance for textile design and development.

### *Availability of Data and Materials*

The datasets used and/or analysed during the current study were available from the corresponding author on reasonable request.

### *Author Contributions*

Xiaohui Fu and Leilei Song designed the study; all authors conducted the study; Xiaohui Fu and Leilei Song collected and analyzed the data. Xiaohui Fu and Leilei Song participated in drafting the manuscript, and all authors contributed to critical revision of the manuscript for important intellectual content. All authors gave final approval of the version to be published. All authors participated fully in the work, took public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or completeness of any part of the work were appropriately investigated and resolved.

### *Conflict of Interest*

The authors declare no conflict of interest.

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### *Acknowledgment*

Not applicable.

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