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Thermophysiological Insights Into Madaline®-Based Multilayer Textiles For Medical Protection

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ABSTRACT

Healthcare workers often experience thermal discomfort when using multilayer protective clothing, as barrier protection is often prioritized over comfort. This study evaluated a Madaline®-based multilayer textile system developed for medical applications, consisting of an outer Madaline® layer, two polyurethane membranes, and a quilted Nomex® Comfort liner. Results showed that adding membranes increased thermal resistance, with Membrane B performing slightly better than Membrane A. The inclusion of the quilted liner further enhanced insulation (65.43 mK·m²/W) but reduced vapour permeability (≈21–23%) and increased RET (14.2–15.8 Pa·m²/W), placing both three-layer systems in the moderate comfort range. The Membrane B + liner assembly is more suitable for high-risk environments requiring maximum protection, while the Membrane A + liner offers a better balance of comfort and safety for moderate-risk or extended-wear conditions.

Tıbbi Koruyucu Giysilerde Kullanılan Madaline® Tabanlı Çok Katmanlı Tekstillerin Termofizyolojik Analizi

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Sorumlu Yazar

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Anahtar Kelimeler

Madaline® kumaş
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Tıbbi koruyucu giysi
Termofizyolojik konfor
Su buharı direnci (RET)

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ÖZ

Sağlık çalışanları, çok katmanlı koruyucu giysiler kullanırken, genellikle koruyucu bariyer performansının konforun önünde tutulması nedeniyle termal rahatsızlık yaşamaktadır. Bu çalışma, tıbbi uygulamalar için geliştirilen, dış Madaline® katmanı, iki poliüretan membran ve kapitone Nomex® Comfort astardan oluşan çok katmanlı bir tekstil sistemini değerlendirmiştir. Bulgular, membran eklemenin termal direnci artırdığını ve Membran B'nin Membran A'ya göre biraz daha iyi performans gösterdiğini ortaya koymuştur. Kapitone astarın dahil edilmesi, yalıtımı daha da artırmış (65.43 mK·m²/W), ancak su buharı geçirgenliğini azaltmış (≈%21–23) ve RET değerini yükseltmiştir (14.2–15.8 Pa·m²/W). Bu durum, her iki üç katmanlı sistemi de orta konfor kategorisine yerleştirmiştir. Membran B + astar kombinasyonu, maksimum koruma gerektiren yüksek riskli ortamlar için daha uygunken, Membran A + astar kombinasyonu orta riskli veya uzun süreli kullanım koşullarında konfor ve güvenlik arasında daha iyi bir denge sağlamaktadır.

1. INTRODUCTION

Healthcare professionals frequently operate in thermally challenging environments where physiological comfort, moisture management, and adequate protection against biological hazards are essential for sustaining performance, safety, and well-being. Work in healthcare settings, such as wards, operating rooms, or emergency environments, often requires wearing multilayered clothing systems that prioritize barrier protection over thermal comfort, leading to increased thermal strain and discomfort [1-3]. Such discomfort has been shown to reduce perceived work performance, impair concentration, and increase the risk of heat-related illnesses, particularly under conditions of high physical activity or limited environmental control [4-8].

Protective medical clothing is designed primarily to act as a barrier against pathogens and hazardous fluids; however, these protective properties frequently come at the expense of breathability and moisture vapor permeability [9]. Previous research has shown that surgical gowns, scrub suits, and cleanroom apparel differ considerably in their thermal insulation and evaporative resistance values, directly affecting thermophysiological responses and subjective comfort of the wearer [10-13]. Studies have emphasized the necessity of balancing thermal insulation with vapor transmission to prevent excessive heat and moisture accumulation within the clothing microclimate. Inadequate moisture management can increase skin wetness and perceived clamminess, which in turn accelerates heat strain and impairs comfort [9-10].

A growing body of empirical work has evaluated thermal comfort of healthcare workers across diverse environments and garment systems. For example, Wang et al. demonstrated that medical protective clothing in hot and humid conditions significantly elevates skin temperature, sweat accumulation, and cardiovascular strain, particularly during high-intensity tasks [14]. Abreu, et al. compared the thermo-physiological behavior of single-use scrub suits and demonstrated significant differences in thermal insulation, highlighting how ensemble design directly affects comfort [15]. Derks et al. showed that staff in hospital wards often report “slightly warm” sensations that lower work performance [1], while Khodakarami & Knight found that measured thermal comfort conditions in Iranian hospitals were often unacceptable compared with international standards [16].

Recent research highlights the growing importance of advanced textile solutions for managing thermal comfort in protective and functional clothing. Studies on personal thermal management garments show that localized cooling strategies and adaptive garment designs can effectively address body-specific comfort needs, improving both physiological stability and wearer perception [17]. Similarly, investigations into cold intolerance emphasize how innovative textile engineering and multilayer constructions enhance heat retention and user comfort in challenging conditions [18]. Research focused on high-thermal comfort wearables for sports underscores the relevance of material selection, coatings, and system-level textile design in enhancing breathability and heat dissipation [19]. Within medical contexts, pilot studies assessing disposable protective clothing confirm that safe working durations are limited by physiological heat strain, highlighting the need for improved thermal management in such garments [20]. Experimental investigations have also demonstrated that personal protective equipment substantially elevates heat stress in hot environments, affecting both physiological responses and subjective comfort [21]. To address these challenges, targeted interventions such as water-absorbing resins and condensation–dehumidification technologies have been proposed, showing measurable reductions in heat burden and discomfort [22]. Finally, recent reviews synthesize advances in thermoregulatory clothing, noting that dual-mode and responsive textile architectures offer promising pathways toward integrating protection with enhanced comfort [23]. These studies demonstrate that innovation in textile engineering from sportswear applications to medical protective clothing provides essential strategies for achieving both thermal comfort and protective functionality in healthcare and other high-intensity settings.

