

# Thermophysiological Comfort Assessment of Football Jersey Fabrics used in Hot and Humid Weather

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Thermophysiological comfort, single jersey derivatives, fabric properties, sportswear, fabric performance

## Abstract

Optimizing thermophysiological comfort is crucial for enhancing athletic performances and well-being during intense exercise in hot and humid climates. This study assessed the comfort properties of four commercially available 100% polyester microfibre fabrics used in football jerseys: mini mesh (MM), polar eyelet (PE), eyelet (EY), and interlock (IT). Fabric assessments were conducted to evaluate thermal resistance, water vapour resistance, water vapour permeability, air permeability, and moisture management properties. Among the fabrics, the PE fabric demonstrated to give the most superior thermophysiological properties, with the lowest thermal resistance ( $0.009 \text{ m}^2\text{K/W}$ ), the lowest water vapour resistance ( $0.44 \text{ m}^2\text{Pa/W}$ ), and the highest water vapour permeability ( $237.7 \text{ g/m}^2/\text{day}$ ) and air permeability ( $2149.2 \text{ mm/s}$ ). These values are attributed to the fabric's porous, open-knit structure that enhances heat and moisture dissipation, resulting in improved breathability and wearer comfort. Statistical analysis confirmed significant differences among the fabric structures, reinforcing the influence of fabric design on comfort performance. The findings suggest that, among the fabrics, the PE fabric performs better as sportswear for tropical climates like Malaysia.

## 1. Introduction

The rapid development of novel textile fibers, yarns, and fabric design has led to the development of technical textiles that enhance wear comfort, improve athletic performance, and meet consumer expectations for high-quality sports garments [1], [2]. Athletes and individuals who engage in physical activities require clothing that assists rather than hinders their athletic performances by offering optimal thermophysiological comfort under diverse environmental conditions [3]. Poor thermophysiological comfort, resulting from the body's inability to regulate temperature during activity, can negatively impact athletic performance. Discomfort caused by heat and humidity leads to poor comfort and reduced performance, with negative emotions [4]. In simulated Tokyo Olympic environmental conditions, non-acclimatized elite athletes showed a 26% reduction in endurance capacity, along with significant increases in core and skin temperatures and reduced thermal comfort. These physiological responses were pronounced in endurance and power athletes [5]. These observations highlight the importance of external interventions such as clothing in managing thermal strain.

Therefore, the technical evaluation of sportswear fabrics has taken on new significance to guarantee exercise or competitive performance, satisfaction, and well-being. Several material properties, including breathability, moisture management, and thermal regulation in combination with skin sensation, contribute to the thermophysiological comfort possibly experienced by a wearer as part of overall garment comfort. It is well-documented that the related properties of fabric, such as thickness, porosity, and thermal resistance, as well as evaporative ability, play a vital role in thermophysiological comfort [6], [7]. Fabrics that promote good airflow and effectively manage moisture transmission and heat transfer away from the skin, such as Coolmax knitted fabric, may maintain clothing wearing comfort during long-term physical activity [8]. As a main principle for thermal comfort of sportswear, it allows wearers to be comfortably dry by providing breathability as well as being comfortable while achieving good performance by efficiently removing excess heat and moisture from the skin without interfering with body movements during physical activity [9], [10]. The excessive demands placed on athletes, along with the demanding training and competitive circumstances they encounter, cause their lives to become both physically and mentally exhausting.

Fabric technologies play a key role in improving performance for athletes by providing comfort and safety. Manufacturers have introduced new materials, fabric construction, and finishing processes to create textiles that can actively adapt to the heat, moisture, and airflow needs of an athlete's body during exercise [11]. Recent high-performance sportswear integrates advanced features such as moisture-wicking fibres, breathable materials, and ventilation panels to control body temperature, reduce irritation, and optimise comfort during prolonged physical activity. Advanced fabric technologies such as porous warp knitted structures and Coolmax fabric can improve moisture management and allow moisture to evaporate more easily, influencing athlete performance [12].

Factors influencing thermophysiological comfort in sportswear include fabric properties, air permeability, moisture management properties, thermal regulation, and water vapour permeability [6], [13]. Several types of research have been performed to analyse the impact of fabric properties on the thermal comfort of sportswear. Öner and Okur studied the thermophysiological comfort properties of different fabric types and fabric structure combinations and the design of T-shirts for active sports. The polyester and cotton/Coolmax fabrics with float stitches have good liquid moisture transport properties, while high air permeability and low water vapour resistance have been obtained in viscose and Tencel LF fabrics with tuck stitches [14]. Ziemele et al. emphasized the comfort benefits of polyester and polyamide/elastane blends, highlighting their low water vapour permeability properties [15]. Ahmad and Jamshaid examined the moisture-wicking properties of modal and micro-polyester materials, particularly suitable for warmer climate sportswear [16]. Tesinova and Atalie conducted an extensive study of commercial sportswear fabrics and found that thermal comfort is strongly influenced by fabric structure, fiber composition and layering arrangement, showing that polyester elastane combinations provided higher thermal resistance and better thermal diffusivity, while polyamide based fabrics offered greater moisture absorption but lower breathability, highlighting the critical role of material selection in optimizing sportswear comfort and performance [17].

Özkan and Kaplangiray investigated the thermophysiological comfort properties of fabrics for athlete clothes using seven different types of fabrics with two different knit structures, which are single jersey and mesh knitted. Tencel single jersey and polyester mesh knitted fabric showed higher thermophysiological comfort properties, making them ideal for sportswear production [18]. Mohapatra et al. examined the thermal comfort properties of polyester with various types of polyester yarn (spun, micro-denier, continuous filament, and hollow). They found that different polyester yarns, linear density, and loop length significantly affect the thermal comfort properties of single jersey fabrics, with micro denier yarns having the highest air permeability and spun yarns having the lowest air permeability [19]. Ramratan and Choudhary correlated high comfort performance with micro polyester plain single jersey fabric and highlighted the importance of structure porosity and microchannels for moisture management [20]. Ziaei et al. carried out a study on the effect of fabric structure on surface temperature distribution in weft-knitted fabrics using a thermal imaging technique. They reported that heat transfer in fabrics is influenced by the fabric structure, where the presence of tuck stitches in fabrics affects their air permeability, thermal

insulation, tensile properties, and thermal conductivity [21]. Overall, these studies emphasise the importance of fabric properties in sportswear comfort.

