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Natural Fiber-Based Bilayer Knitted Fabrics with Flame-Resistant and Antibacterial Properties for Protective Clothing

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ABSTRACT

The development of flame-resistant and comfortable textile materials is essential for advanced protective clothing applications. This study investigates the development of double-layer interlock knitted fabrics using natural bamboo fibers and modacrylic Protex yarns to evaluate the influence of fiber blend ratio and fabric structure on physical, mechanical, comfort, and functional performance. Three fabric structures plain single jersey/plain single jersey (PS/PS), plain single jersey/cross tuck (PS/CT), and plain single jersey/cross miss (PS/CM) – were produced using three bamboo/Protex blend ratios (50:50, 40:60, and 60:40). Yarn characterization revealed that bamboo yarn exhibited higher lea strength (2963), whereas Protex yarn demonstrated greater tenacity (3.8 g/denier) and elongation (17%). Fabric structural parameters showed Wales per inch of 26–32 and courses per inch of 38–44, with stitch density ranging from 161 to 218 stitches/cm². Fabric weight ranged from 251 to 287 g/m² and thickness from 0.84 to 1.10 mm. The highest bursting strength (792.9 kPa) was observed in the PS/CM (50:50) structure. Antibacterial testing confirmed inhibition of *Staphylococcus aureus*, while fabrics with higher Protex content exhibited zero after-flame and after-glow times, demonstrating suitability for protective textile applications.

摘要

開發兼具阻燃性與舒適性的紡織材料，對於先進防護服的應用至關重要。本研究探討採用天然竹纖維與莫代爾 Protex 紗線製成雙層交鎖針織布，並評估纖維混紡比例與織物結構對其物理性能、機械性能、舒適性及功能表現的影響。本研究採用三種竹纖維與 Protex 混紡比例 (50:50、40:60 及 60:40)，製備了三種織物結構：平紋單面針織布 / 平紋單面針織布 (PS/PS)、平紋單面針織布 / 交叉皺褶 (PS/CT) 以及平紋單面針織布 / 交叉缺針 (PS/CM)。經紗線特性分析顯示，竹纖維紗線的萊氏強度較高 (2963)，而 Protex 紗線則展現出更高的韌度 (3.8 克/丹尼爾) 與伸長率 (17%)。織物結構參數顯示，每英寸經紗數為 26–32，每英寸緯紗數為 38–44，針數密度介於 161 至 218 針/cm² 之間。織物克重介於 251 至 287 g/m²，厚度介於 0.84 至 1.10 mm 之間。PS/CM (50:50) 結構的爆破強度最高 (792.9 kPa)。抗菌測試證實其能抑制金黃色葡萄球菌，而 Protex 含量較高的織物在後燃時間與餘輝時間方面均呈現零值，顯示其適用於防護紡織品應用。

KEYWORDS

Natural bamboo fiber; protex fiber; Flame-resistant textiles; knitted structures; protective clothing; comfort properties

關鍵詞

天然竹纖維; Protex纖維; 阻燃紡織品; 針織結構; 防護服; 舒適性

Introduction

The rising rate of fire accidents in recent years has posed a critical danger to human life and property worldwide. The 2023 World Fire Statistics released by the International Association of Fire and Rescue Services claims over 60 million firefighting activities in 38 countries and 26 cities with a population of over 1.2 billion, or about one-sixth of the world population (Brushlinsky, Marty Ahrens, and Wagner 2017; Li et al. 2025). Such startling data proves the paramount significance of health and safety at workstations, especially in situations with high risk in which contact with flames and high temperatures is a frequent occurrence (Kim and Jin Kim 2019; Weil and Levchik 2008). As a result, flame-retardant protective fabrics have been subject to extensive research to reduce the flammability, the rate of fire, and to allow essential escape time in the event of a fire (Faheem et al. 2023; Malucelli 2022; Sarwar, Sohaib Anas, and Jamshaid 2024). Since the 1970s, regulatory authorities like the U.S Consumer Product Safety Commission have imposed flammability requirements to reduce burn damages and improve the safety of people (Nahrawi,

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Fitri Mustapha, and Saidan 2020). Nevertheless, the traditional fire-resistant fabrics fail to address the comfort of the wearers, especially in relation to thermo-physiological comfort and breathability, which are vital in the case of extended usage (Islam, Golovin, and Dolez 2023; Kozłowski, Muzyczek, and Walentowska 2014; Pamuk, Cüreklibatır Encan, and Zeynep Yıldız 2023). Therefore, there is a growing demand for multifunctional protective textiles that not only provide effective flame resistance but also enhance wearer safety, hygiene, and thermophysiological comfort. Such materials are particularly attractive for applications such as protective workwear, flame-resistant undergarments, children's sleepwear, bedding and linen products, healthcare textiles, and institutional garments, where fire protection, antibacterial performance, moisture management, and wearer comfort are all required simultaneously.

There are three broad methods for producing flame-retardant textiles: blending (Cai et al. 2025), copolymerization (Zhou et al. 2022), and surface finishing (Qi et al. 2023). In blending, flame-resistant fibers, flame-retardant fibers, or additives are physically combined with traditional fibers and then spun, providing consistent resistance without sacrificing strength, comfort, dyeability, or cost (Nandy, Nidhi Vahalia, and Mehra 2024). In incorporation, Copolymerization replaces the terminating groups in the polymer backbone with flame-retarding groups during fiber synthesis, producing long-lasting, wash-stable fibers. Still, it requires complex chemistry and substantial investment (Feng et al. 2025). The most common surface finishing is used on fabrics that utilize either inorganic compounds containing phosphorus, boron, zinc, iron, or carbon, or organic compounds containing halogen-, phosphorus-, nitrogen-, or silicone-containing compounds (Dejene, Alubel Abteu, and Pawlos 2025). Although economical and compatible with current processes, the finishing treatment is usually not very long-lasting under laundering and may reduce softness, breathability and tensile properties (Fan et al. 2025). Previously, halogen-based finishes were effective, particularly on cotton, but their toxic combustion by-products have been regulated (Goller, Schartel, and Krüger 2024). Consequently, studies have taken a new turn to environmentally friendly alternatives such as biomass-based, protein-based and inorganic systems (Ali et al. 2024). The problem is how to achieve flame retardancy without sacrificing the desired properties of the textiles, such as comfort and mechanical integrity. Recent developments focus on synergistic combinations of different systems to achieve high thermal stability and high performance with minimal sacrifice.

Several new studies have explored how inherently functional fibers can be used to create flame-retardant and antimicrobial knitted fabrics without chemical finishes (Tsfay and Gidey Welegebreal 2025). In flame protection, fire-resistant fibers, including meta-aramid (e.g., Nomex), based on modacrylic (e.g., Protex), FR-viscose, and carbon fibers, have been considered as intrinsically flame-resistant (Jamshaid et al. 2023; Niu et al. 2023). These fibers are permanently flame-resistant due to their polymer chemistry and char-forming performance and thus can be used in protective knits, including firefighter and industrial station suits. They can also affect comfort and mechanical behavior based on blend ratios and knit designs. Indeed, an example of a study that can be used to demonstrate this is one carried out by Khan et al. (Khan et al. 2023) who showed that knitted fabrics derived from blends of Protex, Nomex, carbon, and FR-viscose have better flame resistance and varying levels of comfort, depending on the knitted structure and composition. On the same note, Jamshaid et al. (Jamshaid et al. 2023) have shown that plain jersey knits of Nomex and Protex blends achieved effective flame retardancy, coupled with better thermo-physiological properties, which were optimized using principal component analysis.

Although high-performance fibers such as Nomex, Kevlar, Carbon fiber, and FR-viscose have been widely adopted in flame-retardant textiles, each presents notable limitations. Nomex offers excellent flame resistance but is costly and often associated with reduced comfort in prolonged wear (Khan et al. 2023). Kevlar provides outstanding tensile strength and thermal stability, yet suffers from poor moisture management and limited comfort properties (Jamshaid et al. 2023). Carbon fibers exhibit exceptional thermal stability and non-flammability, but their stiffness, toxicity, and high production cost limit their widespread application in protective clothing. Similarly, FR-viscose contributes softness and moisture management, enhancing comfort, but its mechanical durability and long-term flame resistance are comparatively lower (Jamshaid et al. 2023). In contrast, Protex (modacrylic) demonstrates a unique balance of properties: it is inherently flame-retardant, lightweight, soft, and easily blendable with other fibers. Moreover, Protex is self-extinguishing and cost-effective, making it particularly suitable for protective textile applications where both safety and comfort are critical. Among commonly used textile fibers, cellulosic fibers

such as cotton and bamboo generally exhibit limiting oxygen index (LOI) values of approximately 18–21, indicating relatively high flammability under atmospheric conditions. Polyester fibers have LOI values of approximately 20–22, whereas inherently flame-resistant modacrylic fibers such as Protex® exhibit considerably higher LOI values of approximately 30–33. Materials with LOI values greater than 26 are generally regarded as flame-resistant because they require oxygen concentrations significantly higher than that available in ambient air (21%) to sustain combustion. Consequently, incorporating Protex® fibers is an effective strategy to enhance the flame resistance of textile structures.

Alongside flame resistance, there is increasing attention to multifunctional knits with inherent antibacterial performance, guided by fiber or structure. In a recent study, bilayer weft-knitted fabrics made with modacrylic (a naturally flame-resistant fiber) and bamboo yarn were engineered to acquire both flame-resistance and antibacterial properties without any chemical treatment, which shows that changing knit arrangements can change the performance of cloth and comfort metrics, both of which remain crucial (Sarwar, Sohaib Anas, and Jamshaid 2024). In addition, research on cotton/Protex knitted multifunctional fabrics has shown the feasibility of integrating flame retardancy with antibacterial and thermal comfort functions in protective undergarments (Abbas et al. 2026). Although much of the literature on antibacterial textiles still relies on post-treatments or coatings, these studies collectively demonstrate a clear trend toward leveraging inherent fiber properties and structural design to achieve multifunctional performance in protective knitted textiles.

Despite the promising performance of bamboo- and Protex-based textiles reported in previous studies, several important limitations remain. Most bamboo-containing textile investigations have focused primarily on antibacterial activity, moisture management, and comfort performance, while paying limited attention to their integration into multifunctional flame-retardant protective systems (Ghosh et al. 2025; Zhang et al. 2021). Likewise, studies involving Protex fibers have predominantly evaluated flame resistance, thermal protection, and comfort characteristics in single-layer knitted structures or homogeneous fiber blends (Jin et al. 2023). Such approaches do not fully exploit the potential of structural engineering to spatially separate protective and comfort-related functions within the same fabric architecture. Furthermore, previous investigations have primarily reported individual performance attributes such as flame retardancy, thermo-physiological comfort, or mechanical behavior. In contrast, the synergistic interactions among flame resistance, antibacterial functionality, moisture management, and fabric structure remain insufficiently understood. Consequently, there is still a lack of knowledge regarding how functionally engineered bilayer knitted structures can simultaneously optimize multiple protective and comfort-related properties through strategic fiber placement.

Most existing studies focus either on blending inherently flame-resistant fibers within single-layer knitted structures or on incorporating antibacterial functionality through chemical finishing treatments, which may compromise durability, environmental sustainability, and wearer comfort. Although some bilayer or hybrid systems have been explored, limited attention has been paid to structurally engineered rib bilayer knitted fabrics that strategically allocate functional fibers based on their performance roles. More importantly, the influence of fiber positioning within a bilayer architecture on the simultaneous achievement of flame resistance, antibacterial performance, moisture management, thermo-physiological comfort, and mechanical characteristics has not been systematically investigated. Therefore, the present study advances current knowledge by developing a functionally engineered Interlock bilayer fabric in which Protex® fibers are strategically positioned in the outer layer to provide flame resistance. In contrast, bamboo fibers are incorporated into the skin-contact inner layer to impart antibacterial activity and enhance moisture management. Unlike previous studies that primarily examined individual fiber effects or conventional blend structures, this work evaluates how bilayer structural design can spatially integrate multiple functionalities within a single textile system. The findings provide new insights into the structure – property – function relationships governing multifunctional protective knitted fabrics and demonstrate a practical route toward simultaneously enhancing fire protection, hygiene, and wearer comfort.

Materials and methods

Materials

In the present paper, natural bamboo and Protex yarns were selected for investigation; their specifications are given in Table 1. The choice of bamboo fiber is motivated by its softness, breathability, moisture control, and natural antibacterial properties, which can be explained by the presence of bioactive compounds in the structure of bamboo fiber, which are naturally found. All these characteristics make bamboo especially useful for next-to-skin use in protective clothing, where comfort and hygiene are paramount. Protex® is a high-tech intrinsically flame-retardant (FR) fiber of the Kanecaron® modacrylic fibers. These are composed of 35–85% acrylonitrile in the polymer. Protex® has an Oxygen Index of 33, indicating high resistance to combustion under atmospheric conditions. In addition to retaining flame resistance, the fiber has desirable textile properties, such as softness, a lightweight feel, chemical resistance, compatibility with other fibers, and ease of processing (spinning and dyeing). The choice of bamboo as the inner layer and Protex® as the outer layer was a deliberate move to create a multifunctional knitted fabric that combines an inbuilt flame-resistance system with antibacterial and comfort attributes, without the use of extra chemical finishing.

Experimental

Factors and their levels

A two-factor experimental design was used to examine the influence of knitted structure and material ratio on the performance of the developed bilayer fabrics. Two independent variables were considered in the study, including (i) knitted structure that has three levels, including Plain Single Jersey (PS), Cross Tuck (CT), and Cross Miss (CM); and (ii) material ratio of Bamboo/Protex with three levels, 50:50, 40:60, and 60:40 as in Table 2.

