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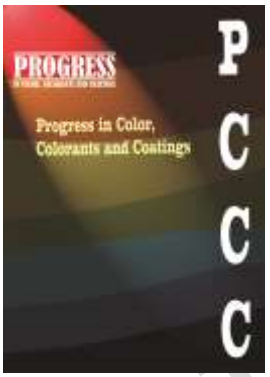

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Evaluation of Fire-Retardant Efficacy and Comfort Properties of Treated Polyester/Cotton and Polyester/Viscose Fabrics

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Abstract

This study evaluates the fire-retardant (FR) performance of polyester/cotton (PC) and polyester/viscose (PV) fabrics treated with an alkyl phosphate ester-based FR agent at concentrations of 100, 150, and 200 g/l, followed by curing at 200°C for 60 or 180 s. Untreated fabrics burned completely, whereas the FR treatment reduced flammability significantly, with char lengths of 2 cm (PC200C60t) and 0.4 cm (PV200C180t). The limiting oxygen index (LOI) increased to 22% (PC) and 23% (PV), confirming enhanced flame resistance. EDX and FTIR analyses confirmed successful FR deposition, showing increased phosphorus and nitrogen content alongside the formation of ester bonds (O-H, C=O, O-C-H). Bending stiffness rose by 29% for PV200C180t, while wrinkle recovery improved by 27.9% (PC) and 23.3% (PV). Air permeability decreased by 41.5% (PC) and 59.5% (PV), and water permeability (PDA) declined by 15.74% (PC) and 35.61% (PV). The treatment achieves an effective balance between flame resistance and wearability, demonstrating strong potential for protective textiles.

Keywords: Flame-retardant Fabrics, Polyester/cotton blends, Polyester/viscose blends,

Alkaline hydrolysis treatment, Comfort oroperties

1. Introduction

Since the 1950s, the creation of heat- and flame-retardant treatments for textiles has been a vital research focus, initially aimed at children's apparel, decorative fabrics, drapes, and nonwoven materials used in industrial settings [1, 2]. Nowadays, flame-retardant protective gear is essential for ensuring the safety of individuals in various high-risk professions, such as firefighting, military roles, and industrial sectors where they face dangers like fire, molten substances, and welding sparks [3]. Without proper fire protection in these environments, there is a risk of severe injuries, loss of life, extensive property damage, and considerable financial repercussions [4].

Blends of polyester/cotton (PC) and polyester/viscose (PV) are highly popular in the production of protective clothing, bedding, and home textiles. This popularity stems from the comfort and breathability offered by cotton and viscose fibers, with the wrinkle resistance and durability provided by polyester fibers [5-9]. Moreover, the relatively high cost of cotton fibers makes polyester blends a more cost-effective option for certain uses. Polyester is particularly valued for its excellent chemical resistance, abrasion resistance, and wrinkle resistance, making it one of the most widely used synthetic fibers. However, its tendency to spread fire through molten droplets during burning presents a significant hazard, highlighting the importance of improving the fire-resistance of polyester-based fabrics [10, 11].

Özer and Gaan have recently reviewed the significant transition towards phosphorus-based flame-retardant (FR) systems that work in conjunction with nitrogen, silicon, and

boron to satisfy both environmental and performance requirements [12]. A variety of studies have investigated different techniques to enhance the fire-retardant characteristics of PC and PV fabrics. For instance, Wang et al. [13] treated PC fabrics with a nanomaterial layer containing phosphorus, nitrogen, and silicon, which significantly improved fire resistance. Pan et al. [14] applied a fire-retardant coating on PC fabrics using polyethyleneimine (PEI) and oxidized sodium alginate (OSA), achieving substantial reductions in heat release rates. Carosio et al. [15] investigated the use of casein to enhance the fire-retardancy of PC, cotton, and polyester fabrics, resulting in increased Limiting Oxygen Index (LOI) values and reduced burning rates. Similarly, Yang and Chen (16) used hydroxy-functional organophosphorus oligomer (HFPO) and N,N′-dimethyloldihydroxyethyleneurea (DMDHEU) to create an anti-aging layer on PC fabrics, improving LOI values and reducing char length. Other studies by Fang et al. [17], Li et al. [18], Wang et al. [19], and Nosaka et al. [1] have demonstrated various fire-retardant treatments, including the use of phytic acid, chitosan, ammonium phytate, phosphoramidite siloxane, and carbon nanotubes, all contributing to enhanced fire-resistance in treated fabrics. Li et al. [20] developed a novel composite coating containing P/N/B and bio-based compounds on polyester/cotton blended fabrics and reported good flame retardancy and exhibited excellent char-forming ability. Lu et al. [21] achieved effective flame retardancy in polyester/cotton blended fabrics by synthesizing a novel high-molecular-weight reactive flame-retardant, phosphoramide ammonium salt of polyethyleneimine derivatives. Xie et al. [22] developed a novel flame-retarding strategy for polyester/cotton (T/C) blended fabrics to inhibit the “scaffolding effect” by applying independent flame retardation to each component. A copolymerized flame-retardant for