As research continues to evolve toward optimising sportswear performance through fabric innovation, this study aims to investigate the thermophysiological comfort of several commercial sportswear fabrics of different structures, specifically mini mesh (MM), polar eyelet (PE), eyelet (EY), and interlock (IT) fabrics. These fabrics are selected based on their structural uniqueness and potential for improved athletic wear performance, such as breathability and moisture-wicking capabilities, making them suitable for high-performance sportswear and activewear. Hence, this study aims to enhance understanding of the comfort properties and suitability of these materials for various athletic activities. The novelty of this study lies in the comparative evaluation of fabric performance under tropical climate conditions that integrates multiple comfort properties such as thermal resistance, vapour resistance, air permeability, moisture management, SEM morphology, and statistical analysis to identify structural performance. The findings of this research contribute to the advancement of textile science for the development of sportswear that emphasizes wearer comfort and performance.

## 2. Materials and Methods

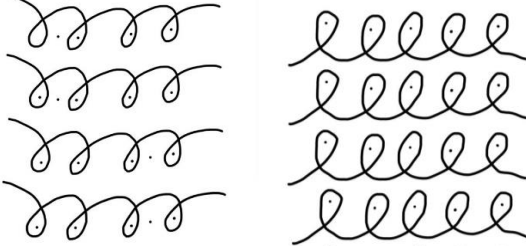
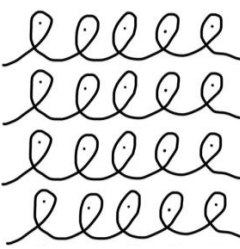
The sportswear fabrics that were used in this study are commercially available and are made from 100% polyester microfibrils. These fabrics were purchased from a local sportswear supplier in Malaysia. Four different knit structures were selected based on their relevance in high-performance sportswear, which are mini mesh (MM), polar eyelet (PE), eyelet (EY), and interlock (IT) fabrics. These fabrics were chosen due to their differences in surface textures, open structures, and mass per unit area, which influence comfort performance under hot and humid environmental conditions. Before testing, all fabric samples were pre-conditioned for a minimum of 24 hours under standard atmospheric conditions (20 ±0.5°C; 65±5% relative humidity) following ASTM D1776 [22].

Fabric physical properties, including fiber content, fabric structure, mass per unit area, thickness, and fabric density, were measured and recorded. The fabric's physical properties, which were measured following the related standards, are presented in Table 1. The mass per unit area was measured according to the ASTM D3776 standard [23], the thickness was measured according to the ASTM D1777 standard [24], and density in courses per inch and wales per inch was calculated according to the ASTM D1577 standard [25]. The fabric structures and point paper notation of the sportswear fabrics are shown in Table 2.

**Table 1** Physical properties of sportswear fabric

Fabric code	Fabric structure	Mass per unit area (g/m <sup>2</sup> )	Thickness (mm)	Wales per inch (wpi)	Courses per inch (cpi)
MM	Single jersey with mini mesh	165.8	0.58	37	55
PE	Single jersey with polar eyelet	189.0	0.51	42	55
EY	Single jersey with eyelet	192.9	0.69	36	30
IT	Interlock	188.1	0.52	53	58

**Table 2** Fabric structures and point paper notation









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### 2.1 Microscopic Evaluation of Fabric Structure

The fabric samples were examined under a light microscope (Olympus CX21) at a 0.10x magnification rate to characterize the surface morphology and visualize the structures. Fabric specimens measuring 1 cm x 1 cm were mounted on glass slides, and micrographs of the front and back surfaces were captured using the integrated camera system. The optical micrographs were used to identify structural variations, such as mesh openness and loop configurations, as shown in Table 3.

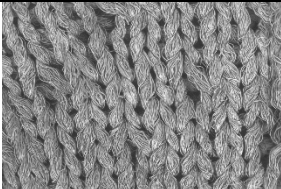
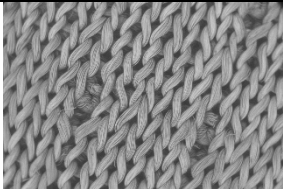
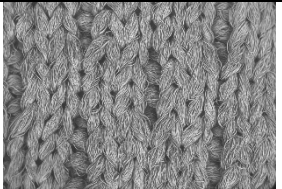
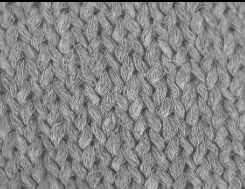
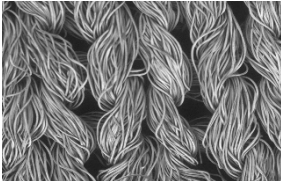


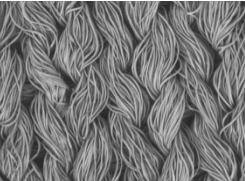
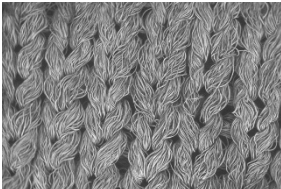
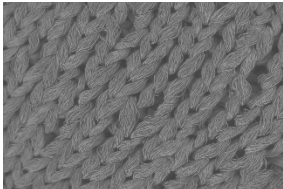
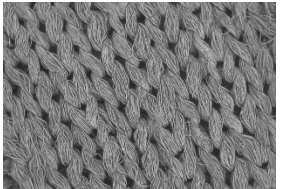
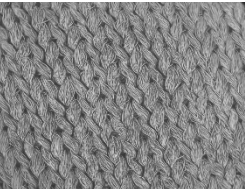
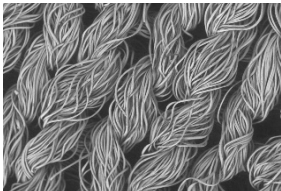
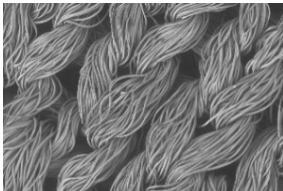
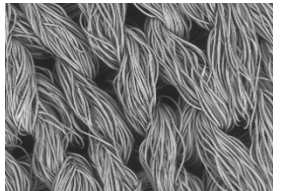