Design of experiment

Based on these factors and levels, a total of 9 fabric samples were produced using a full factorial design (3×3), as shown in Table 3. In all samples, bamboo and Protex yarns were combined in a double-layer configuration, with structural variation introduced in the outer layer. The plain single-jersey structure (PS) was maintained in the base layer, whereas structural modifications (PS, CT, and CM) were incorporated to investigate their influence on functional and comfort properties.

The sample coding system was defined according to structure ($S1 = PS/PS$, $S2 = PS/CT$, $S3 = PS/CM$) and material ratio ($R1 = 50:50$, $R2 = 40:60$, $R3 = 60:40$), resulting in nine specimens labeled $S1/R1$ through $S3/R3$. This design enabled systematic analysis of the individual and combined effects of structural variation and fiber composition on the multifunctional performance of the knitted protective fabrics. The process flow for developing the knitted fabrics is shown in Figure 1.

Table 1. Yarn specifications.

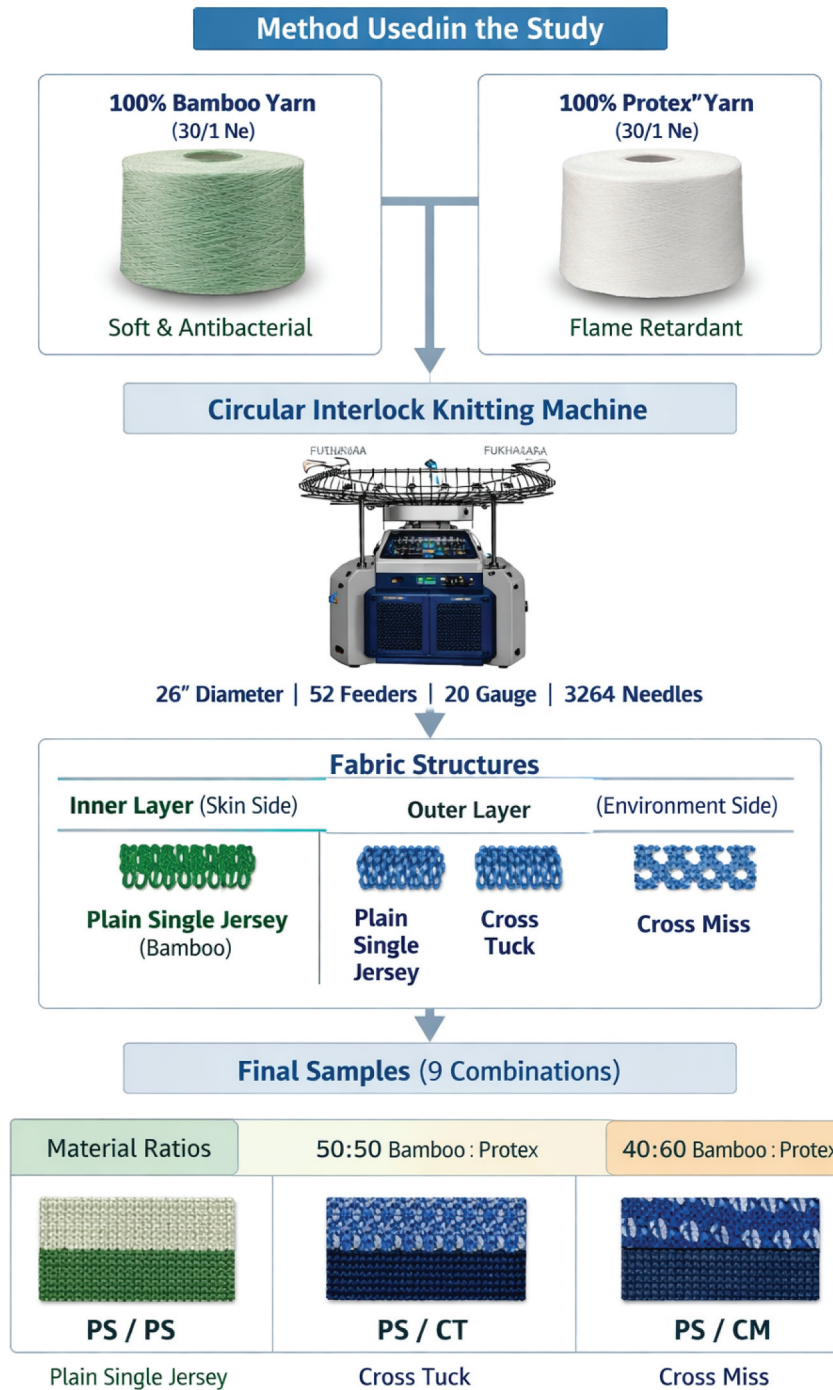
Yarn Property	Bamboo Yarn	Protex Yarn	Test Standard
Fiber type	Bamboo	Modacrylic (Protex®)	–
Blend Ratio	100%	100%	–
Yarn count	30/1 Ne	30/1 Ne	ASTM D1059
Twist (TPI)	18	23	ASTM D1423/D1448
Spinning method	Ring spun	Ring spun	–
Lea strength	2963	2139	ASTM D2256

Table 2. Factors and their levels.

Factors	Levels		
	1	2	3
Knitted Structure	Plain single jersey	Cross Tuck	Cross Miss
Material Ratio	50:50	40:60	60:40

Table 3. Design of experiment.

Sample	Fabric Code	Inner Layer	Outer Layer	Bamboo (%)	Protex (%)	Structure
S1/R1	PS-50	Bamboo PS	Protex PS	50	50	PS/PS
S1/R2	PS-40	Bamboo PS	Protex PS	40	60	PS/PS
S1/R3	PS-60	Bamboo PS	Protex PS	60	40	PS/PS
S2/R1	CT-50	Bamboo PS	Protex CT	50	50	PS/CT
S2/R2	CT-40	Bamboo PS	Protex CT	40	60	PS/CT
S2/R3	CT-60	Bamboo PS	Protex CT	60	40	PS/CT
S3/R1	CM-50	Bamboo PS	Protex CM	50	50	PS/CM
S3/R2	CM-40	Bamboo PS	Protex CM	40	60	PS/CM
S3/R3	CM-60	Bamboo PS	Protex CM	60	40	PS/CM

**Figure 1.** Experimental process flow for sample development.

Methods

In this study, 30/1 Ne yarns of 100% bamboo and 100% Protex® (modacrylic) fibers were prepared and subsequently used to develop double-layer interlock weft-knitted fabrics. All fabric samples were produced on a circular interlock knitting machine (FUKUHARA) equipped with a dial-and-cylinder (double-bed) configuration. In interlock knitting, the dial and cylinder needles are positioned exactly opposite each other, producing technical face loops on both sides of the fabric. Compared to conventional rib structures, the interlock structure offers greater dimensional stability, resilience, and structural compactness. The selected circular interlock machine with 24 RPM had a cylinder diameter of 26 inches, 52 yarn feeders, a gauge of 20, and 3,264 needles. A double-face interlock structure was engineered in which two fabric layers were integrated using tuck stitches, forming a bilayer construction. The cam track settings and design diagrams are illustrated in [Figure 2](#). The skin-facing inner layer was knitted from bamboo yarn in a plain single jersey

Plain Single Jersey (PS)/Plain Single Jersey (PS)

Track	F1	F2	F3	F4	F5	F6
Dial 2	M	K	T	M	K	T
Dial 1	M	K	M	M	K	M
Cylinder 1	K	M	T	K	M	T
Cylinder 2	K	M	M	K	M	M



Plain Single Jersey (PS)/Cross Tuck (CT)

Track	F1	F2	F3	F4	F5	F6
Dial 2	M	K	T	M	K	T
Dial 1	M	K	M	M	K	M
Cylinder 1	T	M	T	K	M	T
Cylinder 2	K	M	M	T	M	M



Plain Single Jersey (PS)/Cross Miss (CM)

Track	F1	F2	F3	F4	F5	F6
Dial 2	M	K	T	M	K	T
Dial 1	M	K	M	M	K	M
Cylinder 1	M	M	T	K	M	T
Cylinder 2	K	M	M	M	M	M



Notation used in the Figure: K = Knit, T = Tuck, M = Miss

Figure 2. Knitting notation and cams used for bilayer fabrics.

(PS) structure to enhance comfort and antibacterial functionality. The inner bamboo layer was knitted on dial needles, whereas the outer Protex layer was knitted on cylinder needles. The two layers were interconnected through periodic tuck stitches introduced at predetermined feeders. Material ratios (50:50, 40:60, and 60:40) were controlled by adjusting yarn-feeding proportions and feeder allocation during knitting, while maintaining a constant stitch length of 2.8 mm. The environment-facing outer layer was knitted from Protex® yarn in three different structural variations: Plain Single Jersey (PS), Cross Tuck (CT), and Cross Miss (CM).

The plain single jersey structure was selected for its softness, flexibility, and comfort. The cross-tuck structure was incorporated to enhance thickness, texture, insulation, and structural compactness. Cross-miss architecture was employed to enhance fabric thickness, durability, and recovery characteristics without compromising extensibility. A total of nine different fabric samples were created by varying the outer-layer structure (PS, CT, CM) and the bamboo-to-Protex material ratio (50:50, 40:60, and 60:40), and summarized in Table 3. The binding (tucking) style of the yarn was modified to control the bilayer's material composition. This systematic variation in structure and material composition enabled evaluation of the combined influence of knitted architecture and inherent fiber functionality on the performance characteristics of the developed protective fabrics.

Characterization

Physical properties

The physical properties of both yarns and knitted fabrics were evaluated in accordance with relevant ASTM standards. The lea strength (CLSP) of the yarns was determined following ASTM D2256. Yarn twist per inch (TPI) for Bamboo and Protex yarn was measured in accordance with ASTM D1448. Single yarn strength (tenacity) and elongation percentage were also assessed using ASTM D2256 procedures. Additional physical parameters of the yarn were evaluated using a Uster Tester 5 (ASTM D1425).

After knitting, the physical parameters of all nine developed structures were measured. Wales per inch (WPI) and courses per inch (CPI) were determined using a pick glass at five locations per sample, and the average values were calculated in accordance with ASTM D8007-15. Stitch length and stitch density were analyzed for all samples. Fabric areal density (g/m^2) was determined in accordance with ASTM D3776. Fabric thickness was measured using a calibrated digital thickness gauge under standard testing conditions.

Microscopic analysis

The structure of knitted fabric samples was examined under a 4X-magnification light microscope to investigate the behavior of the yarn & structures precisely.

Mechanical characteristics

The ICI Pilling Box technique was used to measure pilling resistance in line with ISO 12945-1: 2000. The samples were exposed to 14,400 revolutions. The fabrics were tested and then scored visually on the standard pilling gray scale, ranging from Grade 1 (severe pilling) to Grade 5 (no visible pilling or surface change). The bursting strength was determined in accordance with ASTM D3786. The circular specimens (112 mm²) were clamped around a rubber diaphragm, and hydraulic pressure was slowly increased until rupture occurred. This was documented as the bursting pressure at failure in kPa.

Comfort characteristics

Air permeability was tested in accordance with ASTM D737-18. A circular test area of 20 cm² had an air pressure difference of 100 Pa. The velocity of air permeating the fabric perpendicular to its surface was measured and reported in mm/s. The parameter is the breathability of the knitted structures. The liquid

moisture management properties were assessed using a Moisture Management Tester (SDL-ATLAS M-290) in accordance with AATCC 195–2011. In this method, a fabric specimen was placed between two concentric moisture sensors. A fixed amount of synthetic sweat solution was applied to the top surface of the sample. The measured liquid moisture content enabled evaluation of the fabric's dynamic moisture-transport performance. The overall moisture management capacity (OMMC) index was used to compare samples. The average of five measurements was reported for each structure. Thermal resistance of the knitted fabrics was measured using an Alambeta Thermolab instrument in accordance with ISO 11092. Before testing, all samples were conditioned under standard atmospheric conditions of $20 \pm 2^\circ\text{C}$ temperature and $65 \pm 4\%$ relative humidity for 24 h. During measurement, the fabric specimen was placed between the measuring plate and the instrument's sensing head. The Alambeta device determines thermal resistance by evaluating transient heat flow through the fabric immediately after contact with a heated surface. Thermal resistance reflects the fabric's ability to resist heat transfer and is expressed in $\text{m}^2 \cdot \text{K/W}$. For each fabric type, measurements were taken at five locations, and the average was reported.

Antibacterial activity

The antibacterial performance was evaluated using the agar diffusion method. An overnight culture of *Staphylococcus aureus* was prepared in nutrient broth. Sterile nutrient agar was poured into 90-mm Petri dishes and allowed to solidify. The diluted bacterial culture was evenly spread over the agar surface. Fabric samples containing bamboo yarn were placed on the inoculated agar plates and incubated at 37°C for 24 hours. After incubation, bacterial growth in the contact area was examined to assess antibacterial effectiveness.

Flame resistance

Flame resistance was evaluated following the horizontal flame method under laboratory-developed conditions aligned with BS EN ISO 15025. Samples were conditioned for 4 hours under standard atmospheric conditions and cut to dimensions of 5 in $\times$ 12 in. Each sample was exposed to a small flame (approximately 1.5 in. high) for 10 seconds. After flame removal, the after-flame time was recorded. The char length was measured using a scale. Results were reported as pass/fail, indicating whether the fabric met the required flame-resistance performance.