Recent reviews emphasize that advances in nanomaterials, phase-change composites, and multilayer textile architectures can significantly enhance thermoregulation without compromising protective performance [24]. Similarly, research on smart clothing systems has demonstrated how responsive fabric technologies can actively support personal thermal management, offering potential applications in healthcare apparel

[25]. Hygroscopic and adaptive fibers can play a key role in buffering rapid changes in humidity and temperature, thereby improving thermophysiological comfort during and after activity. For instance, Peng et al. introduced an integrated cooling (i-Cool) textile that combines heat conduction and sweat transportation, significantly enhancing perspiration management and thermal comfort [26]. Similarly, Chai et al. demonstrated that thermoregulatory clothing incorporating temperature-adaptive, multimodal body heat regulation can dynamically adjust to thermal loads, reducing heat stress while maintaining comfort [27]. Together, these studies confirm that advanced fiber engineering and textile architectures provide promising strategies to balance moisture management, thermal regulation, and comfort in protective clothing systems.

Phase-change inserts and active cooling systems, such as ice vests and forced-air devices, have also demonstrated effectiveness in reducing heat strain for healthcare personnel [28]. Experimental results demonstrate that integrating phase-change cold storage into protective apparel leads to marked improvements in both physiological and perceptual comfort [29]. Beyond garment engineering, several field investigations have highlighted how contextual factors, such as hospital ventilation systems, ward zoning, and local climate, affect comfort. For instance, Udom found that healthcare workers in remote hot-arid clinics often faced conditions outside comfort limits, showing the need for climate-specific comfort standards [30]. Likewise, indoor studies in Iran [31] revealed that standard PMV (Predicted Mean Vote)-based indices often underestimate discomfort in hospital environments due to clothing and activity-specific effects. These finding highlights the importance of integrating both environmental and clothing parameters into comfort evaluation.

Given these complexities, standardized and quantitative evaluation methods are essential. Tools such as the sweating guarded hot plate [ISO 11092] and thermal manikins [ASTM F1291, F2370] have been widely applied to measure thermal resistance (Rct), evaporative resistance (Ret), and permeability index across single and multilayer systems [32-33]. Studies using thermal manikins to assess surgical gowns, scrub suits, and protective ensembles [28,32] provide objective metrics that, when combined with wearer trials, yield valuable insights into how fabric density, membrane type, and air layer thickness influence thermal and moisture transfer.

In light of these considerations, the present study focuses on the development and evaluation of a Madaline®-based multilayer textile system specifically designed for medical protective applications. The system integrates an outer Madaline® fabric with inherent liquid repellency, two types of polyurethane membranes with different densities, and a quilted Nomex® thermal liner. This configuration was selected to optimize the trade-off between thermal comfort and protective performance by enhancing moisture vapor transmission, regulating heat flow, and ensuring effective liquid barrier protection. By systematically assessing thermophysiological parameters such as thermal conductivity, resistance, and water vapor permeability, this study aims to provide new insights into how Madaline®-based multilayer assemblies can inform future standards for healthcare garment design and improve occupational comfort for medical personnel working under demanding conditions. While previous studies have explored thermal comfort and barrier properties of protective clothing in general, this work uniquely investigates the combined performance of Madaline® fabric with polyurethane membranes and a Nomex® Comfort liner under standardized ISO 11092 testing. This integrated approach offers a novel perspective on optimizing both comfort and protection in medical apparel.

2. MATERIALS AND METHODS

2.1. Materials

In this study, a multilayer textile system was developed to ensure user comfort, moisture regulation, and protection against biological fluids. The system consists of three distinct layers: a functional outer protective layer, a middle membrane layer for moisture management, and an inner quilted layer for thermal insulation.

Table 1 summarizes the detailed characteristics of the multilayer textile system components used in this study, including key parameters such as material type, basis weight, thickness, and the functional role of each layer. Figure 1 provides a visual representation of the multilayer textile system components, showing the arrangement of the layers within the system.

Outer Layer (Functional Protective Layer):

The outermost fabric used was Madaline®, a nonwoven microfiber textile provided by Mogul Nonwoven, composed of 70% polyester (PET) and 30% polyamide 6 (PA6), with a basis weight of 130 g/m². Produced using bi-component spunbond technology, this fabric combines softness, strength, and high dimensional stability. It was treated to be blood- and alcohol-repellent, making it well-suited for use in protective clothing intended for medical or hazardous settings.

Madaline® has a dense microfilament structure, which provides effective barrier and filtration properties while remaining breathable and quick-drying. It also shows good moisture management, thermal insulation, and wind resistance. In addition, its fabric-like handling characteristics allow for standard textile processes such as dyeing, cutting, and sewing, making it versatile for garment manufacturing.

Middle Layer (Moisture Management):

To promote moisture vapor transfer and improve overall physiological comfort, two types of polyurethane (PU) membranes were utilized in separate configurations. Membrane A is polyurethane membrane with a basis weight of 145 g/m², offering enhanced flexibility and improved moisture permeability. Membrane B is polyurethane membrane with a basis weight of 859 g/m², providing a more robust barrier effect and structural support.

These membranes were placed between the outer and inner layers in various combinations to assess their influence on comfort, moisture transport, and garment breathability.

Inner Layer (Thermal Insulation):

The innermost layer consisted of a two-layer nonwoven structure (55 g/m² + 55 g/m²) quilted to a Nomex® Comfort fabric, forming the inner lining of the system. This multilayer configuration was selected to provide thermal insulation, flame resistance, and wearer comfort. Nomex® Comfort offers inherent heat and flame protection while maintaining breathability and a soft textile feel, which enhances user comfort during extended wear. The quilted construction improves air permeability, contributes to thermal regulation, and ensures mechanical stability, making the layer suitable for high-performance protective garments.