**Table 3** Microscopic fabric analysis

Fabric code	MM	PE	EY	IT
Face				
Back				

## 2.2 Morphological Analysis by Scanning Electron Microscopy (SEM)

Further structural examination of the fabric samples was performed using Scanning Electron Microscopy (SEM). Small fabric specimens were mounted on stubs, sputter-coated with a conductive layer, and imaged using secondary and backscattered electron modes. High-resolution micrographs were captured at magnifications of 30x and 120x to reveal fine details of the fiber morphology, yarn structure, and surface textures, as shown in Table 4.

**Table 4** SEM analysis

Fabric code	MM	PE	EY	IT
Face 30x				
120x				
Back 30x				
120x				

Referring to Tables 3 and 4, the MM fabric has small open holes on the fabric face. In principle, this type of mesh structure allows air, water vapour, or sweat to evaporate more readily, promoting ventilation and reducing heat buildup. It also contributes to lighter fabric weight and enhanced breathability. The PE fabric structure features larger and more defined holes or eyelets, typically arranged in a repeating grid pattern. The open structure facilitates rapid evaporation of moisture and keeps the wearer dry and comfortable. The increased airflow helps regulate body temperature, preventing overheating for the wearer. The EY fabric structure features smaller and more closely spaced eyelets compared to the PE fabric, with a thin pattern of smaller eyelet size. The open structures allow for moisture evaporation, but at a slightly slower rate than PE Fabric. The IT fabric does not have any mesh or eyelet structures. The fabric has a smooth and flat surface with no visible textures or holes. The tight-knit structures contribute to limiting the airflow, making it less breathable, but manage moisture effectively due to the properties of polyester microfibres.

### 2.3 Thermal Resistance

The thermal resistance ( $R_{ct}$ ) of the fabrics was evaluated using a sweated guarded hotplate according to ISO 11092 [26]. This test simulates the transfer of heat and moisture through the fabric that occurs when in contact with human skin. Fabric samples were placed over the hotplate surface, and the assembly was enclosed in an environmental chamber maintained at 35°C and 40% relative humidity. A vapour pressure gradient was established across the fabric by keeping the hotplate surface at a slightly higher temperature and water vapour pressure than chamber conditions. The heat flow and water vapour transmission through the fabric were then measured, allowing the calculation of the thermal resistance in units of square meters kelvin per watt ( $m^2 \cdot K/W$ ). This parameter shows the warmth and breathability performance of the fabric, which is critical for sportswear applications where insulation and moisture management are important comfort attributes. When the system reaches a stable state, the thermal resistance of the fabric is calculated using the formula:

$$R_{ct} = \frac{(T_p - T_a)}{q} - R_{ct0} \quad (1)$$

where,

$R_{ct}$  = Thermal resistance ( $m^2K/W$ )

$R_{ct0}$  = Thermal resistance without a sample ( $m^2K/W$ )

$T_p$  = Temperature of the plate in the test enclosure (35 °C)

$T_a$  = Temperature of the air in the test enclosure (20 °C)

$q$  = Heat flow per unit area through the test specimen ( $W/m^2$ )

### 2.4 Water Vapour Resistance

According to ISO 11092, the water vapour resistance ( $R_{et}$ ) of the fabric was measured using the same sweated guarded hotplate setup, which simulates the water vapour transferred from one side to the other side of the fabric when worn next to human skin [26]. The hotplate was set to 35°C and 40% humidity, and a polytetrafluoroethylene (PTFE) membrane, simulating skin contact, was placed on the plate. The fabric was then carefully placed on the PTFE insert. The hotplate surface temperature, ambient conditions, and power input were recorded. The water vapour transfer rates between the fabric and the skin were monitored. The water vapour resistance ( $R_{et}$ ) was calculated using the formula:

$$R_{et} = \frac{(T_p - T_a)}{(W_{vp} / A)} \quad (2)$$

where,

$T_p$  is the hotplate temperature

$T_a$  is the ambient temperature

$W_{vp}$  is the water vapour transfer rate

$A$  is the sample area

### 2.5 Water Vapour Permeability

The water vapour permeability of the fabrics was measured using a water vapour transmission tester in accordance with ASTM E96-22 standard method [27]. The fabric samples were sealed in the open mouth of a test dish with 46 mL of water. The triangular sample support was positioned in the dish. The cover ring was placed over the dish rim and pressed firmly into place. The strip of adhesive tape was applied around the full circumference of the assembly, sealing the join between the cover ring and the dish. The assembly was placed onto the turntable

and rotated in the controlled atmosphere for a further period of not less than 5 hours. Fabric samples were exposed to a controlled water vapour environment, and their ability to allow water vapour transmission was measured. The weight gain of the samples over time was measured, which indicates the amount of water vapour that had passed through the fabric. The water vapour permeability was calculated using the formula:

$$WVTR (g/m^2.day) = \frac{G}{(A \times t)} \quad (3)$$

where,

G = mass change (g)

A = test specimen area (m<sup>2</sup>)

T = time elapsed (days)

## 2.6 Air Permeability

The air permeability of the fabric was determined using a MESDAN Air-Tronic tester following ASTM D737 [28]. The fabric was clamped tightly by a test rig, and a guard ring surrounding the test specimen ensures that all the measured airflow passes through the specimen with no leakage. The test area is a circle of 10 cm<sup>2</sup>, and the air volume is 100 litres. The measurement of airflow was done when a pressure of 100 Pa was applied. The rate of air flow passing perpendicularly through a known area of fabric was adjusted to obtain a prescribed air pressure differential between the two fabric surfaces. From this rate of airflow, the air permeability of the fabric was subsequently measured in mm/seconds to assess breathability.