Statistical analysis

Statistical analysis was performed using Minitab 19 software to evaluate the effects of knitted structure and bamboo/Protex blend ratio on the functional and mechanical properties of the developed fabrics. Since the results of the property measurements followed a normal Gaussian distribution, a general linear model (GLM)-based two-factor analysis of variance (ANOVA) was employed at a 95% confidence level ($\alpha = 0.05$). Before ANOVA, the normality of residuals was assessed using the Shapiro – Wilk normality test. The homogeneity of variance assumption was evaluated through residual plots. A p -value less than 0.05 was considered statistically significant. Main-effect plots were generated to evaluate the independent influence of knitted structure and blend ratio on fabric performance characteristics.

Results and discussions

Physical properties of the yarns

The physical properties of the bamboo and Protex yarns used in this study were evaluated to understand their influence on the performance of the knitted structures as shown in Table 4. The results of yarn characterization are presented in Table 5. Both yarns were produced with the same Ne count of 30, ensuring a comparable linear density for a fair comparison in subsequent fabric development. However, differences in their intrinsic fiber properties and yarn construction parameters influenced their mechanical behavior. Bamboo yarn lea strength (CLSP) was measured at 2963, which is higher than that of Protex yarn (2139).

Table 4. Physical characteristics of yarn.

Material	Count (Ne)	Ratio (%)	CLSP	TPI	Fiber Fineness (mic)	Elongation (%)	Tenacity (g/denier)
Bamboo	30	100	2963	18	2.1	15	3.2
Protex	30	100	2139	23	1.7	17	3.8

Table 5. Physical properties of the knitted fabrics.

Sample Code	WPI	CPI	Stitch density	S. L (mm)	GSM (g)	Thickness (mm)
S1/R1 50:50	29	39	1131	2.8	251	0.84
S1/R2 40:60	30	39	1170	2.8	258	0.86
S1/R3 60:40	29	38	1102	2.8	257	0.86
S2/R1 50:50	28	43	1204	2.8	280	1.10
S2/R2 40:60	28	42	1176	2.8	274	1.10
S2/R3 60:40	26	40	1040	2.8	255	1.04
S3/R1 50:50	32	44	1408	2.8	287	1.06
S3/R2 40:60	30	42	1260	2.8	277	1.00
S3/R3 60:40	30	43	1290	2.8	276	0.96

This shows that the overall bundle strength of bamboo yarn is better. The enhanced CLSP of the bamboo yarn could be explained by the relatively high fiber fineness (2.1 microns) and the inherent strength of natural bamboo fibers, which help ensure improved fiber storage within the yarn structure.

On the contrary, Protex yarn had a higher twist per inch (TPI) of 23, compared with 18 TPI for bamboo yarn. The high degree of twist in Protex yarn enhances fiber binding and yarn compactness, boosting yarn stability and fiber anti-slip properties. Synthetic or modified fibers frequently require this increased twist to preserve the yarn's integrity throughout processing. In terms of fiber fineness, Protex fibers were finer (1.7 microns) than bamboo fibers (2.1 microns). The finer fibers normally enhance the flexibility and softness of the yarn, which can affect the comfort properties of the final knitted fabrics. The percentage of elongation of Protex yarn (17%) was a little higher than that of the bamboo yarn (15%). Increased elongation implies increased extensibility; thus, Protex yarn will be able to tolerate a larger amount of deformation before breaking. It is a property that is of special use in knitted structures where elasticity and recovery are also of concern. Protex yarn has a higher tenacity (3.8 g/denier) than bamboo yarn (3.2 g/denier). This implies that the intrinsic fiber strength of Protex is higher when the linear density is normalized, as demonstrated by higher leaf strength with bamboo yarn. The tenacity of Protex yarn has been enhanced, attributable to an engineered fiber structure that delivers good mechanical performance. All in all, bamboo yarn has better bundle strength, whereas Protex yarn is superior in terms of twist, elongation, and tenacity. It is also anticipated that these differences will affect the mechanical performance, comfort behavior, and functional properties of the developed knitted fabrics, which may be applied in flame-resistance and protective textile-structure applications.

Yarn characterization was conducted to establish the intrinsic properties contributing to subsequent fabric performance. For example, the higher tenacity and elongation of Protex yarn are expected to improve the integrity of flame-resistant fabric during thermal exposure. In contrast, the higher lea strength of bamboo yarn may contribute to enhanced tensile and bursting performance observed in bamboo-rich fabrics. Therefore, yarn-level properties provide a mechanistic basis for interpreting fabric-level mechanical and functional behavior.

Physical properties of the fabrics

The physical properties of the produced knitted fabrics were examined in the realms of the wales per inch (WPI), courses per inch (CPI), stitch density, stitch length, areal density (GSM), and thickness. The importance of these parameters is evident in their effects on the structural compactness, weight, wear and tear, and comfort performance of knitted fabrics. The findings of the nine developed samples are shown in Table 5.

WPI and CPI are the structural density of knitted fabrics in the wale and course directions, respectively. The WPI range across all samples was 26–32, and the CPI range was 38–44. The PS/CM structure (S3) had relatively higher WPI and CPI values, especially in sample S3/R1 (32 WPI and 44 CPI), which demonstrated

a more compact, tighter structure. The increased WPI and CPI observed in PS/CM fabrics can be attributed to the incorporation of miss loops, which restrict loop extension and draw adjacent loops closer together, thereby increasing structural compactness. A higher loop density reduces inter-yarn spacing and increases fabric cover factor, leading to greater stitch density and areal mass. Similar observations have been reported for engineered knitted structures where miss-loop incorporation increases fabric compactness and dimensional stability (Sarwar, Sohaib Anas, and Jamshaid 2024). This structure has more loop interlocking, making it a denser fabric. On the other hand, the PS/CT structure, limited to a 60/40 (S2/R3) ratio, yielded the lowest WPI (26) and CPI (40), indicating a more open fabric structure. Fiber blend ratios also influenced these parameters. Fabrics with a higher Protex content (40:60) tend to have slightly higher WPI and CPI, presumably due to greater yarn twist and structural stability in the Protex yarn.

Stitch density is the product of WPI and CPI, and this defines the number of loops of cloth per square inch. An increased stitch density indicates a reduced, firmer fabric structure. The density of stitches ranged from 161 to 218 stitches/cm². The PS/CM (S3/R1) had the highest stitch density (218 stitches/cm²), attributable to its high WPI and CPI. Conversely, S2/R3 (PS/CT, 60:40) had the lowest stitch density (1040 stitches/in²), indicating a relatively loose fabric construction. The increased stitch density tends to enhance the mechanical strength, durability, and dimensional stability of the fabric. To maintain a constant loop count, the stitch length was kept at 2.8 mm throughout the knitting process, allowing appropriate comparison of the various fabric structures and material ratios. The apparent changes in the other physical parameters may be explained by keeping the stitch length constant, with the fabric structure and the proportion of fibers as the primary causes of these changes, rather than by differences in loop size.

The developed samples had a fabric weight (GSM) in the range of 251 g/m²–287 g/m². The maximum GSM was recorded in S3/R1 (287 g/m²), which is consistent with its having the most stitches and being compact. In the same way, a PS/CT type of fabric (S2) also had somewhat larger GSM rates (274–280 g/m²), so that the constructions are heavier and thicker. S1/R1 had the lowest GSM (251 g/m²) and a PS/PS structure, resulting in a much lighter fabric. The rise of GSM in the structures can be attributed to the increased density and complexity of the architectures of the CT and CM knitted structures.

The thickness of the fabric depends on the bulkiness of the yarns, the arrangement of loops, and the construction structure. The samples ranged in thickness from 0.84 mm to 1.10 mm. The PS/CT structures (S2/R1 and S2/R2) had the greatest thickness (1.10 mm), which could be attributed to tuck or structural features of the CT design that add more vertical bulk to the fabric. Conversely, PS/PS (S1/R1) had the minimum thickness (0.84 mm), indicating a flatter, more compact surface arrangement. The PS/CM structures (S3) had moderate thicknesses (0.96–1.06 mm), indicating a balanced bulk for the fabric compared with the other structures. In general, the findings suggest that fabric structure is a bigger factor in physical properties than blend ratio. The PS/CM structure yielded the most compact and dense fabrics, whereas the PS/PS structure yielded lighter, thinner fabrics. Also, a general increase in stitch density increased GSM and softness, which could affect the mechanical strength and performance of knitted fabrics for protective textile applications.

Microscopic analysis of knitted structures

Microscopic observations were conducted to study the structural features of the knitted fabrics produced and to examine how various fabric structures affect loop arrangement and compactness. The microscopic pictures of the front and back sides of three typical samples, namely, S1/R1 (PS/PS, 50:50), S2/R1 (PS/CT, 50:50), and S3/R1 (PS/CM, 50:50), are given in Figure 3. These samples were chosen to show the three varieties of knitted structures adopted in this research. The microscopic analysis of Sample S1/R1 (PS/PS) in Figure 3a showed that the loop structure on the front and back sides of the cloth is relatively homogeneous and symmetrical. The loops were uniform, with equal loop size and direction, as in a plain structure. The loops were interlocked, creating a stable arrangement with a moderate yarn distance, giving the fabric a balanced structure. The parallel front-back in Figure 3a,b surface shows that the morphology is comparatively homogeneous in the PS/PS structure. Sample S2/R1 (PS/CT) in Figure 3c,d, on the contrary, exhibited a significant variation in loop structure owing to the occurrence of tuck loops in the structure. The microscopic images showed elongated loops and significant overlap of the yarns, resulting in a slightly thicker fabric surface. The tuck loops

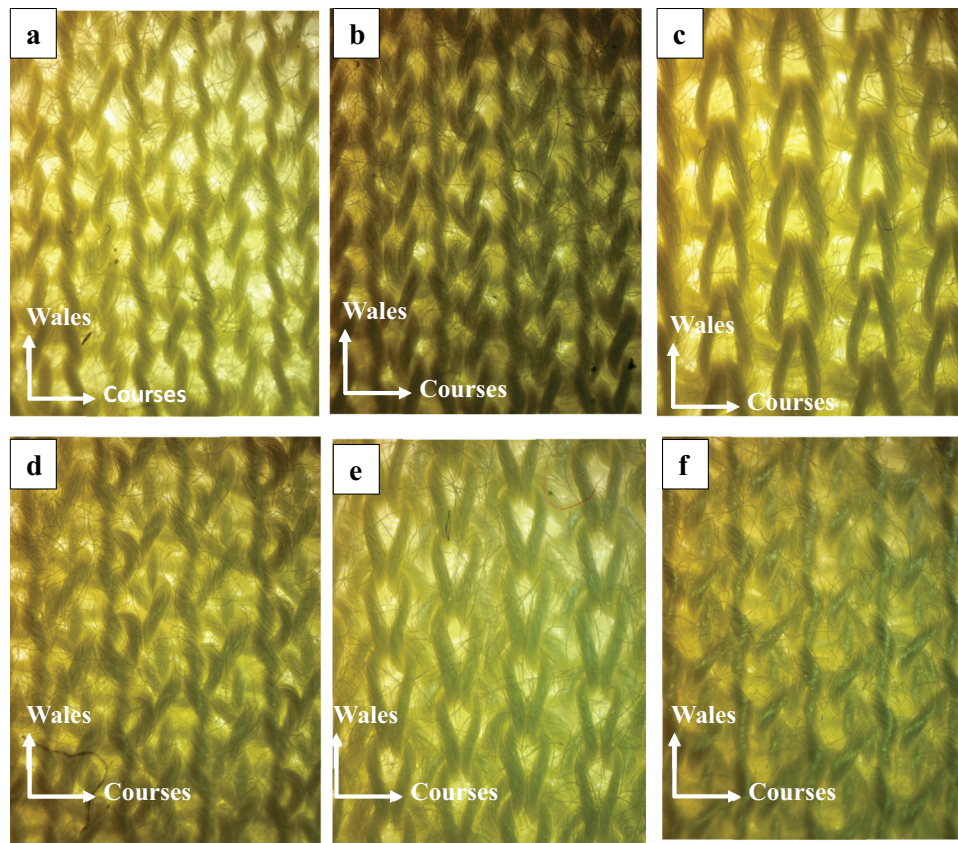


Figure 3. Microscopic images of (a) (PS/PS) Protex side, (b) (PS/PS) bamboo side, (c) (PS/CT) Protex side, (d) (PS/CT) bamboo side, (e) (PS/CM) Protex side, (f) (PS/CM) bamboo side.

increased inter-loop spacing and uneven loop offsets in the PS/PS structure. Such structural differences also help increase fabric thickness and porosity, which may affect air permeability and moisture transport behavior. The Sample S3/R1 (PS/CM) in Figure 3e, was observed to have a tight and compact loop under microscopic examination. The missing loops in the CM structure led to interlocking loops, reducing the spacing between loops in the fabric. Consequently, the fabric looked smaller than the PS/PS and PS/CT fabric. The loops on the front surface were well-defined, and the loops on the back were much tighter, indicating greater structural density. This small regime is consistent with the increased stitch density observed in the physical characterization findings. In general, observations under the microscope show that the structure of fabrics plays an important role in determining the loop geometry, pore size, and the arrangement of the yarns in knitted fabrics. The PS/PS structure has a regular, balanced loop structure; the PS/CT structure results in a more open structure with bulkier loops due to tuck loops; and the PS/CM structure is a compact, dense fabric. These structural variations, as observed at the microscopic level, are consistent with the measured physical, mechanical, and comfort properties of the developed fabrics.

Mechanical properties of the knitted fabrics

Another essential mechanical characteristic of knitted fabrics is bursting strength, which determines how the fabric may resist multidirectional pressure before breaking. The tensile bursting strengths of the invented fabrics ranged from 599 kPa to 792.9 kPa, depending on the fabric's structure and percentage composition, as illustrated in Figure 4.