Table 1. Characteristics of the multilayer textile system components

	Fabric type	**Basis weight (g/m^2)**	**Thickness (mm)**	**Function**
Outer layer	*Madaline*® fabric (70% PET/ 30% PA6, bi-component spunbond nonwoven)	130	0.51 (± 0.02)	Blood and alcohol repellent barrier; primary defense against biological fluids and contaminants
Membrane A	Polyurethane (PU) lightweight membrane	145	0.31 (± 0.004)	Enhances moisture vapor permeability
Membrane B	Polyurethane (PU) dense membrane	859	0.48 (± 0.004)	Enhances moisture vapor permeability
Thermal liner	Two-layer nonwoven structure quilted to Nomex® Comfort	55+ 55	1.73 (± 0.05)	Provides thermal insulation, flame resistance, and wearer comfort

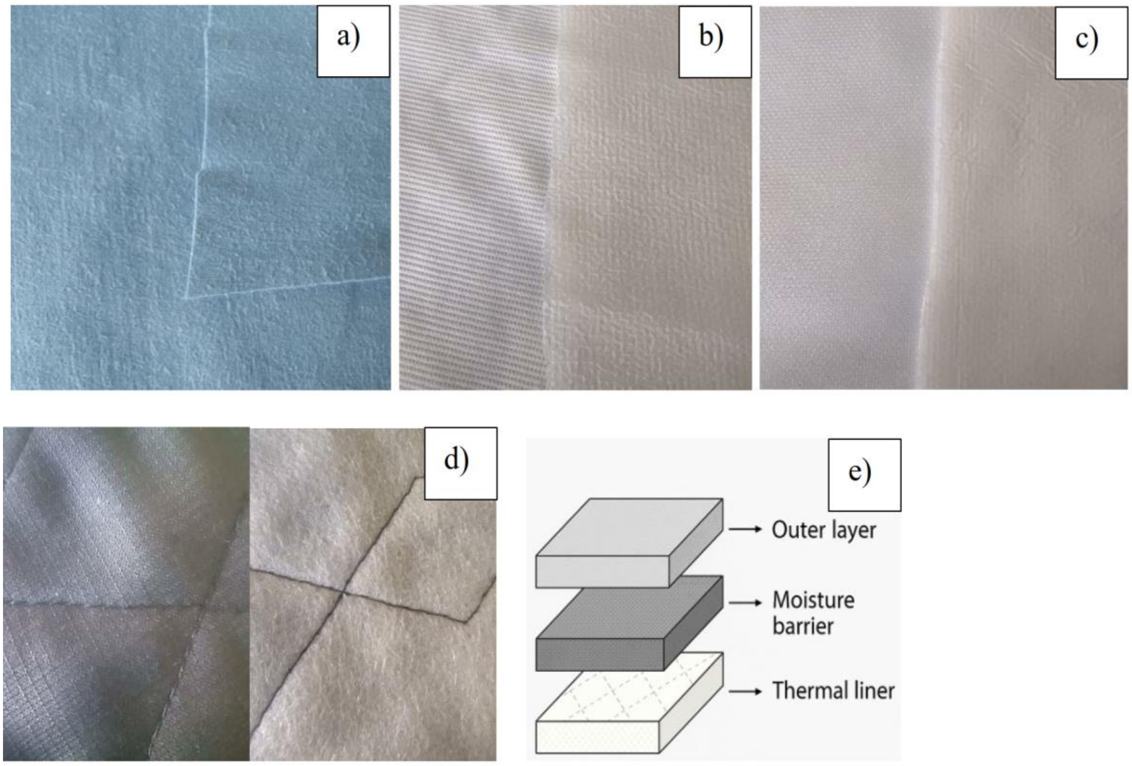

Figure 1. Visual representation of the multilayer textile components used in the study: Face and back surfaces of a) Outer layer (b) Membrane A (c) Membrane B (d)Thermal liner, and e) Placement/stacking sequence of layers

2.2. Method

The thermal properties of the fabric samples and their multilayer assemblies were evaluated in accordance with the ISO 11092 standard [34], which specifies the determination of thermal conductivity (λ), thermal absorptivity (b), thermal diffusivity (a), and thermal resistance (r).

The Alambeta instrument (Sensora, Czech Republic) was employed to precisely assess thermal characteristics, while the Permetest device (Sensora, Czech Republic) was used to measure water vapour permeability and evaporative resistance (RET), simulating skin perspiration under steady-state conditions. These evaluations provided key thermophysiological parameters essential for understanding the performance of different textile configurations. The calculations were based on standardized formulas and widely reported methodologies in the literature [35], ensuring reliable and consistent results across all fabric systems tested.

3. RESULTS AND DISCUSSION

3.1. Evaluation of Thermal Properties

The results of the thermal performance measurements are presented in Table 2, which summarizes the thermal conductivity, diffusivity, absorption, resistance, thickness, and maximum heat flux values for each fabric configuration. All measurements were conducted in accordance with related standard and average values are accompanied by standard deviations to reflect measurement repeatability and material uniformity. In addition, Figure 2 specifically illustrates the thermal conductivity and thermal resistance values for the same fabric configurations, offering a complementary graphical representation of these two key parameters.