## 2.7 Moisture Management

The Moisture Management Tester (MMT) was used to measure and classify the liquid management properties of fabrics. This standardised procedure measures the ability of fabric to absorb, transfer, and dry liquid moisture. The test was conducted following the American Textile and Colorists Association (AATCC) 195-2011 [29]. Each fabric specimen, with a size of 80 x 80 mm, was placed flat between the top and bottom sensors, and the saline solution was pumped onto the upper surface of the fabric to simulate a drop of liquid sweat. These were assisted with sensor rings on the top and bottom plates. The fluid dynamics properties of the fabrics in Overall Moisture Management Capability (OMMC), accumulative one-way transport capability, wetting time for top and bottom surfaces, the absorption rate for top and bottom surfaces, the maximum wetted radius for top and bottom surfaces, and spreading speed for top and bottom surfaces were measured. The indices are graded and converted from a numerical value to a grade using a five-grade scale. Based on the grading, fabrics are categorized into waterproof, water-repellent, slow absorbing and slow drying, fast absorbing and slow drying, fast absorbing and quick drying, readily water permeable, and moisture management fabrics [30].

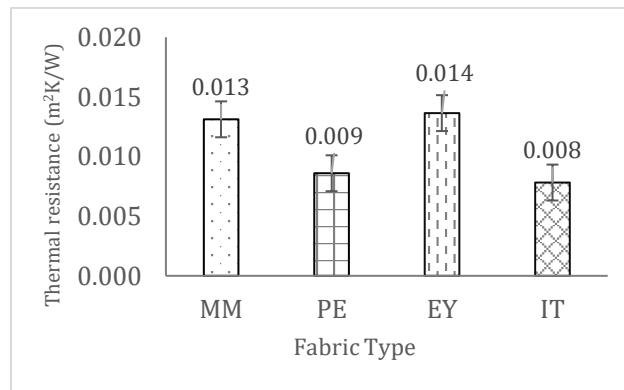
## 2.8 Statistical Analysis

Data obtained from laboratory testing were analysed using one-way Analysis of Variance (ANOVA) and Tukey's Honest Significant Difference (Tukey's HSD) post-hoc test to determine significant differences between fabrics. A 95% confidence interval ( $p < 0.05$ ) was used to assess the significance.

## 3. Results and Discussion

### 3.1 Thermal Resistance

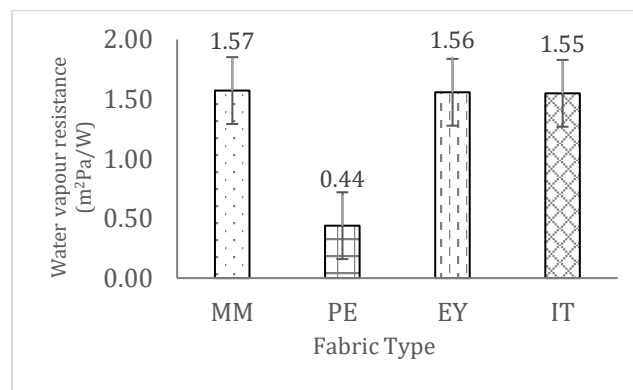
Thermal resistance refers to a fabric's ability to resist heat flow, with lower values showing better heat dissipation, which is a desirable feature for sportswear in hot and humid weather. The thermal resistance results are shown in Figure 1. The EY fabric showed the highest thermal resistance, 0.014 m<sup>2</sup>K/W, followed by the MM fabric, 0.013 m<sup>2</sup>K/W. The IT fabric and PE fabric had a lower thermal resistance of 0.008 m<sup>2</sup>K/W and 0.009 m<sup>2</sup>K/W, respectively. The higher resistance in EY and MM fabric is likely due to their higher thickness (EY = 0.69 mm, MM = 0.58 mm), which traps more air within the fabric, providing better insulation but reduced heat transfer efficiency. Thicker fabrics contribute to greater thermal resistance due to higher insulation through trapped air spaces within the fabric structure. This trapped air acts as an insulator, minimizing heat loss from the body during physical activity. In contrast, PE and IT fabrics, which are thinner (PE = 0.51 mm, IT = 0.52 mm), allow for greater convective and conductive heat transfer, improving ventilation and wearer cooling during exercise. These results align with earlier studies that fabric mass and thickness were correlated with thermal resistance and dominant factors influencing thermophysiological comfort [31], [6]. Therefore, sportswear with lower thermal resistance is suitable for warm weather.



**Fig. 1** Thermal resistance

### 3.2 Water Vapour Resistance

Water vapour resistance (Ret) reflects a fabric's ability to allow moisture vapour from sweat to pass through it. It measures a critical factor in maintaining skin dryness and evaporative cooling. Lower values indicate better moisture permeability, which enhances thermoregulation and overall comfort. The water vapour resistance results are shown in Figure 2. The PE fabric exhibited the lowest water vapour resistance, which is 0.44 m<sup>2</sup>Pa/W, showing the highest breathability among the four fabrics. IT, EY, and MM fabrics have higher water vapour resistance values, which are 1.55, 1.56, and 1.57 m<sup>2</sup>Pa/W, respectively, indicating lower breathability and less comfort compared to the PE fabric. PE fabric has low water vapour resistance because its open structure in a repeating grid pattern enhances moisture evaporation and airflow. This is supported by findings that polyester mesh fabrics exhibit the lowest water vapour resistance due to their high air permeability and open knit design, which enables efficient heat and moisture transfer, further enhancing thermophysiological comfort in sportswear [18], [32]. From a physiological comfort perspective, lower water vapour resistance indicates better breathability, enabling effective removal of moisture vapour from the skin. This reduces dampness and helps maintain body temperature stability during exercise in humid weather.