The PS/CM structure, compared with the other two fabric structures, had the greatest bursting strength, specifically the 50:50 blend (792.9 kPa). The increased strength is attributed to higher stitch density and greater loop interlocking in the PS/CM structure, which enhances load distribution across the fabric surface.

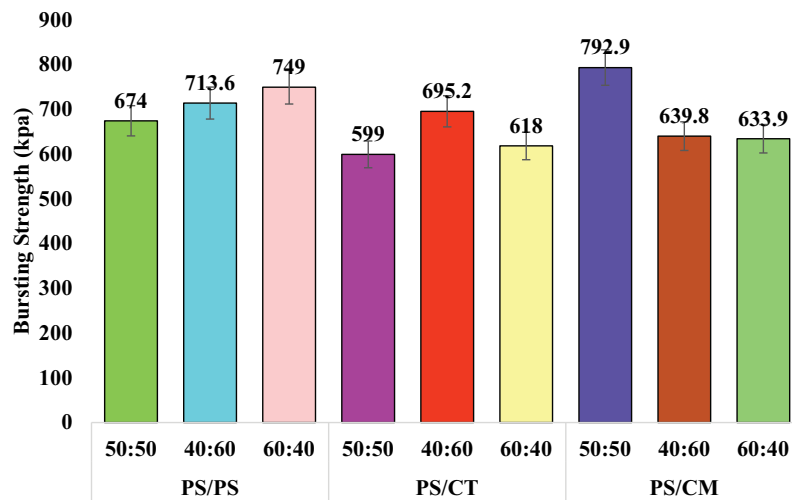


Figure 4. Bursting strength of the knitted fabric samples.

Bursting strength in knitted fabrics is governed by the ability of loop networks to redistribute multi-directional stresses through loop deformation, yarn slippage, and loop extension. Fabrics with higher stitch density generally exhibit improved bursting resistance because more loops participate in load sharing. The superior bursting performance of PS/CM fabrics can therefore be attributed to their compact architecture and increased loop constraint, which reduce localized stress concentration and delay rupture initiation (Abbas et al. 2026). A smaller form allows the applied pressure to be distributed across additional loops, preventing fabric tears. The PS/PS structure had an average bursting strength of 674–749 kPa. The maximum value in this structure was obtained at the 60:40 ratio (749 kPa). This means that the comparatively balanced loop formation in plain structures offers the structures reasonable resistance to stress in many directions.

On the other hand, the PS/CT structure had the lowest bursting strength, ranging from 599 kPa to 695.2 kPa. The 50:50 blend yielded the lowest result (599 kPa). This decrease in bursting strength could be attributed to tuck loops in the CT structure, which leave larger loop spaces and reduce the structure's compactness, making the fabric more prone to rupture under pressure. Bursting strength was also dependent on the proportion of bamboo and Protex yarns. In the PS/PS structure, the higher the bamboo content (60:40), the higher the bursting strength, which reached 749 kPa. This may be linked to the fact that the leaf strength of bamboo yarn is higher, thereby enhancing the cloth's load-bearing capacity. In the PS/CT structure, the sample with the highest bursting strength was 40:60 (695.2 kPa). This could be because the higher percentage of Protex fiber makes it more tenacious, which could have improved the fabric structure. The 50:50 mixture exhibited the highest bursting strength (792.9 kPa) among the PS/CM structures, making it the most effective at providing structural reinforcement in this loop form. Overall, it can be concluded that the fabric structure has a greater impact on bursting strength than the fiber blend ratio. The PS/CM structure had the highest resistance to bursting pressure, followed by the PS/PS structure, while the PS/CT structure had lower resistance due to its more open-loop structure. Also, balances or bamboo-rich mixtures were found to enhance the performance of bursting in various structures, probably because the strength of the yarn bundles of bamboo fibers is higher.

The tensile strength and elongation at break results in Figure 5 clearly demonstrate the combined influence of fabric structure and blend ratio on the mechanical behavior of the developed knitted fabrics. For the PS/PS structure, tensile strength increased with increasing bamboo content, ranging from 269.37 N (50:50) to 315.2 N (60:40). This trend can be attributed to the higher contribution of bamboo fibers, which provide better load-bearing due to their relatively higher leaf strength and structural stability. Tensile behavior of knitted fabrics depends not only on fiber strength but also on loop orientation and yarn mobility. Bamboo-rich fabrics exhibited higher tensile strength because the higher leaf strength of bamboo yarn enhanced resistance to yarn rupture during load application. However, the accompanying reduction in elongation indicates restricted loop mobility and lower elastic recovery compared with Protex-containing

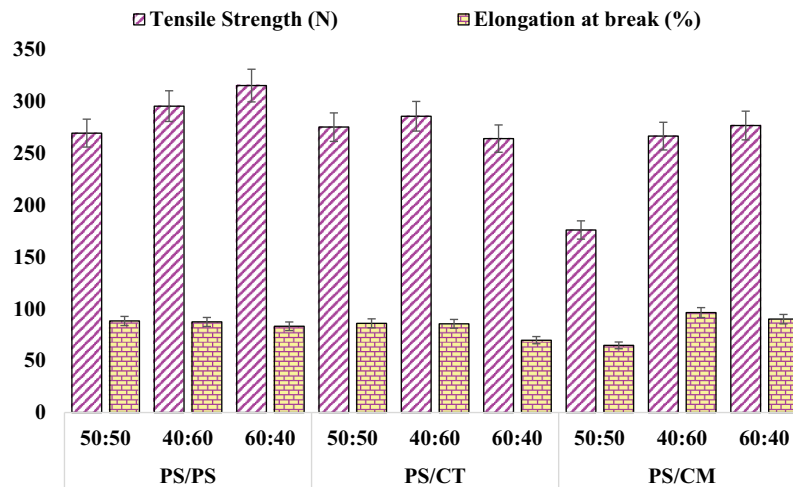


Figure 5. Tensile strength and elongation at break of all the fabric samples.

fabrics. Similar strength – extensibility trade-offs have been reported in multifunctional knitted protective fabrics. However, elongation decreased slightly from 88.31% to 83.21%, indicating that increasing bamboo content reduces fabric extensibility due to bamboo's lower elasticity compared to Protex.

For PS/CT structures, moderate tensile strength values were observed, with the highest at 40:60 (285.62 N). However, a significant drop in both tensile strength (264.07 N) and elongation (69.78%) was noted at the 60:40 ratio. This reduction can be attributed to the presence of tuck loops, which introduce structural irregularities and stress concentrations, thereby reducing the fabric's ability to withstand load and deformation at higher bamboo content. For the PS/CM structure, a different trend was observed. The lowest tensile strength (175.99 N) and elongation (64.77%) were recorded at the 50:50 ratio, indicating poor load distribution due to the miss loop configuration. However, with increasing bamboo content, tensile strength improved significantly to 276.71 N (60:40), while elongation also increased to 90.07%. This suggests that bamboo fibers provide better structural reinforcement in the CM structure when present at higher proportions. Overall, PS/PS fabrics exhibited the highest tensile strength, particularly at higher bamboo content, due to their uniform loop structure and better stress distribution. PS/CT fabrics exhibited moderate performance, influenced by tuck-loop-induced structural variations. In contrast, PS/CM fabrics exhibited the lowest strength at balanced ratios but showed a significant increase with higher bamboo content. Elongation behavior indicates that Protex-rich fabrics generally enhance flexibility, whereas bamboo-rich fabrics improve strength but may reduce extensibility, depending on their structure. These results highlight that both fiber composition and knitted structure play a crucial role in determining the mechanical performance, with structure having a more pronounced effect on load distribution and deformation behavior.

The pilling performance of the knitted fabric samples showed that all samples had a pilling rating of 5, the maximum. This implies that once the required number of revolutions had been completed, no pills, fuzz formation, or any observable changes on the surface were observed on all the tested fabrics. Pilling resistance is very good and is attributable to several factors. To begin with, the fiber characteristics of Protex, with relatively high tenacity and durability, enhance fiber cohesion within the yarn, thereby minimizing fiber breakage and migration to the fabric surface. Second, a moderate twist of the yarn, as well as a tightly twisted loop structure in the knitting structures, is applicable to hold fibers together and reduce protrusion of fibers during abrasion. Also, the combination of bamboo and Protex fibers can enhance the integrity of the yarn, restricting loose fiber sections that normally cause pills. Moreover, the relatively high structural stability and stitch density in the developed fabrics are additional factors that could contribute to enhanced resistance to surface abrasion. The small size of the structure limits fiber movement, thereby preventing the development and deposition of pills. Generally speaking, the data indicate that all knitted fabrics made of bamboo/Protex have strong pilling resistance, which means they can be used in areas where textile items are to be covered. Their appearance is to be preserved over the long term, especially in protective or utilitarian clothing.

Comfort properties of the fabrics

A parameter of great comfort significance is air permeability, which defines a fabric's ability to permit air to pass, directly affecting breathability and thermal comfort. The developed fabrics were tested for air permeability through the face and back sides, with measurements ranging from 759.4 mm/s to 1016.4 mm/s, as indicated in Figure 6.

The PS/CT fabrics had the highest air permeability among the three structures. The highest reading was observed in PS/CT using a 50:50 mixture, with values of 996.4 mm/s on the face side and 1016.4 mm/s on the back side. Air permeability is primarily controlled by effective pore size, pore connectivity, and fabric thickness rather than intrinsic fiber chemistry. The significantly higher permeability of PS/CT fabrics can be attributed to the presence of tuck loops, which increase inter-loop spacing and generate larger air channels within the fabric structure. According to Darcy-type airflow principles in porous textiles, increased pore volume facilitates airflow and reduces resistance to air transport. This increased permeability is probably due to the CT structure having tuck loops that create more space between loops, enabling air to travel through the fabric more easily. The air permeability of the PS/PS structure was moderate, ranging from 759.4 mm/s to 874.2 mm/s. The optimum value in this structure was at the 60:40 blend ratio, which may be related to reduced structural compactness and more pores in the fabric. Comparatively, the PS/CM structure recorded the lowest value of air permeability with a range between 761.6 mm/s and 810.2 mm/s. This construction was less dense in stitches and had a tighter, looped form, making the air passages in the fabric smaller and thus restricting airflow. The ratio of fiber blend also, to some extent, affected the air permeability. The 60:40 ratio was the most permeable in PS/PS (860.4 mm/s face, 874.2 mm/s back), indicating that increased bamboo content can slightly increase fabric porosity due to the nature of the fibers.

In the PS/CT structure, the higher the bamboo proportion, the lower the air permeability. The 50:50 blend recorded the best value, with the 60:40 blend recording a relatively low airflow output (891 mm/s face, 870.8 mm/s back). There were also minor differences in the blend ratios of the PS/CM fabrics, indicating that fabric structure had a stronger influence on airflow than the fiber ratio. The rear of the cloth in most samples was slightly more air-permeable than the face side. This could be because the back surface is generally designed as a loop, which usually has more open space or other loop directions, allowing air to move into it more easily. On the whole, the findings suggest that fabric structure is a primary factor in defining air permeability. The PS/CT design offers the greatest breathability, while the PS/CM design creates a tight, impermeable garment. These variations mostly concern the arrangement of the loops, the stitch density, or the pore size in knitted designs, which determine how easily air passes through the fabric.

A Moisture Management Tester was used to assess the moisture management behavior of the developed knitted fabrics, measuring wetting time, absorption rate, spreading behavior, one-way transport capability, and the amount of moisture the fabrics could absorb. The superior moisture transport behavior observed in

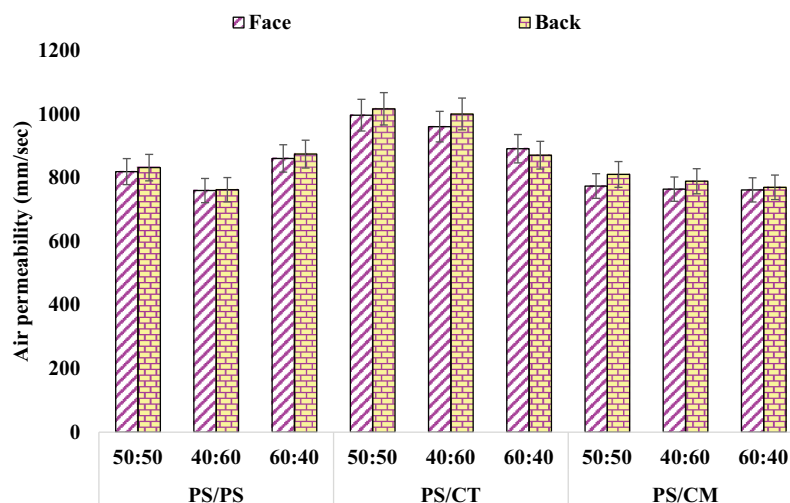


Figure 6. Air permeability results of all the fabric samples.

bamboo-containing fabrics is attributed to the hydrophilic cellulose structure of bamboo fibers, which contains abundant hydroxyl groups that enable rapid moisture sorption. Simultaneously, the bilayer architecture promotes capillary-driven liquid transfer from the inner bamboo layer toward the outer Protex layer, generating a moisture gradient that enhances one-way transport and OMMC performance. All of these parameters characterize a fabric's ability to absorb, transport, and evaporate liquid moisture, which is key to the wearer's comfort. Table 6 provides the results of all these parameters.