polyester and cotton fibers was used, followed by grafting halogen-free ammonium vinyl phosphonate (AMVP) onto the cotton. The treated fabric achieved a limiting oxygen index (LOI) of 37.2%, with significant reductions in peak heat release rate (PHRR) and total heat release (THR) by 54.3% and 66.5%, respectively. Zhang et al. (23) developed a durable flame-retardant coating for polyester/cotton (T/C) blend fabrics using in-situ polymerization of phosphorus/nitrogen-based compounds. The coated fabrics showed excellent flame retardancy, with an LOI of 28% and a 39.7% reduction in peak heat release rate. The coating maintained self-extinguishing properties after 65 washes and had minimal impact on fabric properties like whiteness, strength, and breathability. A novel biobased flame-retardant (FR), phytic acid–urea (PA-UR) salt, was synthesized by Dong et al. [24] to enhance the flame retardancy of polyester/cotton (T/C) fabrics. The PA-UR-coated fabric achieved self-extinguishing with a limiting oxygen index (LOI) of 31.8% and significantly reduced heat release capacity, indicating lower fire hazards. Innovative solutions like Zhang et al.'s phosphoryl imidazolate compound (DOPIM) demonstrate how small-molecule FR agents can simultaneously suppress polyester melting and cotton flammability via condensed-phase char formation [25].

Cutting-edge developments continue to push the boundaries of FR technology. Recent advances in FR treatments for polyester blended fabrics include:

- Nanocomposite coatings, as comprehensively reviewed by Attia et al. [26]
- Bio-based systems such as Xie et al.'s chitosan-AMVP complexes, which achieve LOI >30% while preserving fabric hand feel [27].
- Multifunctional approaches like Li et al.'s phosphorylation chitosan, integrating flame retardancy, antibacterial properties, and hydrophobicity [28].

- Smart textiles, such as the study of Wu et al. [29], with GO@PA/CNTs coatings, enabling super-fast fire alarms.

Despite progress, challenges persist in balancing FR efficacy with other properties like comfort, cost, and mechanical properties. For instance, Ali et al. showed gamma-irradiated PVA/starch coatings with Al/P additives improve LOI but require careful optimization to maintain mechanical properties [30]. Similarly, Zhang et al. developed AP/N FR agents that enhance char formation without compromising fabric strength [31].

In this study, PC and PV fabrics were washed, desized, and subjected to alkaline hydrolysis before being treated with varying concentrations of an alkyl phosphate ester fire retardant. The treated fabrics were padded, dried, and cured. Fire retardancy was assessed using direct flame tests and LOI measurements, with EDX and FTIR. Additionally, comfort properties, including bending stiffness, wrinkle recovery, air permeability, and water permeability, were evaluated.

2. Experimental

2.1. Materials

In this study, an organophosphate flame-retardant material was used to treat the fabrics. The primary component of this material is alkyl phosphate ester, with a phosphorus content exceeding 19%, and it is soluble in water. This flame-retardant was supplied by Hangzhou Chungyo Chem Co. (China) under the trade name Sylic FU5107. Polyester/cotton (PC) and polyester/viscose (PV) fabrics with similar structural properties were also prepared for this study. The specifications of the fabrics used are provided in Table 1.

Table 1. Specifications of fabrics

Type	Warp density [threads/cm]	Weft density [threads /cm]	Warp yarn count [Ne]	Weft yarn count [Ne]	Weave pattern	Weight [g/m^2]
polyester/cotton (70/30)	31	23	30/2	30/2	Twill 2/1	377
polyester/viscose (70/30)	34	23	32/2	32/2	Twill 2/1	356

2.2. Methods

2.2.1. Pre-treatment of fabrics

PV and PC fabrics underwent pre-treatment to optimize surface and hydrophilic properties for subsequent processing.

a) Washing of PV fabric: The PV fabric was washed using 5 g/L of soap with a liquor ratio of 1:20 at 60 °C for 20 minutes.

b) Washing and desizing of PC fabric: The PC fabric was washed and desized using a solution containing 5 g/L of soap and 2 g/L of Amylase enzyme Perizym P-AM (from Parand Chemical Co., Iran) with a liquor ratio of 1:20 at 60 °C for 30 minutes.

c) Alkaline hydrolysis of PC fabric: To enhance the surface and hydrophilic properties of the PC fabric, alkaline hydrolysis was performed. The fabric was treated with a solution containing 5 g/L of soap and 20% soda with a liquor ratio of 1:20 at 80 °C for 60 minutes.

2.2.2 Fabric treatment procedure

PC and PV fabric samples, each measuring 30 × 10 cm, were prepared for treatment. The fire retardant solution was prepared at three concentrations: 100, 150, and 200 g/L, with a liquor ratio of 1:10. The samples were immersed in this solution for 5 minutes, then passed through calender rollers of an SDL Atlas D394A machine, ensuring a 100% pickup. Following this, the samples were dried in an oven at 120 °C for 3 minutes. Subsequently, the samples were cured using an SDL Atlas D398 stenter machine at 200 °C with two different curing times: 60 and 180 seconds. To enhance treatment effectiveness, the fabrics were padded twice before the curing process. After the second curing, the samples were rinsed and dried at ambient temperature. The samples were coded according to the type of fabric, concentration of the fire-retardant solution, and curing conditions. For instance, the code PC100C60t denotes a polyester/cotton fabric treated with a 100 g/L concentration of fire retardant and cured for 60 seconds. Untreated samples were coded as PC-U for polyester/cotton and PV-U for polyester/viscose.