Table 2. Thermal performance parameters of the fabric combinations, Including thermal conductivity (La), Thermal diffusion (a), Thermal absorption (b), Thermal resistance (r), Thickness (h), and Maximum heat flux (q_{max}) values measured for each sample configuration

Sample group	La (mW/m.K)	a (mm²/s)	b (W.s$^{1/2}$/m².K)	r (mK.m²/W)	h (mm)	q_{max} (W/m²)
Outer layer	34.4 ± 1.21	0.05± 0.02	154.50± 22.16	14.77± 0.21	0.51± 0.02	674.53± 34.39
Membrane A	33.63± 1.88	0.053± 0.02	150.46± 19.8	9.4± 0.43	0.31 ± 0.004	810.1 ± 4.05
Membrane B	40.53± 1.16	0.048± 0.02	191.4± 33.4	11.9± 0.25	0.48 ± 0.004	790.6 ± 52.3
Thermal layer	34.7± 2.76	0.128 ±0.008	97.1 ± 5.83	50.03 ± 5.6	1.73 ± 0.05	489.4 ± 8.07
Outer layer + Membane A	41.03 ± 1.06	0.08± 0.06	131.67± 21.97	21.40± 0.70	0.87± 0.02	663.93± 50.86
Outer layer + Membrane A + Thermal layer	41.47± 0.98	0.12± 0.01	122.33± 4.60	61.33± 1.29	2.54± 0.05	618.07± 15.45
Outer layer + Membane B	44.93± 0.91	0.10± 0.02	140.77± 9.73	23.07± 0.50	1.04± 0.004	689.77± 22.34
Outer layer + Membrane B + Thermal layer	42.6 ± 0.52	0.11± 0.01	129.63± 4.45	65.43± 0.81	2.79± 0.02	647.80± 52.48

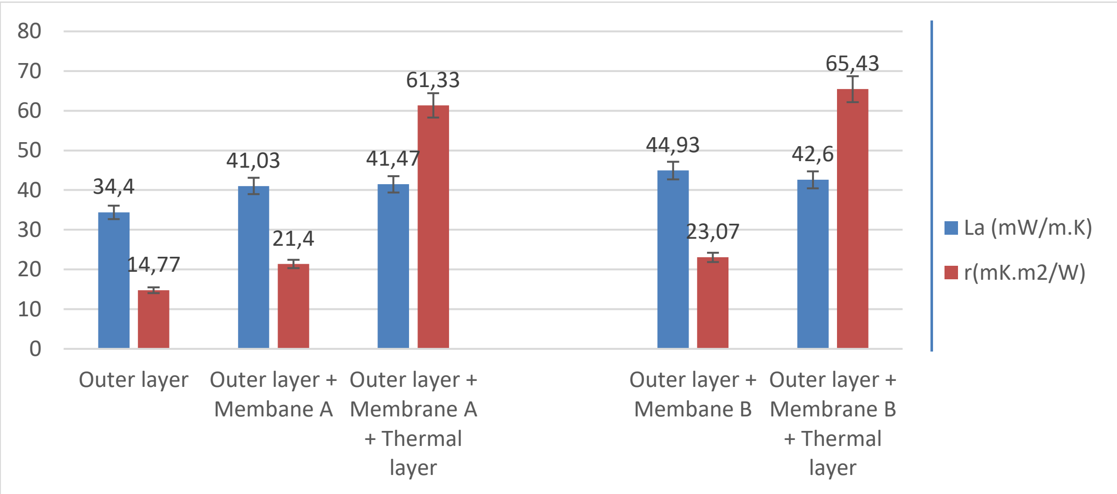

Figure 2. Thermal conductivity and thermal resistance of the fabric combinations

The outer layer alone, with the lowest basis weight of 130 g/m², exhibited the lowest thermal conductivity (34.4 ± 1.21 mW/m·K), which is expected for a single textile layer without any additional insulating or structural components. This result reflects the relatively simple construction of the fabric, which limits its ability to conduct heat and provides only a basic barrier to thermal transfer. When Membrane A (145 g/m²) was added, the thermal conductivity increased to 41.03 ± 1.06 mW/m·K. Despite being only slightly heavier than the outer layer, its denser polymer matrix offers more continuous pathways for heat transfer, increasing conduction. However, when the thermal liner (110 g/m²) was incorporated alongside Membrane A, the conductivity value (41.47 ± 0.98 mW/m·K) remained almost the same as the membrane-only configuration. The liner's quilted structure traps air within its layers, reducing heat transfer and compensating for the increase caused by the membrane [36]. This balance shows how lower-density, air-trapping components like the liner counteract the conductive effects of slightly denser materials, maintaining stability in overall conductivity [37,38].

The highest thermal conductivity was measured in the outer + Membrane B configuration (44.93 ± 0.91 mW/m·K**)** which can be attributed to the high density (859 g/m²) and compact microstructure of Membrane

B, facilitating more efficient heat conduction compared to other membrane type [39]. In contrast, the outer + Membrane B + thermal liner assembly exhibited a slightly lower conductivity (42.6 ± 0.52 mW/m·K**).** This reduction is likely due to the insulating effect of the quilted Nomex® thermal liner, which introduces additional air gaps and reduces the direct conductive pathways present in the membrane-only configuration [40]. The layered construction of the liner, combined with its inherent low thermal conductivity, counteracts some of the conduction-enhancing effects of Membrane B, resulting in an overall decrease in measured conductivity [41].

Thermal diffusivity, a key measure of how quickly a material responds to temperature changes [42], was found to be 0.05 ± 0.02 mm^2/s for the outer layer and ranged between 0.08 and 0.12 mm^2/s in the layered assemblies, exhibiting relatively low variation across samples. These values are consistent with typical textile diffusivity ranges and indicate that the materials respond at a stable and controlled rate when exposed to temperature fluctuations. The small standard deviations further suggest excellent repeatability and uniformity in sample structure. The diffusivity trend aligns with material density: denser layers like Membrane B react slightly faster to temperature changes due to their continuous, compact structure, while lighter layers provide more buffering effects.