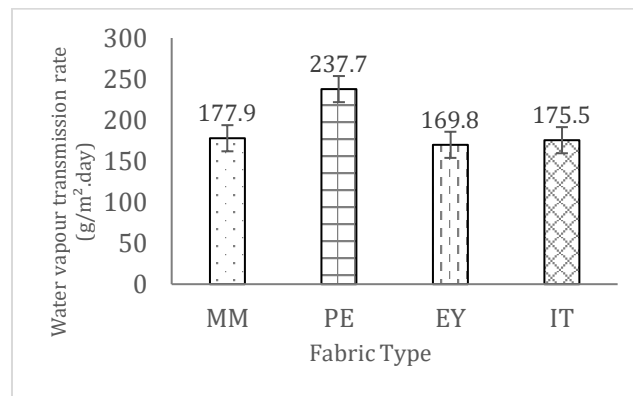


**Fig. 2** Water vapour resistance

### 3.3 Water Vapour Permeability

Water vapour permeability is the fabric's ability to allow moisture vapour to pass through it over time. Thinner fabrics generally have higher water vapour permeability, as the reduced thickness allows for easier passage of water vapour. The water vapour permeability results are shown in Figure 3. The PE fabric has the highest water vapour permeability at 237.7 g/m<sup>2</sup>. day, compared to the MM fabric, 177.9 g/m<sup>2</sup>. day, while the EY fabric has the lowest water vapour permeability, 169.8 g/m<sup>2</sup>. day. These results relate to fabric thickness, where PE fabric is the thinnest, 0.51 mm, and EY fabric is the thickest, 0.69 mm. Thinner fabrics offer a shorter diffusion path for water vapour molecules, thereby enhancing their permeability. This finding aligns with an earlier study, which observed that increased fabric thickness leads to higher water vapour resistance, confirming that thinner fabrics promote better breathability and moisture transfer [33]. Moreover, the open eyelet structure of PE fabric facilitates vapour passage, acting as channels for moisture migration. The higher water vapour permeability of the PE fabric can be attributed to its lower water vapour resistance, lower thickness, and lower thermal resistance compared to the other fabric. These fabric properties create a more permeable structure that allows for efficient water vapour transmission, resulting in the observed high water vapour permeability. These findings highlight that fabric structure, surface texture, and density, combined with low thickness, contribute directly to vapour permeability. The

superior performance of the PE fabric aligns well with its lower vapour resistance and thinner profile, making it the most effective fabric in facilitating evaporative cooling and promoting dryness during physical activity in tropical conditions.

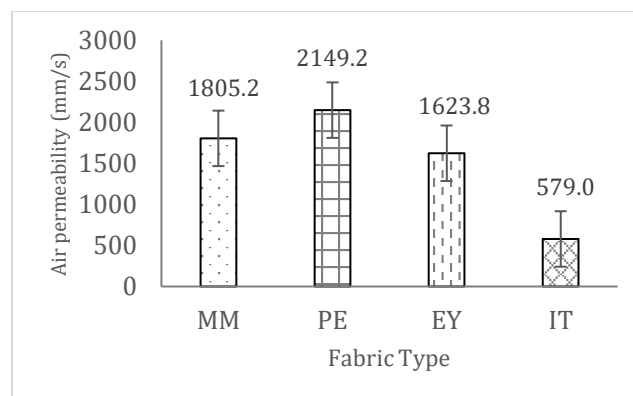


**Fig. 3** Water vapour permeability

### 3.4 Air Permeability

Air permeability is the rate of air flow passing perpendicularly through a known area under a prescribed air pressure differential between two material surfaces [34]. This property plays a critical role in enhancing ventilation, facilitating evaporative cooling, and reducing heat buildup, especially during high-intensity exercise in humid weather. Air permeability values of fabrics used in the study are compared in Figure 4. The PE fabric showed the highest air permeability at 2149.2 mm/s, indicating the highest breathability and airflow. This can be attributed to its open polar eyelet knit structures, which include large, regularly spaced holes that enable air flow. This is supported by findings that open mesh structures significantly improve air permeability and reduce thermal retention in the main sweat-prone area, enhancing ventilation in sportswear [35]. The MM fabric shows the second-highest level of air permeability, measuring at 1805.2 mm/s. Then, followed by the EY fabric at 1623.8 mm/s. The IT fabric has the lowest air permeability at 579 mm/s due to its dense interlock knit structure, which has no visible openings or mesh features, resulting in a compact surface that restricts air flow. This observation is in agreement with the previous research showing that interlock knits exhibit lower air permeability than jersey structures, owing to their compact structure that reduces airflow [36].

Fabrics with greater air permeability, such as PE and MM fabric, also demonstrate higher water vapour permeability, indicating superior breathability and moisture transfer. The correlation between air permeability and water vapour resistance is apparent, since the PE fabric exhibits the lowest water vapour resistance and the maximum air permeability. Fabrics that are thinner and have lower thermal resistance generally show higher air permeability, enabling improved heat and air transfer. The PE fabric with a higher air permeability of 2149.2 mm/s is the optimal choice for sportswear applications that require outstanding breathability and air circulation. The MM and EY fabrics demonstrate moderate air permeability values, consistent with their intermediate structure and smaller eyelet configurations. These findings confirm that fabric structure is the main factor influencing air permeability. For sportswear designed for tropical climates, higher air permeability as seen in the PE fabric, is suitable because it supports heat dissipation and improved wearer comfort during prolonged physical activity.



**Fig. 4** Air permeability

### 3.5 Moisture Management

Moisture management is a main factor in determining thermophysiological comfort in active sportswear, as it reflects the fabric's ability to absorb, transfer, and dry liquid sweat from the skin. Moisture management properties indicate that moisture is transported to the outer surface in the shortest possible time [37]. Six parameters were assessed: wetting time, absorption rate, maximum wetted radius, spreading speed, accumulative one-way transport index (AOTI), and overall moisture management capability (OMMC), as shown in Table 5. The PE fabric recorded the fastest wetting time with 2.92 seconds on the top surface and 2.96 seconds on the bottom surface, categorized as very fast, followed by the MM fabric, with 3.78 seconds on the top surface and 3.56 seconds on the bottom surface, within the fast category. The EY and IT fabrics exhibited a slower wetting time, ranging from 5.43 to 9.34 seconds, classified as a medium wetting time. In terms of absorption rate, all fabrics demonstrated slow to medium moisture absorption. The MM fabric recorded the highest absorption rate on the top surface (21.87%/sec), while the EY fabric performed best at the bottom surface (39.01%/sec). This suggests that the MM fabric absorbs moisture quickly upon contact, while the EY retains more moisture on the outer side. The IT fabric had the lowest absorption rate overall.