Wetting time is the measure of the rate at which the fabric material is wet when in contact with liquid. Lower wetting time values indicate faster liquid uptake. In most samples, the bottom wetting time was considerably shorter than the top wetting time, indicating that water moved rapidly to the bottom surface of the cloth. Of the samples, PS/PS (60:40) had the lowest top wetting time (7.04 s), indicating fast wetting on the fabric surface. Conversely, PS/CM (60:40) had the longest wetting time (60.97 s) and might not absorb the moisture as swiftly on the top face. The reduced wetting time in certain samples may be attributed to the hydrophilic nature of bamboo fibers, which favor the rapid uptake of liquids.

The rate of absorption is the rate at which the fabric absorbs water when it begins to wet. The more the values, the more rapidly the liquid is taken up. Most of the samples had a significantly higher bottom absorption rate than top absorption rate, indicating effective moisture movement across the thickness of the fabric. The maximum bottom absorption rate was recorded for PS/CM (50:50) at 156.90%/s, indicating a high moisture absorption rate at the bottom surface. By comparison, the best absorption rates were lower, and the highest value was observed in PS/PS (60:40) at 35.94%/s. This action confirms that the fabrics are working well at transferring moisture from the inner surface to the outer surface, which is desired in comfort textiles.

The highest wetted radius shows the distance to which the liquid can be dispersed on the fabric surface, and the speed of spreading shows the speed at which it disperses. The top and bottom wetted radii in the PS/PS structure were 15–16.67 mm, which is good behavior of moisture spreading. PS/CT (50:50) exhibited the highest spreading speed on the bottom surface, at 2.20 mm/s, indicating rapid lateral moisture spreading. On the whole, the bottom-surface spreading was faster than the top-surface spreading, which validated the assumption of efficient transfer and distribution of moisture across the outer fabric surface, where it can evaporate.

The one-way transport index indicates how well the fabric transfers moisture between the inner (top) and outer (bottom) surfaces. Higher values are better for directional moisture transport. PS/CT (60:40) had the highest score (1120.17), followed by PS/CM (60:40) at 1035.81, and PS/PS (50:50) at 966.02. These high values indicate a very good ability to transfer moisture from the skin to the outer layer of the cloth. This characteristic is especially significant for activewear and protective clothing, where effective sweat removal is essential.

OMMC is a composite index that quantifies a fabric's overall capability to handle liquid moisture, including absorption, spreading, and unidirectional transport. The maximum OMMC was observed at PS/CT (40:60) (0.84) and at PS/PS (50:50) (0.83). Such outcomes reflect high moisture management performance. Conversely, PS/PS (60:40) had the lowest OMMC value (0.42), indicating a comparatively poor moisture-handling capacity in general. The findings show that fabric structure and fiber blend ratio have a strong effect on moisture management performance. Fabrics with higher Protex content tended to exhibit better moisture transport and OMMC values, likely due to structural stability and enhanced liquid-transfer

Table 6. Liquid moisture management properties of the knitted fabrics.

Fabric Structure Material Ratio	PS/PS			PS/CT			PS/CM		
	50:50	40:60	60:40	50:50	40:60	60:40	50:50	40:60	60:40
Wetting time Top(s)	55.39	22.66	7.04	7.07	23.51	47.29	19.07	29.35	60.97
Wetting time Bottom(s)	11.02	8.78	8.77	7.45	8.11	8.26	8.81	6.21	7.64
Top absorption Rate(%/s)	12.17	24.28	35.94	20.47	9.96	6.58	8.34	6.45	5.99
Bottom Absorption Rate(%/s)	123.25	73.74	67.7	73.1	92.13	90.33	156.9	67.83	75.14
Top Max Wetted Radius (mm)	6.67	15	15	11.67	15	8.33	10	10	5
Bottom Max Wetted Radius (mm)	10	16.67	15	15	10	10	6.67	6.67	8.33
Top Spreading Speed (mm/s)	0.12	1.01	1.7	1.44	0.52	0.18	0.85	0.29	0.08
Bottom Spreading Speed (mm/s)	2.02	1.42	1.66	2.2	2.4	1.12	0.63	0.99	0.91
Accumulative One-way transport index (%)	966.02	388.33	127.23	204.65	722.1	1120.17	621.45	998.51	1035.81
OMMC	0.83	0.61	0.42	0.55	0.84	0.73	0.67	0.67	0.68

properties. PS/CT fabrics tended to perform better in moisture transport behavior (e.g., one-way transport index, OMMC), and PS/CM structures had high absorption but slower spreading behavior. In general, the findings indicate that the PS/CT architecture with a 40:60 bamboo/Protex ratio is the most balanced in moisture control; thus, it applies to applications that require high efficiency in sweat transport and a high level of comfort for wearers.

Thermal resistance is a significant comfort parameter that determines how a fabric withstands heat flow and offers thermal insulation. The greater the thermal resistance, the better the insulation properties, i.e., the greater the fabric's capacity to retain heat. Figure 7 shows that the thermal resistance values of the developed knitted fabrics ranged from about 0.041 to 0.086 m² K/W, a result of the fabric structure and the fiber blend ratio. The findings indicate that the PS/PS structure exhibited relatively higher thermal resistance than the other structures. Thermal insulation in knitted fabrics is governed by the volume of entrapped still air, which possesses significantly lower thermal conductivity than textile fibers. Consequently, fabric structures that retain stable air pockets exhibit higher thermal resistance. The PS/PS structure generated superior insulation because its balanced loop geometry produced a stable air layer while minimizing convective heat transfer through the fabric thickness. The PS/PS fabric, with a 40:60 bamboo/Protex ratio, yielded the highest value, approximately 0.085 m² K/W. Such an improved value is possible due to the balanced loop design and a comparatively small design, which aids in the entrapment of still air in the fabric. It works because trapped air is a good thermal insulator, which increases overall thermal resistance.

The PS/CT structure exhibited moderate thermal resistance, with values ranging from approximately 0.051 to 0.078 m² K/W. The 40:60 blend ratio yielded the highest value again in this structure. Even though the tuck loops introduced into the CT structure add bulk to the fabric, they can also create slightly larger pores that transfer some heat, making it moderately insulating compared to PS/PS fabrics. On the other hand, the PS/CM structure had the lowest thermal resistance, with a figure between 0.041 and 0.050 m² K/W. This could be explained by the stitch density and loop arrangement being more compact, so less air is trapped in the fabric structure, thereby reducing heat transfer through the fabric.

Thermal resistance was also affected by the fiber blend ratio. In the vast majority of results, the 40:60 bamboo/Protex mixture showed comparatively higher thermal resistance than other ratios. Protex fibers, which are available and provide good bulk and structural stability, may be beneficial for trapping air within the fabric structure, thereby improving insulation performance. But at a bamboo percentage of 60:40, a minimal reduction in thermal resistance was observed in certain structures. This can be linked to increased moisture absorption and the smoother surface of bamboo, which conducts heat. All in all, the fabric structure and blend ratio affect the thermal resistance of knitted fabrics. Among the samples tested, the PS/PS structure with a 40:60 bamboo/Protex blend exhibited the highest thermal resistance, indicating improved thermal insulation. On the other hand, the PS/CM structures were less thermally resistant,

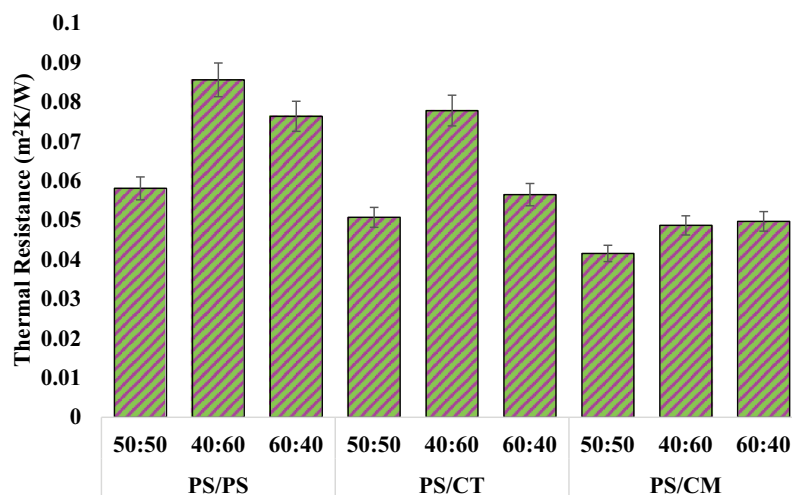


Figure 7. Thermal resistance of the knitted fabric samples.

indicating better heat transfer and possibly better cooling resistance. These results indicate that the structural design of a fabric is important in determining the thermal comfort properties of knitted fabric, as this design directly influences air entrapment, fabric thickness, and heat transfer behavior.

Antibacterial characteristics

The antibacterial activity of the developed knitted fabrics was evaluated against the bacterium *Staphylococcus aureus* using the agar diffusion method. All fabric samples exhibited antibacterial behavior, which can be attributed primarily to the inherent antibacterial properties of bamboo fibers incorporated into the bilayer knitted structures. Representative antibacterial test results for two samples are presented in Figure 8. Following incubation, both microscopic and visual examination revealed no bacterial growth in the areas directly covered by the fabric specimens. No distinct inhibition zone was observed around the samples. However, bacterial growth directly beneath the bamboo-containing fabrics was effectively suppressed, indicating a contact-active antibacterial mechanism rather than diffusion-based antibacterial behavior (Sarwar, Sohaib Anas, and Jamshaid 2024). This phenomenon is commonly observed in non-leaching antibacterial textile materials, where antimicrobial activity occurs through direct interaction between the fiber surface and microorganisms rather than through the release of active agents into the surrounding agar medium.

The antibacterial effect of bamboo fibers has been attributed to naturally occurring bioactive constituents, often referred to as bamboo kun, which can interfere with microbial cellular processes and inhibit bacterial proliferation. The absence of a measurable inhibition zone suggests that the antibacterial components remain largely bound within the fiber structure and are not readily diffusible through the agar medium. Consequently, the agar diffusion method provides qualitative evidence of antibacterial effectiveness but does not permit quantitative determination of the inhibition zone diameter or the percentage reduction in bacteria. Similar observations have been reported for inherently antibacterial and bio-based textile materials exhibiting contact-based antimicrobial activity.

In addition to the intrinsic antimicrobial nature of bamboo fibers, the observed antibacterial performance may also be associated with the moisture-management characteristics of bamboo-based knitted fabrics. Fabrics that rapidly transport moisture and promote evaporation create less favorable conditions for bacterial growth, as microorganisms generally proliferate in warm, humid environments. Samples 6 and 9

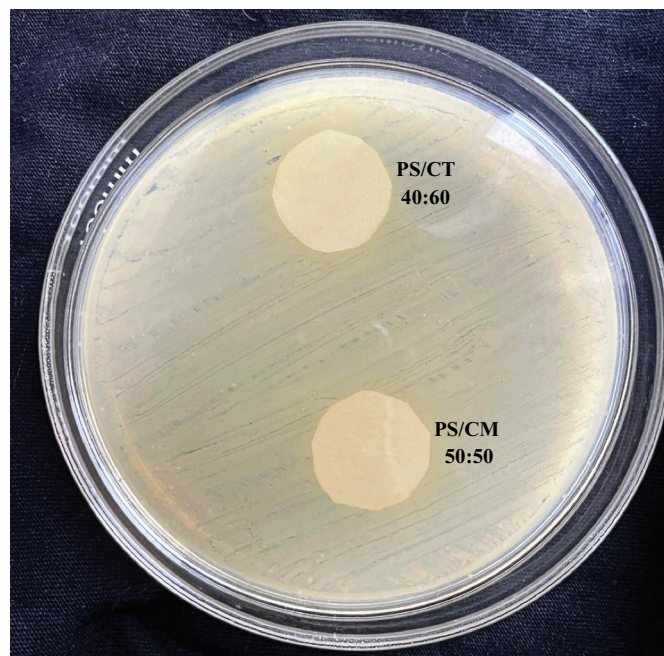


Figure 8. Antibacterial results of the knitted fabric samples.

exhibited particularly strong antibacterial behavior, with no visible bacterial colonies observed on the fabric surface after incubation. The bilayer knitted architecture strategically positions bamboo yarn on the skin-contact side, maximizing direct interaction between the antibacterial bamboo surface and the surrounding environment. While all fabric structures demonstrated antibacterial activity, relatively open structures such as PS/CT may facilitate moisture evaporation and reduce microclimate humidity, thereby further restricting bacterial proliferation. In contrast, more compact structures may retain moisture longer, potentially influencing microbial growth conditions. Overall, these findings demonstrate that the developed bamboo bilayer knitted fabrics possess effective antibacterial properties, making them promising candidates for protective clothing, healthcare textiles, and hygiene-related applications where microbial control is essential.

Flame retardant results of the knitted fabrics

The surface flammability behavior of the developed knitted fabrics was evaluated in accordance with ISO 15025, measuring key parameters, including after-flame time, after-glow time, hole formation, flame spread to the edge, melting behavior, and debris formation. These parameters are essential for assessing the fire resistance and burning characteristics of textile materials when exposed to direct flame. The results in Table 7 demonstrate that both fabric structure and bamboo/Protex blend ratio significantly influence flame behavior.

After-flame time is the duration for which the fabric continues to burn after the ignition source is removed. Lower values indicate better flame resistance. In the present study, very low after-flame times (0–3 seconds) were observed for all samples, indicating excellent flame-retardant performance across all structures. Specifically, PS/PS (50:50 and 40:60) and PS/CT (40:60) exhibited an after-flame time of 0 seconds, indicating immediate self-extinguishing behavior. Samples with higher bamboo content (60:40 ratio) showed slightly higher after-flame times (2–3 seconds), such as PS/PS (60:40: 3 s), PS/CT (60:40: 3 s), and PS/CM (60:40: 2 s). However, these values remain very low, indicating that the presence of Protex fibers effectively suppresses sustained burning even at higher bamboo proportions.