Thermal absorption (b), also known as thermal absorptivity, represents a material's ability to absorb heat, especially in the initial contact phase, and is often associated with the feeling of immediate warmth or coolness upon touch. In our measurements, the outer layer alone exhibited the highest thermal absorption (154.50 ± 22.16 $W{\cdot}s^{1/2}/m^2{\cdot}K$), which then decreased with the addition of layers. Incorporating Membrane A reduced absorption to 131.67 $W{\cdot}s^{1/2}/m^2{\cdot}K$, and the further addition of the thermal liner brought it down to 122.33 $W{\cdot}s^{1/2}/m^2{\cdot}K$. A similar trend was observed with Membrane B combinations, where absorption dropped from 140.77 $W{\cdot}s^{1/2}/m^2{\cdot}K$ (outer + Membrane B) to 129.63 $W{\cdot}s^{1/2}/m^2{\cdot}K$ when the liner was added. This reduction is directly linked to the increasing total thickness and air entrapment in the lower-density quilted liner, which slows heat uptake and creates a warmer tactile sensation. This behavior is supported by the study reported by Sampath [43], which has demonstrated that fabrics with lower thermal absorptivity impart a warmer sensation upon contact due to slower heat uptake from the skin, typically seen in materials with thicker or more insulating structures.

For thermal absorption (b), the highest standard deviation was observed in the outer layer configuration **(**± 22.16 $W{\cdot}s^{1/2}/m^2{\cdot}K$**),** indicating greater variability in heat uptake due to the fabric's unprotected, single-layer structure. The addition of Membrane A slightly reduced the standard deviation to ± 21.97 $W{\cdot}s^{1/2}/m^2{\cdot}K$, while the inclusion of the thermal liner alongside Membrane A significantly lowered it to ± 4.60 $W{\cdot}s^{1/2}/m^2{\cdot}K$. On the other hand, adding Membrane B to the outer layer reduced the standard deviation to ± 9.73 $W{\cdot}s^{1/2}/m^2{\cdot}K$, and combining it with the thermal liner yielded the lowest deviation of all configurations **(**± 4.45 $W{\cdot}s^{1/2}/m^2{\cdot}K$). The substantial reduction in standard deviation when the thermal liner is incorporated can be attributed to its quilted, multi-layer structure, which increases measurement consistency by minimizing localized variations in heat absorption and reducing the influence of surface irregularities during testing [44].

Thermal resistance (r) increased progressively with material density. The outer layer (lightest, 130 g/m^2) had the lowest resistance (14.77 $mK{\cdot}m^2/W$). Adding Membrane A (145 g/m^2) raised resistance to 21.40 $mK{\cdot}m^2/W$, while incorporating the liner significantly increased it to 61.33 $mK{\cdot}m^2/W$. Membrane B's dense structure produced slightly higher resistance (23.07 $mK{\cdot}m^2/W$) than Membrane A. When the liner was added, the value peaked at 65.43 $mK{\cdot}m^2/W$. This demonstrates the strong insulating synergy between dense materials like Membrane B and lightweight, air-trapping layers like the liner, which together maximize insulation [45]

The maximum heat flux (q_{max}**)** values ranged from 618.07 W/m^2 to 689.77 W/m^2 across all configurations. For the outer layer**,** q_{max} was 674.53 W/m^2**,** decreasing to 663.93 W/m^2 with the addition of Membrane A, and further to 618.07 W/m^2 when the thermal liner was incorporated, reflecting a progressive reduction in heat transfer capacity as insulation layers were added. In contrast, combining the outer layer with Membrane B resulted in the highest q_{max} value of 689.77 W/m^2, slightly exceeding that of the outer + Membrane A combination. When the thermal liner was added to this configuration, q_{max} decreased to 647.80 W/m^2, but remained higher than the equivalent Membrane A+liner assembly. This trend aligns with previous findings showing that thermal resistance and maximum heat flux, while often inversely related, are not always directly proportional. Thermal resistance describes a material's overall ability to impede steady-state heat transfer over time, which improves with additional layers, trapped air, and low-conductivity components. In contrast, q_{max} represents the peak instantaneous heat transfer rate and is strongly influenced by surface density, intrinsic material conductivity, and contact characteristics. This occurs because q_{max} reflects the transient surface heat transfer upon contact, which depends heavily on surface density and thermal absorptivity, not just insulation [46,47]. Membrane B's dense and compact microstructure enhances barrier performance and increases thermal resistance but also provides more direct conductive pathways at the surface, resulting in higher peak heat transfer. The addition of the quilted Nomex® thermal liner mitigates this effect by introducing insulating air gaps and reducing both conductive and convective heat flow; however, the influence of Membrane B's higher intrinsic conductivity remains evident in the heat flux measurements.

3.2. Evaluation of Water Vapour Permeability & Water Vapour Resistance Properties

Figure 3 summarises the water vapour permeability and resistance (RET) values for each fabric configuration.

The results of the water vapour permeability and resistance (RET) measurements provide important insights into the balance between barrier protection and physiological comfort in multilayer textile systems. The outer layer alone exhibited the highest water vapour permeability (72.9%) and the lowest resistance to water vapour transfer (RET = 1.7 Pa·m²/W). According to the ISO 11092 classification of comfort ranges, values below 6 Pa·m²/W are considered to reflect *very good to excellent breathability* [34]. This confirms that the outer layer, with its relatively simple structure and absence of additional membranes or liners, provides minimal restriction to vapour transfer and is highly suitable for maintaining comfort during prolonged use.

Incorporating Membrane A reduced permeability to 44.4% and increased RET to 5.4 Pa·m²/W, reflecting the membrane's barrier effect, which restricts moisture diffusion through the fabric system. Nevertheless, its ability to maintain RET below 6 suggests that Membrane A still supports adequate moisture management while enhancing fluid protection. When the thermal liner was added alongside Membrane A, permeability further decreased to 21.2% and RET increased substantially to 15.8 Pa·m²/W. This classifies the assembly in the *satisfactory but limited comfort category (13–20)* [34]. The increase reflects the influence of the quilted Nomex® liner, which adds bulk, increases thickness, and introduces more tortuous diffusion paths for vapour. Consequently, although this configuration offers improved thermal insulation and protective performance, it significantly compromises breathability, which may elevate wearer discomfort during extended periods of activity.