2.2.3. Direct flame test

The direct flame test was conducted in accordance with the ISO 15025 standard to evaluate the ignition behavior and flame-spread mechanism of the treated fabrics. This test provides insights into how the fire-retardant treatment influences the material's response to direct flame exposure. Each sample was suspended vertically, and a flame was applied to the bottom surface at a distance of 20 mm ± 2 mm from the lower edge of the sample. The flame was positioned at a 30° angle to the vertical axis and was applied for 3 seconds. Ease of ignition, flame spread, and droplet production were recorded, as

these parameters are critical indicators of fire behavior. After the test, the length of the char was measured to quantify fire resistance.

2.2.4. LOI test

The Limiting Oxygen Index (LOI) test was performed according to the ASTM D2863 standard. This test measures the minimum concentration of oxygen required to support combustion, thereby assessing the relative flammability of the samples. By determining the LOI value, the effectiveness of the fire-retardant treatment can be quantitatively analyzed, providing a comparative measure of the treated and untreated fabrics' fire resistance.

2.2.5. FTIR test

Fourier Transform Infrared Spectroscopy (FTIR) was conducted using a BRUKER Equinox 55 spectrometer to analyze the chemical composition of the samples. FTIR identifies functional groups and confirms fire-retardant deposition, elucidating the chemical mechanisms responsible for improved fire resistance.

2.2.6. EDX test

Energy Dispersive X-ray Spectroscopy (EDX) analysis was performed using a Scanning Electron Microscope (SEM) equipped with an EDX detector to determine the elemental composition of the samples. This analysis verifies the deposition of fire-retardant elements on the fabric surface and provides a better understanding of their distribution and potential bonding mechanisms.

2.2.7. Scanning Electron Microscopy (SEM)

Surface morphology of untreated and coated fabric samples was examined using a TESCAN VEGA3 scanning electron microscope. Samples were mounted on aluminum stubs using conductive carbon tape and sputter-coated with a 10 nm gold layer to prevent charging effects. Imaging was performed at an accelerating voltage of 15 kV under high vacuum conditions, with working distances between 8-12 mm. Secondary electron signals were collected at various magnifications (500× to 9000×) to characterize fiber surface topography and coating distribution. Representative images were captured from multiple sample regions to ensure consistency of observations.

2.2.8. Bending length test

The bending length test was conducted according to the BS 3356 standard using the SDL Atlas bending length tester (Model M003B). This test evaluates the flexibility and comfort-related properties of the treated fabrics by measuring their resistance to bending. A narrow strip of fabric was bent to a fixed angle of 41.5°. The two edges of the fabric were aligned with the indicator lines of the machine, which also formed an angle of 41.5° with the horizontal. The length of fabric required to achieve this bend was recorded as the bending length. Bending stiffness, also known as flexural rigidity, is a measure of a fabric's resistance to bending and can be calculated from the bending length of the fabric using equation 1:

$$G = 9.809 \times 10^{6} M C^{3} \qquad (1)$$

where G is the flexural rigidity (μN.m), M is fabric mass per unit area (g/m^2), and C is bending length (mm).

2.2.9. Air permeability test

Air permeability was measured according to the BS 5636 standard using the SDL Atlas air permeability tester (Model M021). This test assesses how easily air can pass through the fabric, which is crucial for determining the comfort of fire-retardant fabrics used in protective clothing.

2.2.10. Water permeability test

Water permeability was evaluated based on the BS 4554 standard. A drop of water was placed from a fixed distance onto the fabric's surface, and the time taken for the water to penetrate and the area of the wetted region were recorded. This test provides information on the treated fabric's ability to repel or absorb moisture, which impacts its comfort and functional properties.

2.2.11. Wrinkle recovery test

The wrinkle recovery test was performed according to the AATCC Method 66 standard using the SDL Atlas wrinkle recovery tester (Model M003A). Fabric samples were folded and compressed under controlled conditions to create a crease. After a specified recovery period, the samples were suspended, and the recovery angle was measured to assess the fabric's ability to return to its original state. Wrinkle recovery is critical for maintaining both appearance and comfort in protective clothing.

3. Results and Discussion

3.1. Flammability

In the direct flame test, untreated samples exhibited rapid flame spread and easy ignition. As the concentration of the flame retardant and curing time increased, the flame spread rate and combustion rate decreased. Table 2 presents the results for polyester/cotton fabrics. It shows that higher concentrations of flame-retardant material reduce the burning time of polyester/cotton samples. Notably, for the 150 and 200 g/l concentrations, increasing the curing time adversely affected the burning time. However, higher concentrations of flame retardant resulted in shorter char lengths. The best-performing samples were PC200C60t and PC200C180t, with char lengths of 2 cm and 5.1 cm, respectively, followed by PC150C60t with a char length of 11.6 cm.

Table 2. Direct flame test results of polyester/cotton samples

Fabric code	burning time [s]	char length [cm]
PC-U	180	Burned completely
PC100C60t	37.77	Burned completely
PC100C180t	39.92	Burned completely
PC150C60t	11.54	11.6
PC150C180t	32.7	Burned completely
PC200C60t	5	2
PC200C180t	7	5.1

Table 3 displays the results for polyester/viscose fabrics. Increasing the concentration of flame retardant and curing time positively affected the burning time and char length. The best samples were PV200C180t and PV200C60t, with char lengths of 0.4 cm and 0.7 cm, respectively.