After-glow time indicates the duration for which the fabric continues to glow after the flame is extinguished. Most samples exhibited very low glow times ranging from 0 to 5 seconds, suggesting minimal smoldering behavior. The lowest glow times (0 seconds) were observed in PS/PS (40:60) and PS/CT (40:60), indicating complete cessation of combustion. Slightly higher glow times were recorded in PS/CM (60:40: 5 s) and PS/PS (60:40: 3 s), which can be attributed to the cellulosic nature of bamboo fibers, promoting minor smoldering.

The results further revealed that no hole formation occurred in any of the tested samples, and no flame spread to the fabric edge was observed. Additionally, none of the fabrics exhibited melting behavior or debris formation during the flame exposure, as shown in Figure 9. These observations indicate that all developed fabrics maintained their structural integrity under direct flame exposure, strongly suggesting excellent flame-resistant performance. Although all samples demonstrated good flame resistance, slight variations were observed due to differences in fabric structure and blend ratios. The PS/PS structure exhibited the most stable behavior, particularly at the 40:60 bamboo/Protex ratio, showing minimal flame and glow times. The superior flame resistance of the 40:60 bamboo/Protex fabrics is attributed to the higher concentration of inherently flame-resistant Protex fibers. Upon exposure to flame, Protex undergoes

Table 7. Surface flame retardancy results of knitted fabric samples.

Fabric Structure	Material Ratio (Bamboo: Protex)	Flame Time (Sec)	Glow Time (Sec)	Hole Develop	Fanning to Edge	Melting	Debris
PS/PS	50:50	0	1	No	No	No	No
	40:60	0	0	No	No	No	No
	60:40	3	3	No	No	No	No
PS/CT	50:50	2	2	No	No	No	No
	40:60	0	0	No	No	No	No
	60:40	3	2	No	No	No	No
PS/CM	50:50	2	1	No	No	No	No
	40:60	0	2	No	No	No	No
	60:40	2	5	No	No	No	No

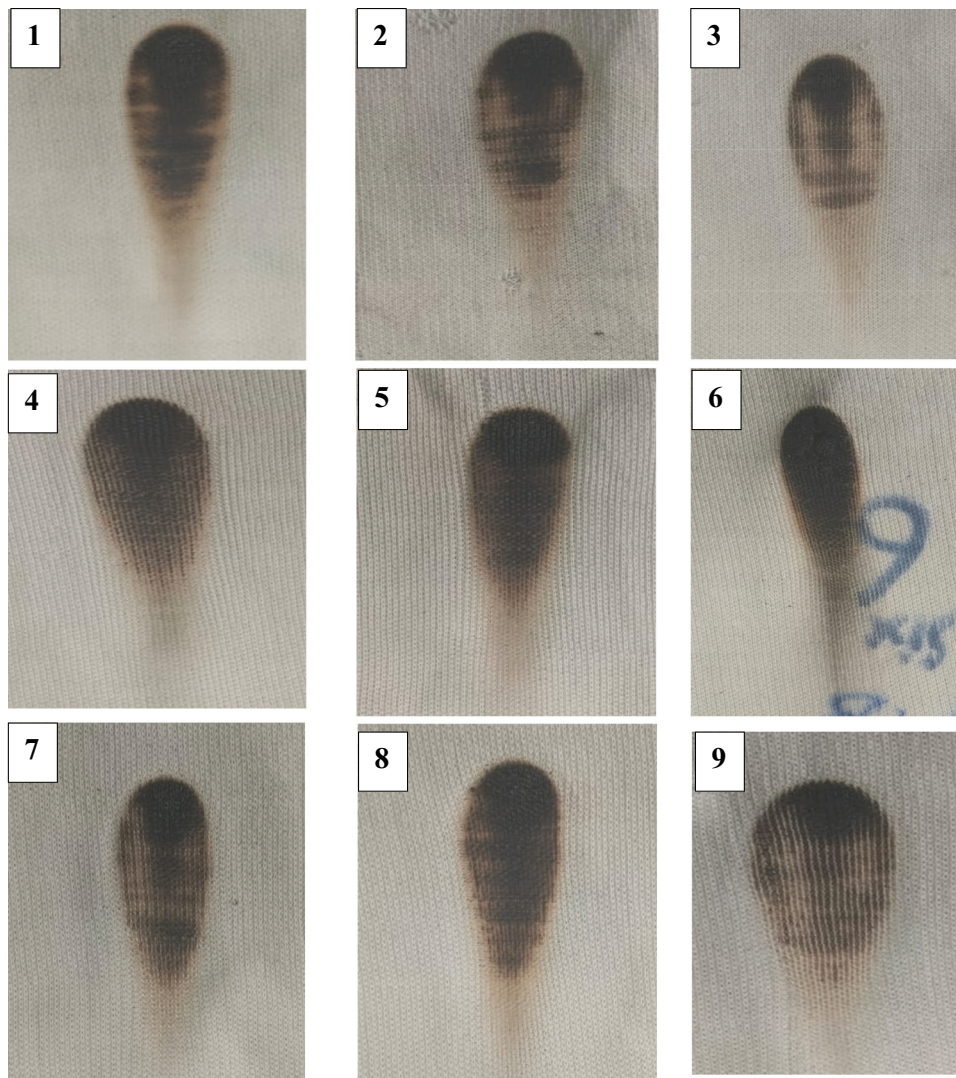


Figure 9. Burnt sample images of all the knitted fabric samples after the surface flame retardancy test.

cyclization and char formation, creating an insulating barrier that restricts oxygen diffusion and heat transfer. When the Protex proportion reaches 60%, a continuous protective network is formed within the knitted structure, promoting rapid self-extinguishment and reducing after-flame and after-glow times. At higher bamboo contents (60:40), the increased proportion of combustible cellulosic fibers contributes to longer flame and glow durations. In comparison, the PS/CT and PS/CM structures exhibited slightly longer glow times, which may be attributed to tuck-and-miss loops that influence heat retention within the fabric structure. Furthermore, an increase in bamboo content (60:40) resulted in a slight increase in both flame and glow times; however, these values remained within an acceptable flame-resistant range.

Figure 10 presents the microscopic images of the fabric samples after flame exposure, providing clear insight into the burning mechanism and structural integrity of the developed knitted fabrics. It is evident from the images that no hole formation, debris generation, or structural collapse occurred in any sample, confirming the excellent flame-resistant performance observed in the flame-retardancy tests. The preservation of loop geometry after exposure indicates the effectiveness of Protex fibers in forming a protective char layer, which restricts flame propagation and maintains fabric integrity. In the PS/PS structure (Figure 10a,b), the Protex side exhibited only partial surface carbonization, while the bamboo side showed limited burning, indicating controlled thermal degradation. This behavior correlates well with the negligible flame time (0–3 s) and minimal glow time (0–1 s) observed for PS/PS samples. The uniform and compact loop structure likely contributed to better heat distribution and

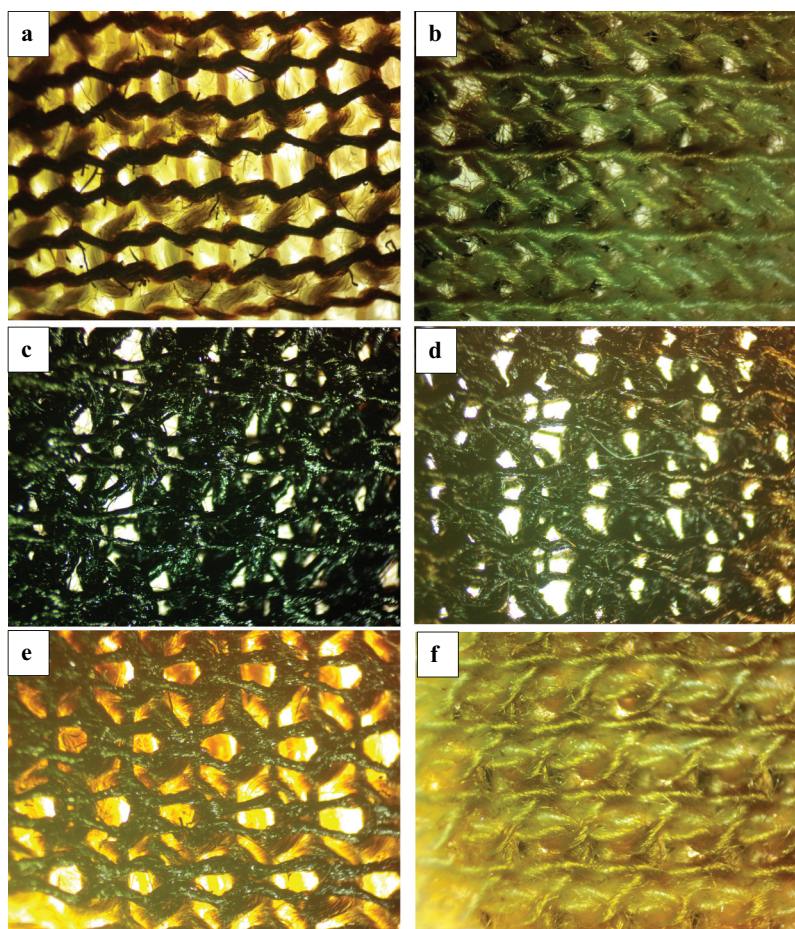


Figure 10. Microscopic images of burnt samples (a) (PS/PS) Protex side, (b) (PS/PS) bamboo side, (c) (PS/CT) Protex side, (d) (PS/CT) bamboo side, (e) (PS/CM) Protex side, (f) (PS/CM) bamboo side.

reduced oxygen availability, thereby enhancing flame resistance. For the PS/CT structure (Figure 10c-d), the Protex yarns appeared charred (blackened) and showed no structural damage, demonstrating effective thermal shielding. However, the bamboo side exhibited more pronounced blackening, indicating greater susceptibility to thermal degradation. This observation is consistent with the slightly longer flame time (2–3 s) and glow time (2 s) observed for PS/CT samples. The presence of tuck loops may have introduced localized heat-accumulation zones, promoting mild afterglow behavior. In contrast, the PS/CM structure (Figure 10e,f) exhibited more pronounced burning and blackening than the PS/PS structure, particularly on the Protex and bamboo sides. The bamboo side exhibited greater thermal degradation, consistent with the relatively longer glow times (up to 5 s) observed for PS/CM samples. The miss loop configuration likely creates a more open, less stable structure, thereby facilitating heat penetration and prolonged smoldering.

The microscopic observations strongly support the flame test results, which showed that all samples exhibited self-extinguishing behavior with very short flame times. However, variations in glow time and extent of carbonization are influenced by the knitted structure and fiber distribution. The PS/PS structure exhibited the most stable burning behavior, followed by PS/CT, while PS/CM showed comparatively higher thermal degradation. These findings confirm that fabric structure plays a critical role in controlling post-flame behavior. At the same time, the presence of Protex fibers ensures overall flame resistance by limiting structural damage and preventing flame spread.

Although the horizontal flammability test provides a useful comparative assessment of flame propagation behavior, it does not fully characterize the fire performance of textile materials. Previous studies by Horrocks and coworkers have demonstrated that comprehensive flame-retardant evaluation should include additional parameters such as Limiting Oxygen Index (LOI), vertical flammability behavior,

thermogravimetric analysis (TGA), cone calorimetry, heat release rate, and char residue formation (Holdsworth, Richard Horrocks, and Kandola 2020). Therefore, the present results should be interpreted as an initial evaluation of relative flame resistance among the developed bilayer structures rather than a complete fire-performance assessment. Nevertheless, the significantly lower flame times observed for fabrics containing higher proportions of Protex® fibers are consistent with the inherent flame-resistant behavior of modacrylic fibers, which exhibit high LOI values (approximately 30–33) and promote self-extinguishing behavior through char formation and reduced oxygen availability during combustion.

Overall, the results confirm that incorporating Protex fibers significantly enhances the flame resistance of knitted fabrics, even when blended with combustible bamboo fibers. All samples exhibited self-extinguishing behavior (≤ 3 seconds flame time), negligible after-glow, and no structural damage, demonstrating excellent fire performance. Among the developed fabrics, those with a 40:60 bamboo/Protex ratio showed the best flame resistance, with zero or near-zero flame and glow times. These findings suggest that the optimized combination of Protex fibers and engineered knitted structures can produce highly flame-resistant fabrics suitable for protective textile applications.

To provide a broader perspective on the flame-retardant performance of the developed bilayer knitted fabrics, the obtained results were compared with reported behavior of pure bamboo and pure Protex® fabrics from the literature. Bamboo fibers are cellulosic in nature and generally exhibit relatively high flammability, with limiting oxygen index (LOI) values typically ranging from 18 to 21. Pure bamboo fabrics readily ignite and sustain combustion, often exhibiting longer after-flame times, significant char formation, and continuous flame propagation due to the combustible cellulose backbone. In contrast, Protex® (modacrylic) fibers are inherently flame resistant and possess significantly higher LOI values of approximately 30–33. Upon flame exposure, Protex® fibers undergo cyclization and char formation, producing a protective barrier that suppresses flame propagation and promotes self-extinguishing behavior.

The developed bamboo bilayer fabrics exhibited after-flame times ranging from 0 to 3 s and after-glow times ranging from 0 to 5 s, with no hole formation, melting, debris generation, or flame spread to the fabric edge. These results indicate substantially improved flame resistance compared with conventional bamboo fabrics reported in the literature and demonstrate flame-retardant behavior approaching that of inherently flame-resistant Protex® textiles. The superior performance of the developed fabrics confirms that incorporating 40–60% Protex® fibers is sufficient to establish an effective flame-resistant network within the knitted structure while retaining the comfort and antibacterial benefits of bamboo fibers. The present results demonstrate that the developed bilayer fabrics possess promising flame-resistant characteristics suitable for protective textile applications.