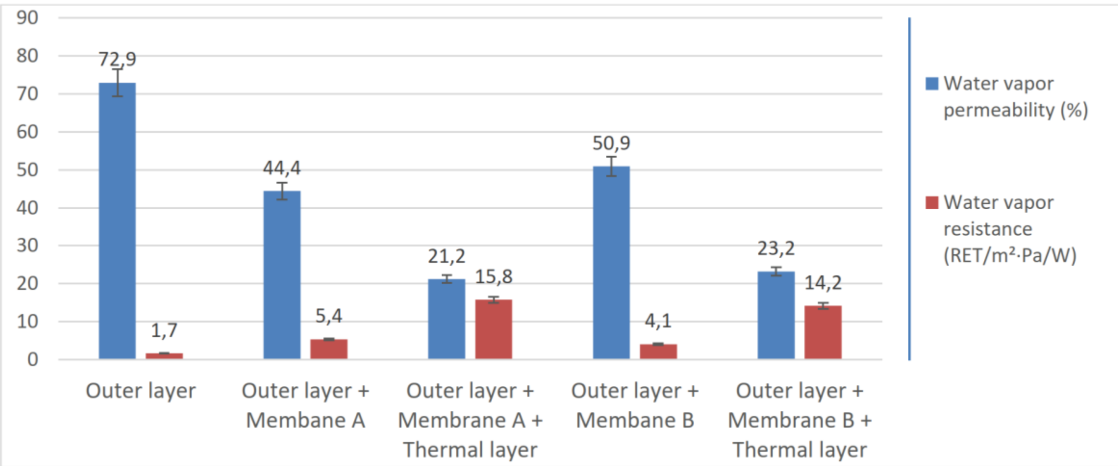

Figure 3. Water vapour permeability and resistance of the fabric combinations

The outer layer + Membrane B configuration demonstrated a water vapour permeability of 50.9% with a corresponding RET value of 4.1 Pa·m²/W, classifying it within the "very good breathability" category (RET < 6) according to ISO 11092 standards [34, 48]. The addition of the quilted thermal liner markedly reduced permeability to 23.2% and increased RET to 14.2 Pa·m²/W, which corresponds to "satisfactory but limited comfort" (Ret value of 13–20). A similar decline was observed in the Membrane A combinations, where permeability dropped from 44.4% (RET = 5.4 Pa·m²/W) to 21.2% (RET = 15.8 Pa·m²/W) with the inclusion of the thermal liner. However, across both two- and three-layer configurations, Membrane B assemblies consistently showed slightly higher vapour permeability and lower RET values compared with Membrane A. This indicates that, although Membrane B is considerably heavier (859 g/m² vs. 145 g/m²) and denser, its structural characteristics, likely related to its pore distribution and microstructural compactness, permit marginally greater vapour diffusion than Membrane A. Previous textile studies have reported that membrane morphology, including pore size and connectivity, exerts a dominant influence on moisture vapour transfer, sometimes overriding thickness effects [49-50]. The dense but potentially more interconnected microstructure of Membrane B may therefore facilitate limited vapour transmission while still ensuring a high barrier effect against liquids.

In both membrane types, the addition of the thermal liner significantly reduced permeability and increased RET. This effect is due to the liner's quilted nonwoven Nomex® structure, which increases thickness, introduces additional air gaps, and creates more tortuous diffusion paths, thereby impeding vapour transfer [48,51].

These results emphasize the inherent trade-off in multilayer protective textiles. While the integration of membranes and quilted liners improves thermal insulation and protective capacity, it also restricts moisture transmission and increases evaporative resistance. This dual effect highlights the importance of careful design optimization to achieve adequate protection while maintaining acceptable levels of wearer comfort in medical and other high-risk settings.

4. CONCLUSION

This study examined the thermophysiological performance of Madaline®-based multilayer textile systems for medical protective clothing, emphasizing the balance between thermal insulation, liquid barrier protection, and wearer comfort. The multilayer system consisted of a Madaline® outer layer, two polyurethane membranes with different densities, and a quilted Nomex® thermal liner. Results demonstrated that incorporating the membranes significantly improved thermal resistance and barrier performance compared to the outer layer alone. Notably, the outer + Membrane B + liner configuration provided the highest insulation (65.43 mK·m²/W) and superior barrier protection. However, this improvement was accompanied by a marked decrease in water vapor permeability (23.2%) and an increase in evaporative resistance (RET = 14.2 Pa·m²/W), placing it in the moderate comfort range according to ISO 11092 standards.

While the Membrane B + liner assembly offers maximum thermal protection and liquid barrier performance, making it highly suitable for high-risk medical applications such as surgical procedures or emergency response duties in contaminated environments, it compromises breathability during extended wear. In contrast, the outer + Membrane A + liner system demonstrated slightly lower insulation (61.33 mK·m²/W) but provided a more favorable balance between comfort and protection, making it better suited for moderate-risk healthcare settings or long-duration activities, particularly in warmer climates.

These findings emphasize the inherent trade-off between protection and comfort in multilayer protective textiles. They also highlight the importance of selecting fabric configurations based on specific healthcare contexts, environmental conditions, and activity levels. Ultimately, this work provides practical guidance for optimizing Madaline®-based protective garments, supporting the development of future standards aimed at improving both safety and occupational comfort for healthcare professionals.

5. REFERENCES

1. Derks, M.T.H., Mishra, A.K., Loomans, M.G.L.C. & Kort, H.S.M. (2018). Understanding thermal comfort perception of nurses in a hospital ward work environment. *Building and Environment, 140*, 119-127.
2. Zhao, Y., Su, M., Meng, X., Liu, J. & Wang, F. (2023). Thermophysiological and perceptual responses of amateur healthcare workers: Impacts of ambient condition, inner-garment insulation and personal cooling strategy. *International Journal of Environmental Research and Public Health, 20*, 612.