Maximum wetted radius measures the horizontal moisture spread on the fabric surface. PE fabric showed the widest spread (22 mm top, 25 mm bottom). The EY fabric showed the smallest wetted radius with 16 mm on both surfaces. MM and IT fabrics showed a moderate spreading behaviour. PE fabric showed the fastest spreading speed on the top (4.77 mm/s) and bottom (5.16 mm/s) surfaces, which supports its ability to disperse moisture quickly. The EY fabric had the slowest spreading speeds across both fabric surfaces (2.25 mm/s top, 2.48 mm/s bottom), which may result in longer drying times. MM and IT fabrics showed moderate spreading speeds, with EY fabric being slightly slower on the top surface, indicating potential wet clinginess during wear. AOTI showed differences among fabrics. Higher AOTI values show better moisture movement from the skin-facing surface to the outer layer, where the IT fabric recorded the highest AOTI value (584.92%), rated as "excellent", showing superior directional moisture transfer from the inner to outer surfaces. EY fabric also performed strongly (417.43%), while MM (247.78%) and PE (155.31%) fabrics had lower but acceptable directional transfer. This shows that the IT fabric is the most effective in transferring sweat outward, while the PE fabric retains more moisture near the inner surface. In OMMC, IT fabric showed the best performance (0.75), followed by EY fabric (0.70), both falling within the "very good" range. MM fabric (0.62) was also rated "very good," while PE fabric (0.56) was categorized as "good." All fabrics were graded within the "good" and "very good" categories for moisture performance. Overall, IT fabric offered the most balanced and efficient performance in terms of wicking, spreading, and transferring moisture, making it suitable for sportswear.

**Table 5** Moisture management data

Index		MM	PE	EY	IT
Wetting time (sec)	Top	3.78	2.92	5.43	9.34
		Fast	Very fast	Medium	Medium
	Bottom	3.56	2.96	5.71	2.73
		Fast	Very fast	Medium	Very fast
Absorption rate (%/sec)	Top	21.87	21.54	18.53	15.72
		Slow	Slow	Slow	Slow
	Bottom	38.64	37.80	39.01	33.09
		Medium	Medium	Medium	Medium
Max wetted radius (mm)	Top	19	22	16	19
		Large	Large	Medium	Large
	Bottom	19	25	16	19
		Large	Very large	Medium	Large
Spreading speed (mm/sec)	Top	3.65	4.77	2.25	2.68
		Fast	Very fast	Medium	Medium
	Bottom	3.83	5.16	2.48	3.40
		Fast	Very fast	Medium	Fast
Accumulative one-way transport index (AOTI) (%)		247.78	155.31	417.43	584.92
		Very good	Good	Excellent	Excellent
Overall Moisture Management Capability (OMMC)		0.62	0.56	0.70	0.75
		Very good	Good	Very good	Very good

### 3.6 Effect of Thermophysiological Comfort Properties of Sportswear Fabrics Using One-Way ANOVA and Tukey HSD Analysis

A one-way ANOVA at a 95% confidence level was conducted to evaluate differences in the thermophysiological properties of sportswear fabrics. A p-value of less than 0.05 was considered statistically significant. The results summarised in Table 6 - 8, indicate significant differences among fabric types for key performance characteristics, including thickness ( $F = 23.636$ ,  $p < 0.001$ ), mass per unit area ( $F = 56.240$ ,  $p < 0.001$ ), thermal resistance ( $F = 157.909$ ,  $p < 0.001$ ), water vapour resistance ( $F = 112.028$ ,  $p < 0.001$ ), water vapour permeability ( $F = 10.059$ ,  $p < 0.001$ ), and air permeability ( $F = 794.398$ ,  $p < 0.001$ ). One-way ANOVA results for the moisture management properties (Table 8) showed significant differences in maximum wetted radius (top:  $F = 3.429$ ,  $p = 0.043$ ; bottom:  $F = 10.364$ ,  $p < 0.001$ ), spreading speed (top:  $F = 6.215$ ,  $p = 0.005$ ; bottom:  $F = 9.672$ ,  $p = 0.001$ ), accumulative one-way transport index (AOTI:  $F = 76.371$ ,  $p < 0.001$ ), and overall moisture management capability (OMMC:  $F = 32.336$ ,  $p < 0.001$ ). No significant differences were observed in wetting time (top:  $F = 2.250$ ,  $p = 0.122$ ; bottom:  $F = 1.943$ ,  $p = 0.163$ ) and absorption rate (top:  $F = 1.159$ ,  $p = 0.356$ ; bottom:  $F = 1.994$ ,  $p = 0.156$ ), suggesting that all fabrics absorbed moisture at comparable rates. Overall, these results confirm that fabric type significantly influences certain aspects of moisture behaviour and thermophysiological performance, requiring further post-hoc testing to identify specific group differences.