Figures 1a and 1b show the polyester/cotton and polyester/viscose samples after the direct flame test. Samples PC, PC100C60t, PC100C180t, PC150C180t, PV, PV100C60t, PV100C180t, PV150C60t, and PV150C180t were completely burned.

Table 3. Direct flame test results of polyester/ viscose samples

Fabric code	burning time [s]	char length [cm]
PV-U	80	Burned completely
PV100C60t	79	Burned completely
PV100C180t	180	Burned completely
PV150C60t	94	Burned completely
PV150C180t	74	Burned completely
PV200C60t	4	0.7
PV200C180t	3.5	0.4

Figurw 1. Polyester/cotton (a) and polyester/viscose samples (b) after direct flame test.

3.2. LOI

Figure 2 presents the LOI test results, which were conducted only on the best-performing samples from the direct flame test (PC200C60t and PV200C180t) and untreated samples from each blend type. The treatment effectively increased the LOI values, with treated samples showing 18.92% (PC) and 24.32% (PV) improvements compared to untreated samples.

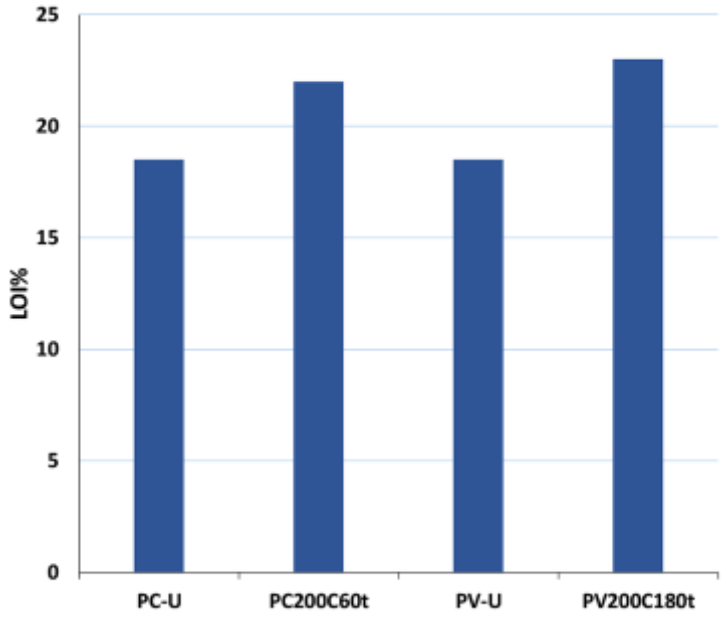

Figure 2. LOI values for polyester/cotton (a) and polyester/viscose (a) samples.

3.3. EDX Analysis

Figure 3 illustrates the EDX test results for PC200C60t, PV200C180t, and the untreated samples. It reveals distinct peaks at ~0.28 keV (C), ~0.53 keV (O), ~0.4 keV (N), and ~2.0 keV (P) in the samples. Figures 3a and 3b show increased weight (W%) and atomic (A%) percentages of N, O, and P in the treated polyester/cotton sample, indicating good penetration of the fire-retardant material. P content increased from 0.07% (untreated) to

1.47 wt% and N from 2.4% to 3.65 wt. %. High W% and A% values for carbon and oxygen are attributed to their presence in the fiber structure. Figures 3c and 3d reveal an increase in W% and A% values for O and P elements in the treated polyester/viscose samples, indicating effective penetration of the fire-retardant material. P content increased from 0.17% (untreated) to 0.54 wt. %, and O from 44.3% to 46.76 wt. %.

These results directly correlate with the enhanced flame retardancy (reduced char length, increased LOI) observed in treated fabrics, confirming effective chemical bonding and thermal stability of the coating.