3. Wibowo, R., Satow, M., Quartucci, C., Weinmann, T., Koller, D., Daanen, H.A.M., Nowak, D., Bose-O'Reilly, S. & Rakete, S. (2025). Impact of heat stress and protective clothing on healthcare workers: Health, performance, and well-being in hospital settings. *Annals of Work Exposures and Health, 69*(6), 665-675.
4. Eryürük, S.H. (2019). Effect of fabric layers on thermal comfort properties of multilayered thermal protective fabrics. *Autex Research Journal, 19*(3), 271-278.
5. Bröde, P., Fiala, D., Błażejczyk, K., Holmer, I., Jendritzky, G., Kampmann, B., Tinz, B. & Havenith, G. (2012). Deriving the operational procedure for the Universal Thermal Climate Index (UTCI). *International Journal of Biometeorology, 56*, 481-494.
6. McLellan, T.M. & Daanen, H.A.M. (2012). Heat strain in personal protective clothing: Challenges and intervention strategies. In: Kiekens, P., Jayaraman, S. (eds) *Intelligent Textiles and Clothing for Ballistic and NBC Protection.* NATO Science for Peace and Security Series B: Physics and Biophysics. Springer, Dordrecht.
7. Sarker, M.E. & Mezarcıöz, S. (2023). The effects of several washings on some of the comfort features of denim fabrics made of cotton and coolmax weft yarns with and without elastane. *Çukurova Üniversitesi Mühendislik Fakültesi Dergisi, 38*(4), 1151-1159.
8. Şenkal Sezer, F. (2016). Sağlık ocaklarında konfor koşullarının değerlendirilmesi: Bursa/Nilüfer örneği. *Çukurova Üniversitesi Mühendislik-Mimarlık Fakültesi Dergisi, 30*(1), 197-208.
9. Lou, L., Chen, K. & Fan, J. (2021). Advanced materials for personal thermal and moisture management of healthcare workers wearing PPE. *Materials Science and Engineering: R: Reports, 146*, 100639.
10. Konečná, K. & Adamovský, D. (2025). Investigation of cleanroom clothing thermal insulation by thermal manikin and impact on thermal comfort of cleanroom users. *Journal of Industrial Textiles, 55*, 1–19.
11. Roskotová, K. & Adamovský, D. (2021). Thermal insulation of clothing: Assessment of cleanroom clothing ensembles. In: *Healthy Buildings 2021 – Europe Proceedings*, 308-314.
12. Eryürük, S.H. (2021). Analyzing thermophysiological comfort and moisture management behavior of cotton denim fabrics. *Autex Research Journal, 21*(2), 248-254.
13. McCullough, E.A. (2005). The use of thermal manikins to evaluate clothing and environmental factors. In: Tochihara, Y., Ohnaka, T. (eds) *Environmental Ergonomics.* Elsevier Ergonomics Book Series, 3, 403-407.
14. Wang, F., Guo, W., Tian, Y., Liu, X., Pang, D., Lian, Z., Deng, C., Li, J. & Zhang, J. (2025). Thermal comfort of medical protective clothing under high temperature and high humidity. *Building and Environment, 270*, 112570.
15. Abreu, M.J., Abreu, I. & Ribeiro, P. (2014). Thermo-physiological behavior of single use scrub suits using a thermal manikin. *2nd International Congress on Healthcare and Medical Textiles*, September 25-26, Izmir, Turkey.
16. Khodakarami, J. & Knight, I. (2008). Required and current thermal conditions for occupants in Iranian hospitals. *HVAC&R Research, 14*(2), 175-193.
17. Tian, M., Qi, N., Jiang, Q., Su, Y. & Li, J. (2024). Addressing localized thermal comfort needs of the human body through advanced personal thermal management garments: Design and evaluation. *Textile Research Journal, 95*(3-4), 429-449.
18. Abuhay, A., Tadesse, M.G., Berhanu, B., Malengier, B. & Van Langenhove, L. (2025). Advancements in clothing thermal comfort for cold intolerance. *Fibers, 13*(2), 13.
19. Orjuela-Garzón, I.C., Rodríguez, C.F., Cruz, J.C. & Briceño, J.C. (2024). High-thermal comfort wearables for sports: Design, materials, and performance. *ACS Omega, 9*(50), 49143-49162.
20. Li, J., Cui, X., Huang, Q. & Li, J. (2024). Determining safe working hours of wearing medical disposable protective clothing from physiological thermal limits: A pilot study. *AATCC Journal of Research, 11*(3), 171-182.
21. Mao, Y., Zhu, Y., Guo, Z., Zheng, Z., Fang, Z. & Chen, X. (2022). Experimental investigation of the effects of personal protective equipment on thermal comfort in hot environments. *Building and Environment, 222*, 109352.
22. Jiang, H., Cao, B. & Zhu, Y. (2023). Improving thermal comfort of individual wearing medical protective clothing: Two personal cooling strategies integrated with the polymer water-absorbing resin material. *Building and Environment, 243*, 110730.
23. Lei, L., Shi, S., Wang, D., Meng, S., Dai, J. G., Fu, S. & Hu, J. (2023). Recent advances in thermoregulatory clothing: Materials, mechanisms, and perspectives. *ACS Nano, 17*(3), 1803-1830.
24. Tang, K.H.D. (2025). Advances in thermoregulating textiles: Materials, mechanisms, and applications. *Textiles, 5*(2), 22.

25. Zhang, Q., Cheng, H., Zhang, S., Li, Y., Li, Z., Ma, J. & Liu, X. (2024). Advancements and challenges in thermoregulating textiles: Smart clothing for enhanced personal thermal management. *Chemical Engineering Journal, 488*, 151040.

26. Peng, Y., Li, W., Liu, B., Jin, W., Schaadt, J., Tang, J., Zhou, G., Wang, G., Zhou, J., Zhang, C., Zhu, Y., Huang, W., Wu, T., Goodson, K.E., Dames, C., Prasher, R., Fan, S. & Cui, Y. (2021). Integrated cooling (i-Cool) textile of heat conduction and sweat transportation for personal perspiration management. *Nature Communications, 12*, 6122.