**Table 6** One-way ANOVA of fabric physical properties

Fabric properties	Source of variation	df	Mean Square	F	Sig.
Mass per unit area	Between Groups	3	755.835	56.240	0.000
	Within Groups	16	13.440		
	Total	19			
Thickness	Between Groups	3	0.072	23.636	0.000
	Within Groups	36	0.003		
	Total	39			

**Table 7** One-way ANOVA of thermophysiological properties

Fabric properties	Source of variation	df	Mean Square	F	Sig.
Thermal resistance	Between Groups	3	0.000	157.909	0.000
	Within Groups	16	0.000		
	Total	19			
Water vapour resistance	Between Groups	3	1.569	112.028	0.000
	Within Groups	16	0.014		
	Total	19			
Water vapour permeability	Between Groups	3	5071.729	10.059	0.001
	Within Groups	16	504.176		
	Total	19			
Air permeability	Between Groups	3	2286736.798	794.398	0.000
	Within Groups	16	2878.578		
	Total	19			

**Table 8** One-way ANOVA of moisture management properties

Fabric properties	Source of variation	df	Mean Square	F	Sig.
Wetting time (top surface)	Between Groups	3	40.501	2.250	0.122
	Within Groups	16	17.998		
	Total	19			
Wetting time (bottom surface)	Between Groups	3	9.229	1.943	0.163
	Within Groups	16	4.749		
	Total	19			
Absorption rate (top surface)	Between Groups	3	41.578	1.159	0.356
	Within Groups	16	35.868		

Fabric properties	Source of variation	df	Mean Square	F	Sig.
Absorption rate (bottom surface)	Total	19			
	Between Groups	3	37.701	1.994	0.156
	Within Groups	16	18.910		
Maximum wetted radius (top surface)	Total	19			
	Between Groups	3	30.000	3.429	0.043
	Within Groups	16	8.750		
Maximum wetted radius (bottom surface)	Total	19			
	Between Groups	3	71.250	10.364	0.000
	Within Groups	16	6.875		
Spreading speed (top surface)	Total	19			
	Between Groups	3	6.288	6.215	0.005
	Within Groups	16	1.012		
Spreading speed (bottom surface)	Total	19			
	Between Groups	3	6.214	9.672	0.001
	Within Groups	16	0.643		
Accumulative one-way transport index (AOTI)	Total	19			
	Between Groups	3	180131.082	76.371	0.000
	Within Groups	16	2358.642		
Overall Moisture Management Capability (OMMC)	Total	19			
	Between Groups	3	0.038	32.336	0.000
	Within Groups	16	0.001		

Tukey's Honest Significant Difference (HSD) test was used to find the pairwise comparisons of mean fabric thickness and mass per unit area across four types of sportswear fabric. Table 9 shows Tukey's analysis of the fabric's physical properties, and Table 10 shows Tukey's HSD pairwise comparisons of the thermophysiological properties. Non-significant results are omitted for clarity and conciseness. The MM fabric has a significantly lower mass per unit area than the PE, EY, and IT fabrics (all  $p < 0.001$ ). For thickness, the MM fabric was significantly thicker than the PE fabric by 0.07 mm ( $p = 0.028$ ), but thinner than the EY fabric by 0.11 mm ( $p < 0.001$ ). Tukey HSD post-hoc analysis (Table 10) showed a significant difference in thermal resistance between MM and PE fabrics (mean diff = 0.0045,  $p = 0.000$ ), as well as between EY and IT (mean diff = 0.058,  $p = 0.000$ ). For water vapour resistance, significant differences were found between PE and all other fabrics. The difference between PE and MM fabric is significantly lower (mean diff = 1.1326,  $p = 0.000$ ), further showing PE fabric as the superior performance in water vapour resistance properties. The difference in water vapour permeability of PE fabric was significantly higher than both EY (mean diff = 67.90,  $p = 0.001$ ) and IT (mean diff = 62.26,  $p = 0.002$ ) fabrics, emphasizing the advantage of the PE's design in enabling moisture transmission. The difference between MM and PE fabric was also statistically significant (mean diff = 59.86,  $p = 0.003$ ). Further analysis of air permeability confirmed significant differences between all fabric types, with all pairwise comparisons of p-values  $< 0.001$ , highlighting variations in breathability among fabric types.

**Table 9** Tukey HSD pairwise comparisons of fabric physical properties

Dependent Variable	Fabric Comparison		Mean Difference	Sig.
Mass per unit area	MM	PE	-23.22*	0.000
		EY	-27.14*	0.000
		IT	-22.34*	0.000
	PE	MM	23.22*	0.000
		MM	27.14*	0.000
		MM	22.34*	0.000
Thickness	MM	PE	0.07*	0.028
		EY	-0.11*	0.000
	PE	MM	-0.07*	0.028
		EY	-0.19*	0.000
	EY	MM	0.11*	0.000
		PE	0.19*	0.000
		IT	0.17*	0.000
	IT	EY	-0.17*	0.000

\*The mean difference is significant at the 0.05 level.

**Table 10** Tukey HSD pairwise comparisons of thermophysiological properties

Dependent Variable	Fabric Comparison		Mean Difference	Sig.	
Thermal resistance	MM	PE	0.0045*	0.000	
		IT	0.0053*	0.000	
	PE	MM	-0.0045*	0.000	
		EY	-0.0050*	0.000	
	EY	PE	0.0050*	0.000	
		IT	0.0058*	0.000	
	IT	MM	-0.0053*	0.000	
		EY	-0.0058*	0.000	
	Water vapour resistance	MM	PE	1.1326*	0.000
			MM	-1.1326*	0.000
EY			-1.1182*	0.000	
EY		PE	1.1182*	0.000	
		IT	1.1095*	0.000	
		PE	1.1095*	0.000	
Water vapour permeability	MM	PE	-59.86*	0.003	
		MM	59.86*	0.003	
	PE	EY	67.90*	0.001	
		IT	62.26*	0.002	
	EY	PE	-67.90*	0.001	
		IT	-62.26*	0.002	
	Air permeability	MM	PE	-344.06*	0.000
			EY	181.34*	0.000
IT			1226.18*	0.000	
PE		MM	344.06*	0.000	
		EY	525.40*	0.000	
		IT	1570.24*	0.000	
EY		MM	-181.34*	0.000	
		PE	-525.40*	0.000	
		IT	MM	1044.84*	0.000

Dependent Variable	Fabric Comparison		Mean Difference	Sig.
	IT	MM	-1226.18*	0.000
		PE	-1570.24*	0.000
		EY	-1044.84*	0.000

\*The mean difference is significant at the 0.05 level.