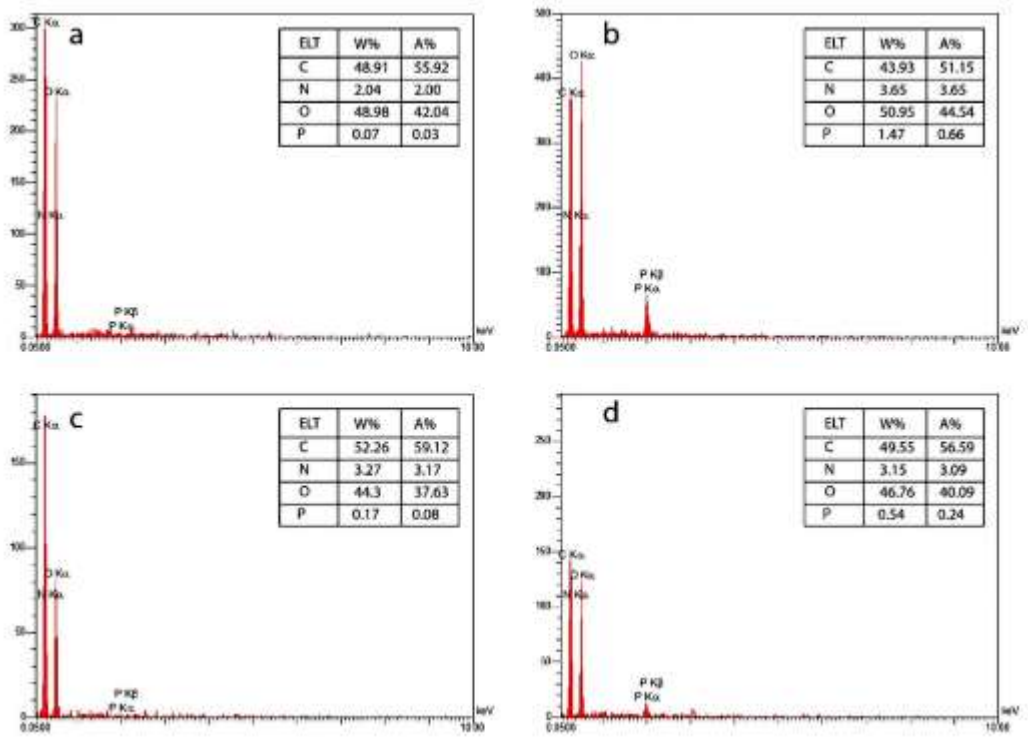

Figure 3. EDX test results for the samples PC-U (a), PC200C60t (b), PV-U (c), PV200C180t (d).

3.4. FTIR Analysis

The FTIR test results obtained for the PC and PV samples are illustrated in Figure 4, which provides valuable insights into the functional groups present in these materials. In

the case of the PC sample, broad peaks were distinctly identified, with one occurring at 3352 cm^{-1} corresponding to the O-H bond, indicating the presence of hydroxyl groups. Additional peaks in the range of 2800-2950 cm^{-1} were observed, which can be attributed to C-H stretching vibrations. Furthermore, a notable peak at 1711 cm^{-1} is associated with the C=O bond characteristic of ester functional groups. Other vibrational modes were also identified, such as the peaks at 1017 cm^{-1} corresponding to the O-C-H bond, and at 1050 cm^{-1} representing C-O stretching vibrations [32]. Interestingly, these peaks were also detected in the PC200C60t samples, although with slight variations in intensity or position.

On the other hand, the FTIR spectrum for the PV-U sample revealed the presence of several bands at specific wave numbers: 3431 cm^{-1}, which is indicative of hydroxyl groups bonded through hydrogen bonding; 1715 cm^{-1} for carboxylic acids; 1408 cm^{-1} associated with C=C stretching typical of aromatic compounds; and 1233 cm^{-1} and 1096 cm^{-1} representing C–H bending and C–O stretching of esters, respectively. Additionally, bands in the range of 690-900 cm^{-1} were observed, which relate to aromatic compounds exhibiting out-of-plane bending vibrations. In contrast, when analyzing the PV treated sample, certain shifts were noted. Specifically, the bands observed at 3237 cm^{-1} were associated with the O-H bond, while the 1715 cm^{-1} peak was again indicative of the C=O bond from esters, along with a strong peak at 1096 cm^{-1} linked to the O-C-H bond, particularly for the PV200C180t sample. As illustrated in Figures 4, it is evident that there is a pronounced decrease in the peak intensity for the carboxylic acid groups at 1715 cm^{-1} and 1096 cm^{-1}. This reduction in intensity can be attributed to the interaction of phosphor with the fabrics, which likely affects the vibrational transitions associated

with these functional groups.

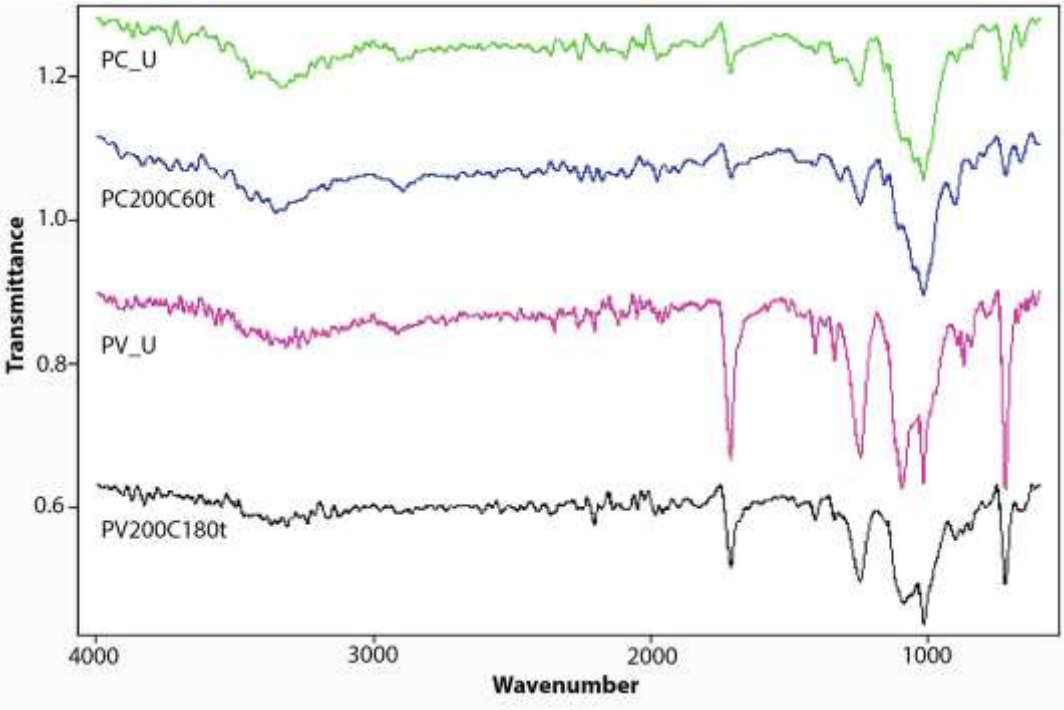

Figure 4. FTIR of treated PC and PV samples.