Mechanism of multifunctional performance

The multifunctional performance of the developed bilayer knitted fabrics originates from the synergistic combination of flame-resistant Protex® fibers and antibacterial bamboo fibers within a strategically designed bilayer architecture, as shown in Figure 11. In this structure, Protex® yarns are positioned on the outer layer, while bamboo yarns are located on the inner skin-contact layer. The flame-resistant behavior is primarily attributed to the inherent flame-retardant nature of Protex® fibers. Upon exposure to a flame source, Protex® undergoes thermal degradation accompanied by cyclization and char formation. The resulting char layer acts as a protective barrier that restricts heat transfer and oxygen diffusion, thereby suppressing flame propagation and promoting self-extinguishing behavior. The relatively high limiting oxygen index (LOI ≈ 33) of Protex® further contributes to its excellent flame resistance. Consequently, fabrics containing higher proportions of Protex® exhibited shorter after-flame and after-glow times.

The antibacterial functionality is mainly associated with the bamboo-rich inner layer. Bamboo fibers have been reported to exhibit natural antibacterial properties and excellent moisture management. By placing bamboo yarns directly on the skin-contact side, the fabric promotes rapid moisture absorption and transport, thereby reducing the humid microenvironment favorable for bacterial growth. The antibacterial effect is primarily contact-based rather than diffusion-based, leading to suppression of bacterial growth on the fabric surface. Furthermore, the bilayer architecture spatially separates the two functionalities. The outer Protex® layer serves as a protective flame-resistant shield, while the inner bamboo layer provides antibacterial performance, moisture management, and wearer comfort. This functional segregation enables

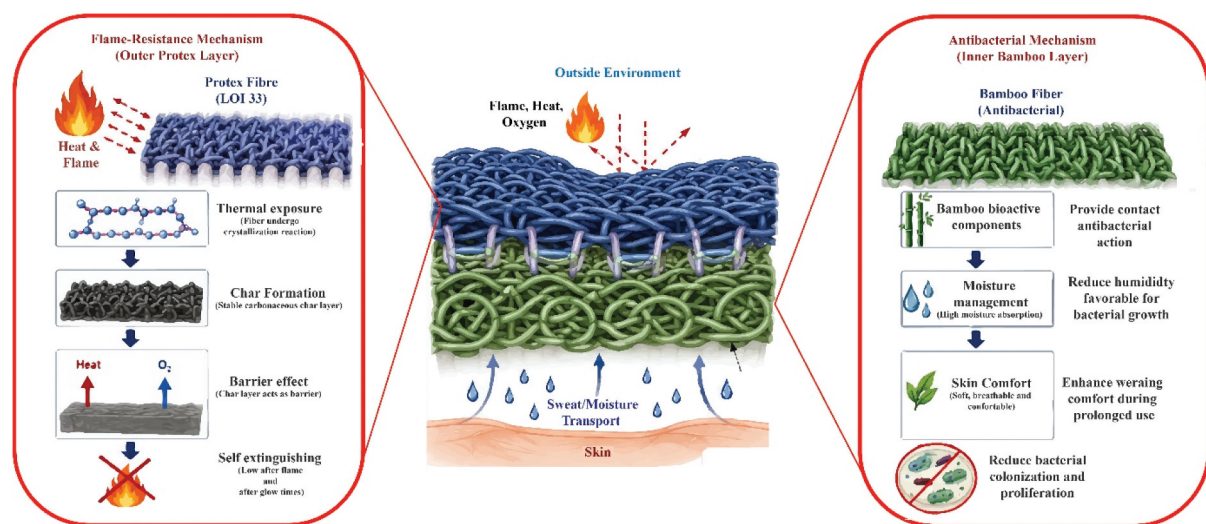


Figure 11. Mechanism of multifunctional flame-resistant and antibacterial performance in bilayer bamboo/Protex knitted fabrics.

simultaneous optimization of fire protection, hygiene, and comfort, which represents the key design rationale and novelty of the developed bilayer knitted fabrics.

Statistical analysis

The statistical analysis using the general linear model ANOVA was performed to evaluate the influence of knitted structure and blend ratio on the functional properties of the developed fabrics at a 95% confidence level ($p < .05$), and the results are shown in Table 8. The results indicate that knitted structure significantly affects air permeability ($p = .036$) and thermal resistance ($p = .025$), confirming that loop geometry and fabric architecture play a dominant role in controlling airflow and heat transfer. In contrast, blend ratio does not significantly influence air permeability ($p = .681$), highlighting that structural parameters are more critical than fiber composition for this property. For thermal resistance, the blend ratio showed a p -value of 0.059, indicating a borderline effect and suggesting that fiber composition has a secondary influence relative to fabric structure.

The moisture management property (OMMC) was not significantly affected by either the knitted structure ($p = .819$) or the blend ratio ($p = .784$), indicating minimal dependence on these design variables. In terms of flammability behavior, blend ratio significantly influenced flame time ($p = .041$), confirming that fiber composition (bamboo vs. Protex) governs flame resistance. However, the knitted structure had no significant effect, and neither factor significantly affected glow time. For mechanical properties, including tensile strength, elongation at break, and bursting strength, neither knitted structure nor blend ratio showed statistically significant effects ($p > .05$). Specifically, bursting strength showed high p -values for both the knitted structure ($p = .530$) and the blend ratio ($p = .939$), indicating that variations in structure and composition within the tested range do not significantly alter the fabrics' multidirectional strength behavior. Overall, the findings suggest that knitted structure primarily governs comfort-related properties. At the

Table 8. General linear model ANOVA results.

Response Property	Knitted Structure (p-value)	Significance	Blend Ratio (p-value)	Significance
Air Permeability	.036	Significant	.681	Not Significant
Thermal Resistance	.025	Significant	.059	Not Significant*
OMMC	.819	Not Significant	.784	Not Significant
Flame Time	.673	Not Significant	.041	Significant
Glow Time	.362	Not Significant	.090	Not Significant
Tensile Strength	.200	Not Significant	.234	Not Significant
Elongation at Break	.840	Not Significant	.577	Not Significant
Bursting Strength	.530	Not Significant	.939	Not Significant

same time, the blend ratio primarily influences flame behavior, whereas mechanical properties (tensile and bursting) and moisture management remain relatively unaffected within the design space studied.

Main effect plot

Main-effect plots in [Figure 12](#) were used to evaluate the independent effects of knitted structure and blend ratio on the functional and mechanical properties of the developed fabrics. The results revealed that the knitted structure had a pronounced effect on air permeability and thermal resistance, which is consistent with the ANOVA findings ($p < .05$). Specifically, the PS/CT structure exhibited the highest air permeability, followed by PS/PS and PS/CM. This behavior is attributed to the presence of tuck loops in PS/CT, which increase fabric porosity and facilitate air flow. In contrast, the PS/CM structure exhibited comparatively lower air permeability, likely due to tighter loop configurations that restrict airflow.

For thermal resistance, the PS/PS structure showed relatively higher values, indicating better heat insulation due to its compact, uniform loop arrangement. The PS/CM structure exhibited lower thermal resistance, which may be attributed to its structural openness and reduced ability to trap still air. The blend ratio significantly influenced flame time, with fabrics with higher Protex content (40:60) exhibiting the lowest flame time, confirming superior flame resistance. In contrast, increasing bamboo content (60:40) led to higher flame time due to the combustible nature of cellulose-based fibers. For mechanical properties, including tensile strength and elongation, the main effect plots indicated moderate trends but no statistically significant differences. However, an increase in bamboo content generally improved tensile strength, while higher Protex content enhanced elongation, reflecting a balance between strength and flexibility. The interpretation of main effect plots indicates that the performance of the developed double-layer knitted fabrics is primarily governed by individual factor contributions, enabling targeted optimization of structure for comfort and composition for flame resistance.

Multi-response optimization using Grey relational Analysis

Since the developed bilayer knitted fabrics exhibited multiple performance responses, including comfort, mechanical, and flame-retardant properties, Grey Relational Analysis (GRA) was employed to identify the optimal fabric configuration considering all performance parameters simultaneously. Air permeability, thermal resistance, bursting strength, OMMC, tensile strength, and elongation at break were treated as higher-the-better characteristics, whereas flame time and glow time were treated as lower-the-better characteristics. After data normalization, gray relational coefficients were calculated using a distinguishing coefficient of 0.5, and the gray relational grade (GRG) was determined as the average of all coefficients.

The calculated GRG values in [Table 9](#) indicated that the PS/CT fabric with a 40:60 bamboo/Protex blend ratio achieved the highest overall performance ($\text{GRG} = 0.801$), followed closely by the PS/PS structure with the same blend ratio ($\text{GRG} = 0.798$). The superior performance of these fabrics can be attributed to the higher proportion of Protex fibers, which significantly improved flame resistance while maintaining satisfactory comfort and mechanical characteristics. In contrast, fabrics containing a higher bamboo proportion (60:40) exhibited lower overall GRG values due to increased flame and glow times.

Analysis of factor effects revealed that the 40:60 bamboo/Protex blend ratio produced the highest average GRG value (0.749), demonstrating that fiber composition was the most influential factor governing multifunctional performance. Among the knitted structures, PS/PS exhibited the highest average GRG value (0.689), indicating that its balanced loop geometry provided the most favorable combination of comfort, strength, and flame resistance. Therefore, the results suggest that a Protex-rich bilayer configuration is the most suitable design for multifunctional protective knitted fabrics requiring simultaneous flame resistance, comfort, and mechanical durability.

Conclusion

This paper investigated the impact of fiber blend ratio and knitted structure on the performance of bamboo/Protex-blended fabrics for use as protective textiles. The characterization of the yarn revealed that bamboo

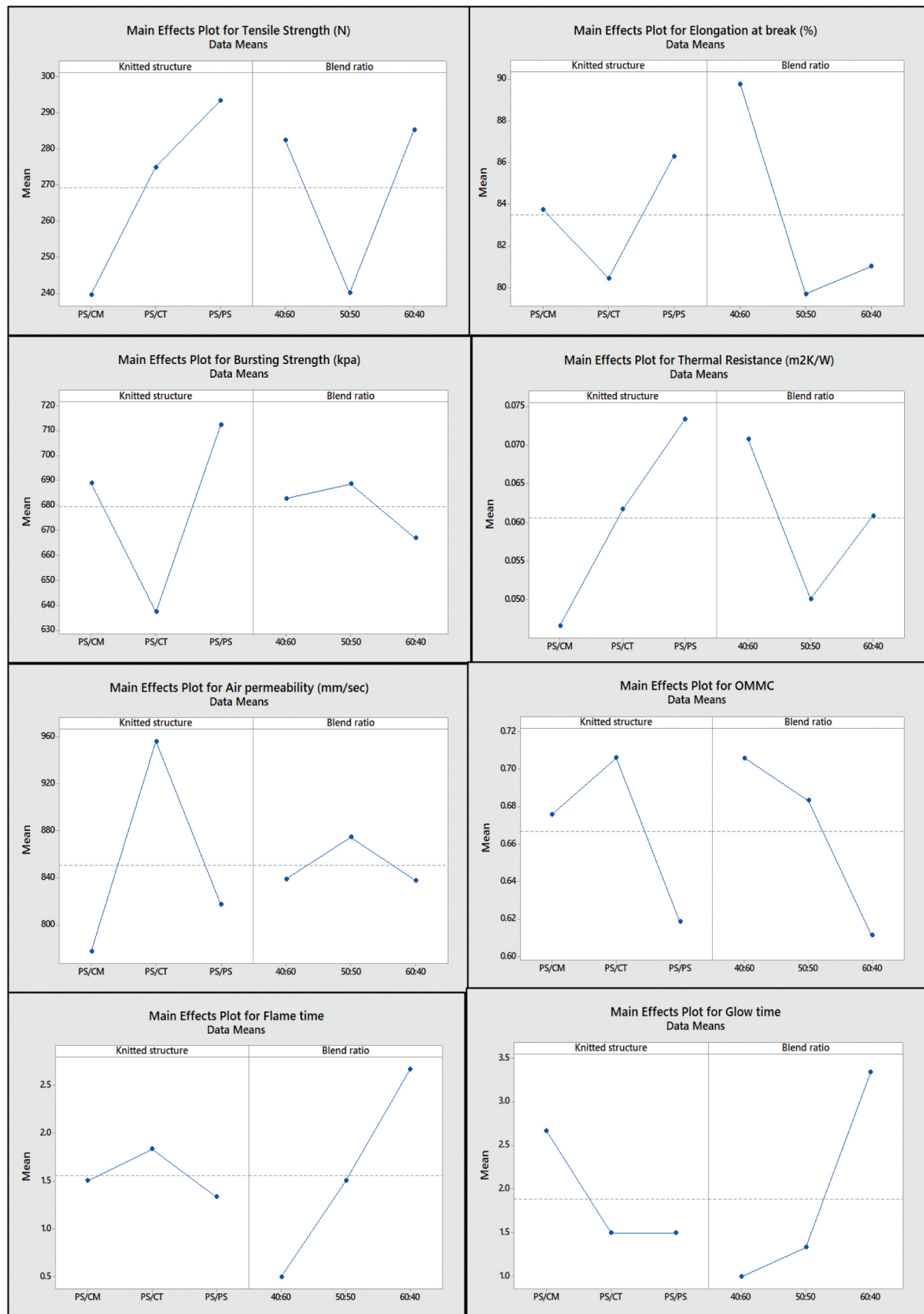


Figure 12. Main effects plots for all the responses.