27. Chai, J., Kang, Z., Yan, Y., Lou, L., Zhou, Y. & Fan, J. (2022). Thermoregulatory clothing with temperature-adaptive multimodal body heat regulation. *Cell Reports Physical Science*, *3*(7), 100958.

28. Zhou, Y., Lou, L. & Fan, J. (2023). Quantitative comparison of personal cooling garments in performance and design: A review. *Processes*, *11*, 2976.

29. Cao, W., Zhang, X., Yao, W., Ruan, M., Zhang, Q., Cao, Z. & Shi, F. (2024). Experimental study on the cooling performance of medical protective clothing coupled with phase-change cold storage materials. *Applied Thermal Engineering, 243*, 122607.

30. Udom, S.U. (2019). Exploring thermal comfort band for healthcare workers in remote clinics in hot and arid climates: An approach for building performance improvement. In: *Proceedings of the 16th IBPSA Conference*, Rome, Italy, Sept. 2-4, 2019.

31. Khodakarami, J., Knight, I. (2007). Measured thermal comfort conditions in Iranian hospitals for patients and staff. In: *Proceedings of Clima 2007 WellBeing Indoors Conference*.

32. Ochoa, N., Giraldo, S.M., Angel, B.E. & Escobar, N.J. (2013). Development of a method for measuring thermal comfort in medical clothing through the hot plate apparatus. In: *2013 Pan American Health Care Exchanges (PAHCE)*, Medellin, Colombia, 1-6.

33. Kim, J.-H., Powell, J.B., Roberge, R.J., Shepherd, A. & Coca, A. (2014). Evaluation of protective ensemble thermal characteristics through sweating hot plate, sweating thermal manikin, and human tests. *Journal of Occupational and Environmental Hygiene, 11*(4), 259-267.

34. ISO 11092:2014. Textiles - Physiological effects - Measurement of thermal and water-vapour resistance under steady-state conditions (sweating guarded-hotplate test). *International Organization for Standardization*.

35. Romeli, D., Barigozzi, G., Esposito, S., Rosace, G. & Salesi, G. (2013). High sensitivity measurements of thermal properties of textile fabrics. *Polymer Testing, 32*(6), 1029-1036.

36. Li, R., Dolez, P.I., Lai, A., Gholamreza, F., Allen, S., Gathercole, R. & Li, R. (2025). Heat transfer through wavy clothing layers with varied permeability. *Building and Environment, 280*, 113114.

37. Firšt Rogale, S., Rogale, D., Knezić, Ž., Jukl, N. (2021). Measurement method for the simultaneous determination of thermal resistance and temperature gradients in the determination of thermal properties of textile material layers. *Materials (Basel), 14*(22), 6853.

38. Rui, K., He, J., Xin, M., Chen, Z. & Guan, J. (2024). Effects of air gap and compression on the dual performance of multilayer thermal protective clothing under low radiant heat. *Journal of Industrial Textiles*, 54.

39. Mortazavinejad, S.M., Alakhdar, M., Vinches, L., Hallé, S. (2025). A novel methodology for calculating thermal conductivity of natural hollow fibers with validation in nonwoven fabric structures. *International Communications in Heat and Mass Transfer, 167*(A), 109269.

40. Wang, Y., Lu, Y., Li, J. & Pan, J. (2012). Effects of air gap entrapped in multilayer fabrics and moisture on thermal protective performance. *Fibers and Polymers, 13*, 647-652.

41. Das, T., Das, A. & Alagirusamy, R. (2022). Study on thermal protective performance of thermal liner in a multi-layer clothing under radiant heat exposure. *Journal of Industrial Textiles, 51*(5_suppl), 8208S-8226S.

42. Romeli, D., Barigozzi, G., Esposito, S., Rosace, G. & Salesi, G. (2013). High sensitivity measurements of thermal properties of textile fabrics. *Polymer Testing, 32*(6), 1029-1036.

43. Sampath, M., Aruputharaj, A., Senthilkumar, M. & Nalankilli, G. (2011). Analysis of thermal comfort characteristics of moisture management finished knitted fabrics made from different yarns. *Journal of Industrial Textiles, 42*(1), 19-33.

44. Jukl, N., Firšt Rogale, S. & Rogale, D. (2023). The influence of compressibility on the thermal contact conductivity of diamond-shaped quilted lining for special purpose clothing. *Tekstil, 72*(3), Online first.

45. Wilson, C.A., Laing, R.M. & Carr, D.J. (2002). Air and air spaces-the invisible addition to thermal resistance. *Journal of the Human Environmental System*, *5*(2), 69-77.

46. Weedall, P.J. & Goldie, L. (2001). The objective measurement of the ‘cool feeling’ in fabrics. *Journal of The Textile Institute, 92*(1, Part 4), 379-386.

47. Li, Y. (2001). The science of clothing comfort. *Textile Progress, 31*(1-2), 1-135.
48. Havenith, G., Holmér, I. & Parsons, K. (2002). Personal factors in thermal comfort assessment: Clothing properties and metabolic heat production. *Energy and Buildings*, *34*(6), 581-591.
49. Knížek, R., Tunák, M., Tunáková, V. & Honzíková, P. (2024). Effect of membrane morphology on the thermo-physiological comfort of outdoor clothing. *Journal of Engineered Fibers and Fabrics*, 19.
50. Khakpour, A., Gibbons, M. & Chandra, S. (2021). Effect of moisture condensation on vapour transmission through porous membranes. *Journal of Industrial Textiles, 51*(2_suppl), 1931S-1951S.
51. He, H. & Yu, Z. (2018). Effect of air gap entrapped in firefighter protective clothing on thermal resistance and evaporative resistance. *Autex Research Journal*, *18*(1), 28-34.