3.5. SEM Analysis

Figure 5 shows scanning electron microscopy (SEM) images of PC-U, PC200C60t, PV-U, PV200C180t fabrics. It can be seen that the fibers of the untreated cotton fabric exhibit a compact and smooth surface morphology (There is a little impurity of nanoparticles on the PC samples after the washing process). The coating process resulted in a coarser fiber morphology. While a uniform coating was achieved across all samples, individual fibers exhibited a non-uniform layered structure (Figures 5b and d). This layering may stem from material agglomeration within the padding, leading to thickness variations, as depicted in Figure 1. Despite this, the presence of the layered structure on individual fibers confirms successful coating deposition [33].

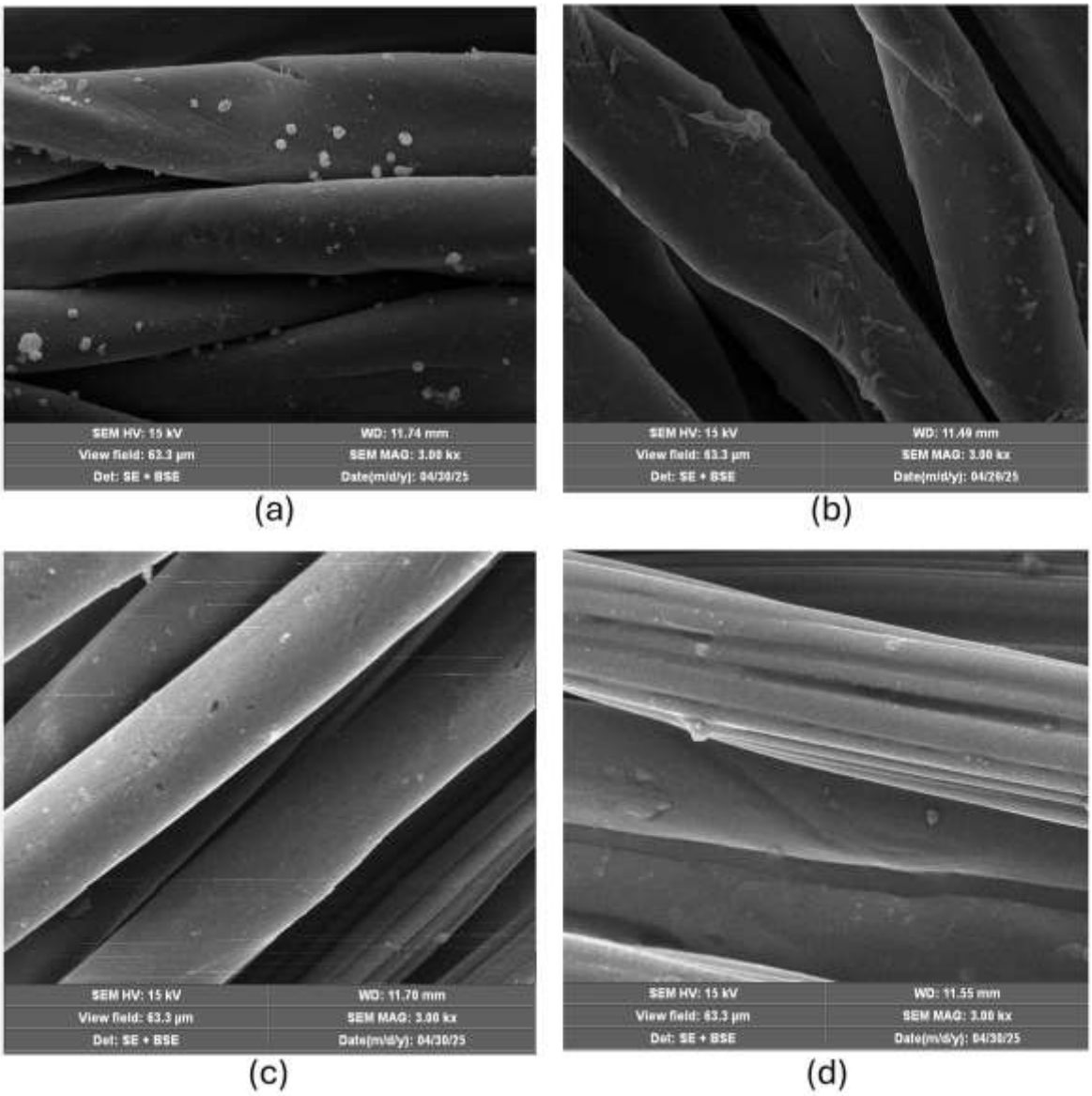

Figure 5. SEM images of PC-U (a), PC200C60t (b), PV-U (c), PV200C180t (d).