Table 9. Grey relational grades and ranking of developed fabrics.

Fabric Code	Structure	Blend Ratio	GRG	Rank
S1/R1	PS/PS	50:50	0.660	3
S1/R2	PS/PS	40:60	0.798	2
S1/R3	PS/PS	60:40	0.608	5
S2/R1	PS/CT	50:50	0.587	6
S2/R2	PS/CT	40:60	0.801	1
S2/R3	PS/CT	60:40	0.531	7
S3/R1	PS/CM	50:50	0.502	8
S3/R2	PS/CM	40:60	0.647	4
S3/R3	PS/CM	60:40	0.491	9

yarn had a greater lea strength (2963). Still, Protex yarn had a greater tenacity (3.8 g/denier) and elongation (17%), which helped to increase the mechanical stability of the blended fabrics. The knitted structure had a great influence on the physical properties of the fabrics. With PS/CM structures, the highest stitch density and fabric compactness were attained, whereas with PS/CT structures, the fabric was relatively thicker and had high air permeability. The PS/CM structures were the most compact, and the maximum bursting strength (792.9 kPa) was obtained, but the PS/CT structures had relatively lower strength of about 599 kPa. All samples were highly resistant to pilling, with a Grade 5 rating. The comfort property showed that PS/CT fabrics were superior to PS/PS fabrics in moisture transport and breathability. In contrast, PS/PS fabrics exhibited superior thermal resistance because they entrap more air within their structure. The developed bilayer knitted fabrics demonstrated that knitted structure significantly affected air permeability ($p = .036$) and thermal resistance ($p = .025$), whereas blend ratio primarily governed flame resistance behavior ($p = .041$). Fabrics containing 60% Protex® fibers exhibited the lowest flame time, confirming the effectiveness of Protex® in enhancing fire resistance. Increasing Protex® content promotes the formation of a more continuous flame-resistant network that generates a stable protective char layer during thermal exposure – during flame resistance testing in line with ISO 15025, fabrics with an increased proportion of Protex fibers exhibited better flame resistance and shorter overall after-flame and after-glow periods. While the horizontal flammability test demonstrated the beneficial effect of Protex® incorporation on flame resistance, future studies should employ complementary fire-performance techniques such as Limiting Oxygen Index (LOI), vertical flame testing, thermogravimetric analysis (TGA), and cone calorimetry to provide a more comprehensive understanding of combustion behavior, thermal degradation mechanisms, and heat release characteristics of the developed bilayer knitted fabrics. Altogether, the results indicate that multifunctional fabrics with high mechanical strength, comfort performance, antibacterial activity, and enhanced flame resistance can be created by combining bamboo and Protex fibers with appropriate knitted structures. Furthermore, the bilayer architecture enabled the integration of flame protection via the outer Protex® layer and antibacterial comfort via the inner bamboo layer, making these fabrics suitable for protective workwear, children's sleepwear, bedding products, and healthcare textiles that require a balance of safety, hygiene, and thermophysiological comfort.

Author contributions

CRedit: **Muhammad Ehtisham Sarwar:** Formal analysis, Investigation, Methodology, Writing – original draft; **Rimvydas Milasius:** Conceptualization, Supervision, Validation, Visualization, Writing – review & editing.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

The data will be made available as per requirement.

References

- Abbas, Adeel, Habib Awais, Waqas Ashraf, Muzzamal Hussain, Muhammad Haroon Rashid, and Hafiz Shehbaz Ahmad. 2026. "Cotton/Protex Knitted Multifunctional Fabrics for Undergarments with Antibacterial, Flame-Retardant and Thermal Comfort Properties." *International Journal of Occupational Safety and Ergonomics* 32 (1): 328–337. <https://doi.org/10.1080/10803548.2025.2540165>.
- Ali, Zaid, Farooq Azam, Bushra Mushtaq, Sheraz Ahmad, Faheem Ahmad, Muhammad Sohail Zafar, Abher Rasheed, and Muhammad Qamar Khan. 2024. "Development of Sustainable Flame-Retardant Bio-Based Hydrogel Composites from Hemp/Wool Nonwovens with Chitosan-Banana Sap Hydrogel." *Scientific Reports* 14 (1): 22116. <https://doi.org/10.1038/s41598-024-73052-0>.
- Brushlinsky, N. N., S V Sokolov Marty Ahrens, and Peter Wagner. 2017. "World Fire Statistics Report No. 10 of the Center of Fire Statistics of CTIF."
- Cai, Yujie, Zewen Li, Bin Wang, Chao Xu, Xing Tian, and Fengyu Quan. 2025. "Cashmere Blended with Calcium Alginate Fibers: Eco-Friendly Improvement of Flame Retardancy and Maintenance of Hygroscopicity." *Polymers* 17 (11): 1497. <https://doi.org/10.3390/polym17111497>.
- Dejene, Bekinew Kitaw, Mulat Alubel Abtew, and Mihret Pawlos. 2025. "Eco-Friendly Flame Retardant and Antibacterial Finishing Solutions for Cotton Textiles: A Comprehensive Review." *Journal of Industrial Textiles* 55. May. <https://doi.org/10.1177/15280837251325779>.
- Faheem, Sajid, Nazia Nahid, Jakub Wiener, Blanka Tomková, Miroslava Pechočáková, Jiří Militký, and Adnan Mazari. 2023. "Flame Retardancy of Textiles—New Strategies and Mechanisms." *In*: 279–317. https://doi.org/10.1007/978-981-99-6002-6_12.
- Fan, Zuwei, Yihai Xue, Hao Liu, Yuanyuan Yu, and Rangtong Liu. 2025. "Durable Flame-Retardant Finishing of Cotton Fabric via Constructing Multiple Crosslinked Layers." *Cellulose* 32 (4): 2649–2661. <https://doi.org/10.1007/s10570-025-06393-2>.
- Feng, Bingtao, Senlong Yu, Hengxue Xiang, Lili Li, and Meifang Zhu. 2025. "Current Status and Future Trends for Modification Technology of Flame Retardant Nylon 66." *Polymers* 17 (8): 1074. <https://doi.org/10.3390/polym17081074>.
- Ghosh, Joyjit, Nishat Sarmin Rupanty, Tasneem Noor, Tanvir Rahman Asif, Tarikul Islam, and Vladimir Reukov. 2025. "Functional Coatings for Textiles: Advancements in Flame Resistance, Antimicrobial Defense, and Self-Cleaning Performance." *RSC Advances* 15 (14): 10984–22. <https://doi.org/10.1039/D5RA01429H>.
- Goller, Sebastian Manfred, Bernhard Scharrel, and Simone Krüger. 2024. "Phosphorus Features Halogen –Calcium Hypophosphite Replaces Antimony Trioxide, Reduces Smoke, and Improves Flame Retardancy." *Thermochimica Acta* 737 (July): 179764. <https://doi.org/10.1016/j.tca.2024.179764>.
- Holdsworth, Alistair F., A. Richard Horrocks, and Baljinder K. Kandola. 2020. "Potential Synergism Between Novel Metal Complexes and Polymeric Brominated Flame Retardants in Polyamide 6.6." *Polymers* 12 (7): 1543. <https://doi.org/10.3390/polym12071543>.
- Islam, Md Rashedul, Kevin Golovin, and Patricia I. Dolez. 2023. "Clothing Thermophysiological Comfort: A Textile Science Perspective." *Textiles* 3 (4): 353–409. <https://doi.org/10.3390/textiles3040024>.
- Jamshaid, Hafsa, Rajesh Mishra, Awais Khan, Vijay Chandan, Miroslav Muller, and Petr Valasek. 2023. "Flammability and Comfort Properties of Blended Knit Fabrics Made from Inherently Fire-Resistant Fibers to Use for Fire Fighters." *Heliyon* 9 (2): e13127. <https://doi.org/10.1016/j.heliyon.2023.e13127>.
- Jin, Liping, Chenpeng Ji, Shun Chen, Zhicong Song, Juntong Zhou, Kun Qian, and Wenwen Guo. 2023. "Multifunctional Textiles with Flame Retardant and Antibacterial Properties: A Review." *Molecules* 28 (18): 6628. <https://doi.org/10.3390/molecules28186628>.
- Khan, Awais Ahmad, Hafsa Jamshaid, Rajesh Kumar Mishra, Vijay Chandan, Viktor Kolář, Petr Jirků, Miroslav Müller, Shabnam Nazari, Tatiana Alexiou Ivanova, and Tanveer Hussain. 2023. "An Analysis of the Performance and Comfort Properties of Fire-Protective Material by Using Inherently Fire-Retardant Fibers and Knitting Structures." *Materials* 16 (23): 7347. <https://doi.org/10.3390/ma16237347>.
- Kim, Hyun Ah, and Seung Jin Kim. 2019. "Flame Retardant, Anti-Static and Wear Comfort Properties of Modacrylic/excel®/anti-Static PET Blend Yarns and Their Knitted Fabrics." *The Journal of the Textile Institute* 110 (9): 1318–1328. <https://doi.org/10.1080/00405000.2019.1565626>.
- Kozłowski, R. M., M. Muzyczek, and J. Walentowska. 2014. "Flame Retardancy and Protection Against Biodeterioration of Natural Fibers." *In Polymer Green Flame Retardants*, edited by Constantine D. Papaspyrides and Pantelis Kiliaris, 801–836. Elsevier. <https://doi.org/10.1016/B978-0-444-53808-6.00023-8>.
- Li, Ping, Yuan-Lin Ren, Ying-Jun Xu, and Yun Liu. 2025. "One-Step and Multi-Functional Polyester/Cotton Fabrics with Phosphorylation Chitosan: Its Flame Retardancy, Anti-Bacteria, Hydrophobicity, and Flame-Retardant Mechanism." *Progress in Organic Coatings* 203 (June): 109179. <https://doi.org/10.1016/j.porgcoat.2025.109179>.
- Malucelli, Giulio. 2022. "How to Reduce the Flammability of Plastics and Textiles Through Surface Treatments: Recent Advances." *Coatings* 12 (10): 1563. <https://doi.org/10.3390/coatings12101563>.
- Nahrawi, Shuhaila, Shahrizad Fitri Mustapha, and Suriati Saidan. 2020. "An Innovation of Children's Outdoor Clothing to Increase the Risk of Playground Injuries." *Ideology Journal* 5 (2): 121–130. <https://doi.org/10.24191/ideology.v5i2.234>.

- Nandy, Shreyasi, T V Sreekumar Nidhi Vahalia, and Neha Mehra. 2024. "Recent Advancements In Flame Retardant Textiles." *BTRA Scan* 53 (1): 10–25. <https://btraindia.com/filemanager/btrascan/jan24/BTRA-Scan-JANUARY-2024-14-29.pdf>.
- Niu, Ben, Xiao Tian, Meiling Wong, Waiyu Siu, Chun Zhang, Yiyi Yang, Mengyan Yang, and Tao Hua. 2023. "Toward High-Performance FR Viscose/meta-Aramid Blended Yarns Enabled by Vortex Spinning Driven Core-Sheath Assembly." *Cellulose* 30 (15): 9829–9841. <https://doi.org/10.1007/s10570-023-05466-4>.
- Pamuk, Gülşah, Berna Cüreklibatır Encan, and Esra Zeynep Yıldız. 2023. "Thermal Characteristics, Mechanical and Comfort Properties of Heat-Protective Textiles." *Fibers and Polymers* 24 (12): 4457–4468. <https://doi.org/10.1007/s12221-023-00398-z>.
- Qi, Peng, Feng Chen, Yuchun Li, Hongfei Li, Xiaoyu Gu, Jun Sun, and Sheng Zhang. 2023. "A Review of Durable Flame-Retardant Fabrics by Finishing: Fabrication Strategies and Challenges." *Advanced Fiber Materials* 5 (3): 731–763. <https://doi.org/10.1007/s42765-023-00255-x>.
- Sarwar, Muhammad Ehtisham, Muhammad Sohaib Anas, and Hafsa Jamshaid. 2024. "Engineering an Eco-Friendly Hybrid Bi-Layer Fabric Having Inherently Flame-Resistant & Antibacterial Characteristics for Children's Protective Clothing." *Thermal Science and Engineering Progress* 49 (March): 102489. <https://doi.org/10.1016/j.tsep.2024.102489>.
- Tesfay, Abrha Gebregergs, and Higus Gidey Welegebreal. 2025. "Optimization of Banana Fiber Treatment Parameters for Improved Textile Performance." *Discover Materials* 5 (1): 101. <https://doi.org/10.1007/s43939-025-00294-8>.
- Weil, Edward D., and Sergei V. Levchik. 2008. "Flame Retardants in Commercial Use or Development for Textiles." *Journal of Fire Sciences* 26 (3): 243–281. <https://doi.org/10.1177/0734904108089485>.
- Zhang, Yaowen, Yuan Liu, Hui Wen, and Qi Wang. 2021. "Durable Flame Retardant and Mechanism of Bamboo Fabric Through Grafting Based on Arginine." *Cellulose* 28 (12): 8187–8204. <https://doi.org/10.1007/s10570-021-04056-6>.
- Zhou, Qingqing, Jiayi Chen, Yue Tao, LiangGui Wang, and Jianzhong Shao. 2022. "Flame-Retardant and Crease-Proofing Finishing of Cotton Fabrics via in-Situ Copolymerization of Ethylene Phytic Acid and Itaconic Acid, Part I: Fabrication Process." *Thermal Science* 26 (3 Part B): 2815–2821. <https://doi.org/10.2298/TSCI210301270Z>.