Table 11 presents the Tukey HSD pairwise comparison of moisture management properties, which summarizes the properties that showed statistically significant differences ( $p < 0.05$ ); non-significant results are omitted for clarity and conciseness. For maximum wetted radius on the top surface, PE and EY fabric show a significant difference ( $p = 0.025$ ) and a mean difference of 6 mm. Other comparisons were not significant. For the bottom surface, PE fabric had a significantly larger maximum wetted radius (25 mm) compared to MM, EY, and IT fabric ( $p \leq 0.011$ ). This is likely due to the open structures, which allow moisture to spread quickly. This result is aligned with the findings of Sampath et al., who reported that open-knit structures like single jersey facilitate rapid moisture absorption and spreading speed [38]. In contrast, no significant differences were found among MM, EY, and IT fabrics, suggesting similar moisture spreading behaviour between those fabrics. For spreading speed, PE fabric spreads moisture significantly faster than EY and IT fabrics on top and bottom surfaces ( $p < 0.05$ ). There is no significant difference between MM, EY, and IT fabric. PE fabric has a very fast ability to disperse moisture quickly across its surface, which may contribute to better drying and comfort, consistent with Bedek et al., who reported that a lower thickness of the fabric allows faster moisture transfer and drying [39].

The AOTI shows significant differences among all fabrics ( $p < 0.05$ ). IT fabric demonstrated the highest AOTI values, indicating superior moisture transport away from the skin, followed by EY, MM, and PE fabric. This highlights the IT fabric's effectiveness in directional moisture movement due to its higher fabric density, which helps move moisture in one direction. This is supported by previous studies, which found that higher fabric density improves AOTI and enhances directional moisture transport [40], [41]. The OMMC showed that the IT fabric has the highest rating (0.75), followed by the EY fabric (0.70), MM fabric (0.62), and PE fabric (0.56). The high OMMC value of the IT fabric may be due to its balanced capacity to absorb, spread, and transfer moisture effectively, aligning with the findings of Jamshaid et al. [42]. However, there is no significant difference between EY and IT fabric, suggesting a similar level of moisture management capabilities.

**Table 11** Tukey HSD pairwise comparisons of moisture management properties

Dependent Variable	Fabric Comparison		Mean Difference	Sig.
Maximum wetted radius (top surface)	PE	EY	6.00*	0.025
	EY	PE	-6.00*	0.025
Maximum wetted radius (bottom surface)	MM	PE	-6.00*	0.011
	PE	MM	6.00*	0.011
		EY	9.00*	0.000
		IT	6.00*	0.011
Spreading speed (top surface)	EY	PE	-9.00*	0.000
	IT	PE	-6.00*	0.011
	PE	EY	2.53*	0.005
		IT	2.09*	0.022
Spreading speed (bottom surface)	EY	PE	-2.53*	0.005
	IT	PE	-2.09*	0.022
	PE	EY	2.68*	0.000
		IT	1.76*	0.015
Accumulative one-way transport index (AOTI)	EY	PE	-2.68*	0.000
	IT	PE	-1.76*	0.015
	MM	PE	92.47*	0.037
		EY	-169.65*	0.000
		IT	-337.14*	0.000
	PE	MM	-92.47*	0.037
	EY	-262.12*	0.000	
	IT	-429.61*	0.000	
Overall Moisture Management Capability (OMMC)	EY	MM	169.65*	0.000
		PE	262.12*	0.000
		IT	-167.49*	0.000
	IT	MM	337.14*	0.000
		PE	429.61*	0.000
		EY	167.49*	0.000
	MM	EY	-0.08*	0.007
		IT	-0.14*	0.000
	PE	EY	-0.14*	0.000
		IT	-0.20*	0.000
	EY	MM	0.08*	0.007
		PE	0.14*	0.000
	IT	MM	0.14*	0.000
		PE	0.20*	0.000

\*The mean difference is significant at the 0.05 level.

#### 4. Conclusion

This study investigated the thermophysiological comfort properties of four commercially available 100% polyester microfibre fabrics used in football jerseys: mini mesh (MM), polar eyelet (PE), eyelet (EY), and interlock (IT) for hot and humid conditions. Key performance metrics included moisture management, thermal resistance, water vapour resistance, water vapour permeability, and air permeability. Among the fabrics, PE fabric consistently demonstrated superior performance in thermophysiological comfort properties, exhibiting the lowest thermal resistance, highest water vapour and air permeability, fastest wetting time, highest spreading speed, and largest wetted radius in moisture management properties. Statistical analysis confirmed significant differences among the fabrics, with fabric structure playing a critical role. Open knit designs, as seen in PE and MM fabrics, promoted rapid moisture and heat transfer, while denser knits like EY and IT fabrics supported more controlled and directional moisture transport. Based on these findings, PE fabric is most suitable for high-intensity activities and tropical climates due to its superior ability to facilitate evaporative cooling and maintain skin dryness. In contrast, IT

fabric with its excellent directional transport and balanced moisture management may be more appropriate for endurance sports where sustained dryness is prioritised. The findings offer valuable information for sportswear designers to optimise fabric selection based on specific climatic conditions and the demands of athletic activities. Future research should explore the effects of various fiber compositions, multilayer combinations, surface treatments, as well as user perception to further enhance fabric engineering for comfort-driven sportswear.

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## Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

## Author Contribution

*The authors confirm contribution to the paper as follows: **study conception and design:** Wan Syazehan Ruznan; **data collection:** Suraya Ahmad Suhaimi, Nurul Hidayah Abdul Aziz; **analysis and interpretation of results:** Suraya Ahmad Suhaimi, Wan Syazehan Ruznan, Raja Nurul Jannat Raja Hussain; **draft manuscript preparation:** Suraya Ahmad Suhaimi, Wan Syazehan Ruznan, Mohd Rozi Ahmad, Mohd Azlin Mohd Nor, Nor Ikhmar Madarsa. All authors reviewed the results and approved the final version of the manuscript.*

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