3.6. Bending stiffness

The results of the bending stiffness test are shown in Figure 6. Overall, increasing the flame retardant concentration and curing time led to higher bending stiffness in both PC and PV samples. Notably, samples with lower concentration and shorter curing times exhibited bending stiffness lower than that of the untreated fabric. This can be attributed to two opposing effects:

(a) Increased Fabric Weight: The addition of flame-retardant materials increases the fabric weight, reducing the bending length and consequently the bending stiffness.

(b) Increased Adhesion and Bonding: Enhanced adhesion and bonding between fibers and yarns restrict their mobility, thereby increasing bending stiffness.

At low concentrations and curing times, the bonding of the flame-retardant material with fabric fibers is not fully developed, leading to a more pronounced reduction in bending stiffness. As the concentration and curing time increase, the effect of increased adhesion overcomes the effect of weight increase. Importantly, the bending stiffness of the best-treated PC sample (PC200C60t) is not significantly different from that of the raw fabric, indicating that the treatment has not adversely affected the fabric's hand. However, the bending stiffness of the best PV sample (PV200C180t) increased by 29% compared to the untreated sample.

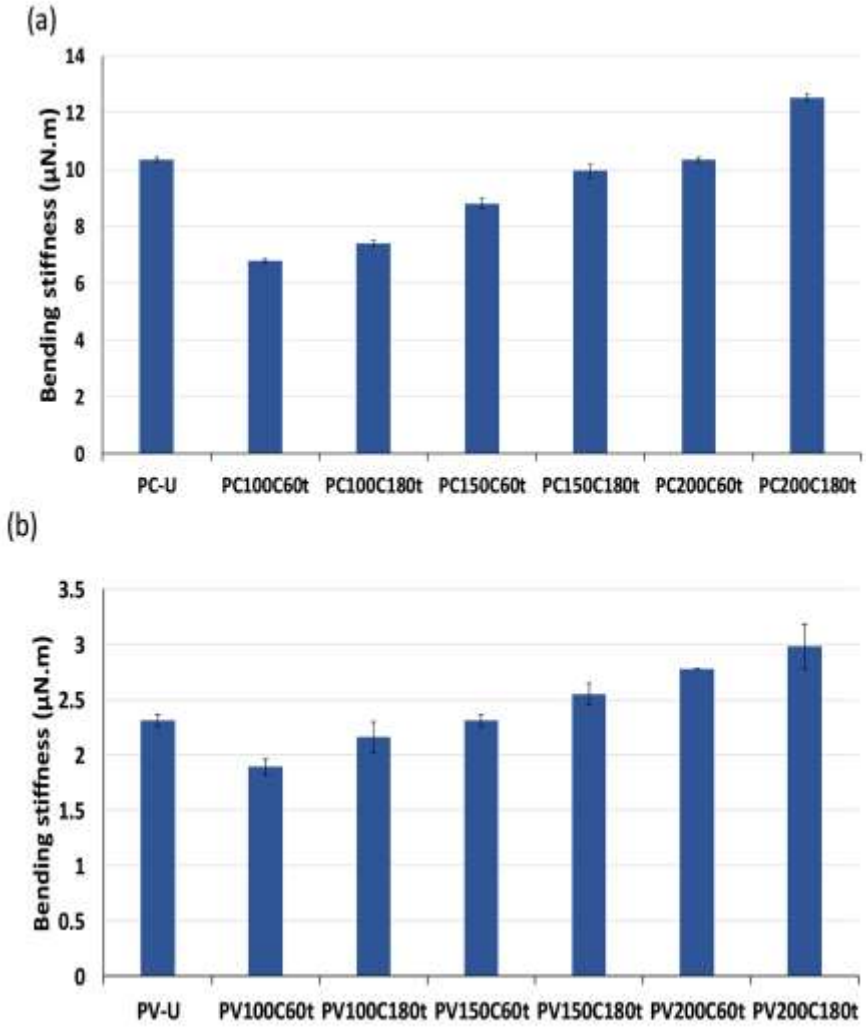

Figure 6. Bending stiffness of PC (a) and PV (b) samples.

3.7. Wrinkle recovery

Figure 7 shows the results of the wrinkle recovery test. Generally, increasing the concentration of the flame retardant and curing time enhanced wrinkle recovery. This improvement is due to the formation of adhesion bonds between fibers, allowing the fabric to return more elastically to its original state when bent. The increase in wrinkle recovery was 27.9% for PC200C60t and 23.3% for PV200C180t compared to their untreated samples.

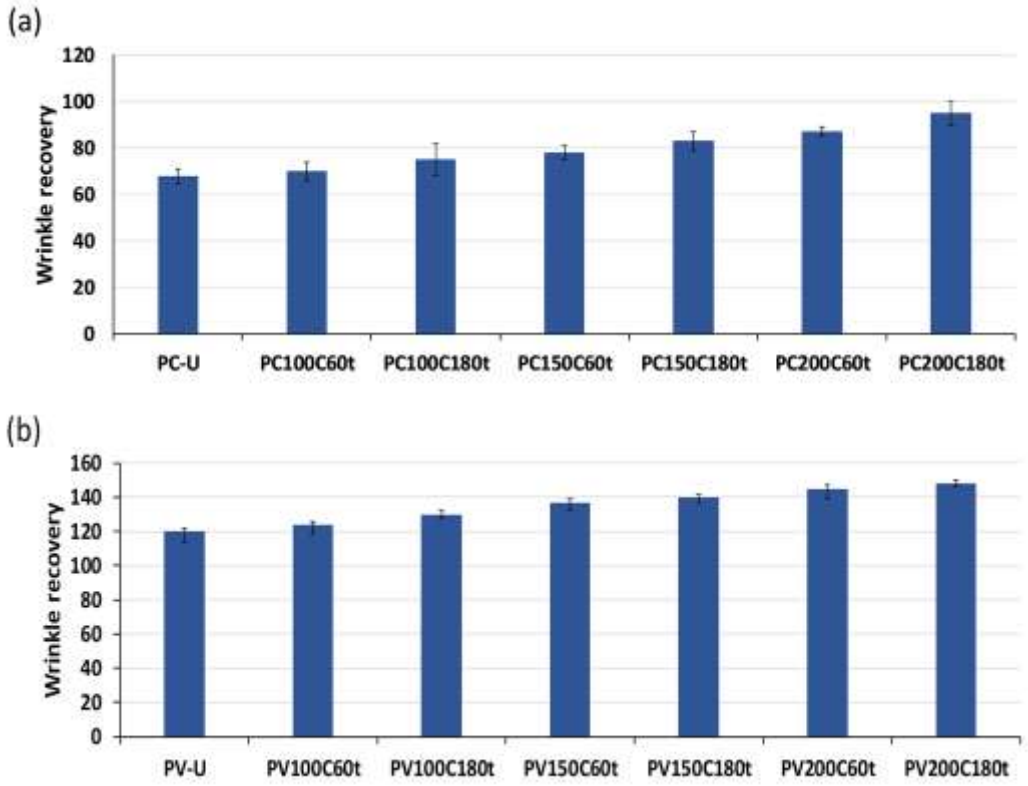

Figure 7. Wrinkle recovery of PC (a) and PV (b) samples.

3.8. Air permeability

Table 4 presents the results of the air permeability test. For all samples, increasing the concentration of the flame retardant and the curing time resulted in decreased air permeability. This reduction is more noticeable in PV samples with longer curing times, likely due to the partial blocking of fabric pores by the flame-retardant material. The decrease in air permeability for PC200C60t and PV200C180t compared to their untreated samples was 41.5% and 59.5%, respectively.

Table 4. Air permeability (AP) of PC and PV samples.

Fabric code	AP [cc/s.cm^2]	CV%	AP reduction percentage compared to untreated samples (%)
PC-U	7.51	1.5	-
PC100C60t	4.73	1.7	37.02
PC100C180t	4.63	3	38.35
PC150C60t	4.54	0.4	39.55
PC150C180t	4.53	1.7	39.68
PC200C60t	4.39	3.6	41.54
PC200C180t	4.17	1.1	44.47
PV-U	7.69	0	-
PV100C60t	4.89	3.4	36.41
PV100C180t	3.74	2.1	51.37
PV150C60t	4.53	0	41.09
PV150C180t	3.41	2.2	55.66
PV200C60t	3.9	7.1	49.28
PV200C180t	3.11	1.5	59.56

3.9. Water permeability

Table 5 summarizes penetrated droplet area (PDA) values from water permeability tests. It is evident that increasing the concentration and curing time decreased water permeability, with a more significant reduction observed in PV samples. On average, the water droplet penetration time was 2 seconds for PC samples and 3 seconds for PV samples. The decrease in PDA for PC200C60t and PV200C180t compared to their untreated samples was 15.74% and 35.61%, respectively.

Table 5. PDA values of polyester/cotton and polyester/viscose samples.

Fabric code	PDA [cm^2]	CV%	PDA reduction percentage compared to untreated samples (%)
PC-U	4.7	6.5	-
PC100C60t	4.15	6.7	11.70
PC100C180t	4.09	8.8	12.98
PC150C60t	4.08	5.1	13.19
PC150C180t	4.02	7.2	14.47
PC200C60t	3.96	6.5	15.74
PC200C180t	3.56	1.9	24.26
PV-U	3.96	3.5	-
PV100C60t	3.72	3.7	6.06
PV100C180t	3.43	7.5	13.38
PV150C60t	2.96	3.7	25.25
PV150C180t	2.85	4.9	28.03
PV200C60t	2.79	4.3	29.55
PV200C180t	2.55	2	35.61

4. Conclusion

This study demonstrated that treating polyester/cotton (PC) and polyester/viscose (PV) fabrics with an alkyl phosphate ester-based flame retardant (200 g/L) significantly enhanced fire-resistance while maintaining wearability, with PC200C60t (60 s curing) achieving a 2 cm char length and 22% LOI, and PV200C180t (180 s curing) showing superior performance (0.4 cm char length, 23% LOI). EDX analysis confirmed successful flame retardant deposition, while FTIR revealed ester bond formation (O-H, C=O, O-C-

H), explaining the improved flame retardancy. Although bending stiffness increased moderately (29% for PV), wrinkle recovery improved by 23-28%, and reductions in air permeability (42-60%) and water permeability (16-36%) remained within acceptable limits for protective textiles, confirming the treatment's effectiveness in balancing safety and comfort for practical applications.

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