

***Araştırma Makalesi / Research Article***

## UV PROTECTION PROPERTIES OF CELLULOSIC-POLYESTER BLEND FABRICS: EFFECTS OF FIBER TYPE AND MOISTURE CONTENT

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**ABSTRACT:** This study investigates the effects of fiber type and moisture content on the ultraviolet (UV) protection properties of cellulosic–polyester blend fabrics. Twill-woven fabrics composed of cotton, viscose, and lyocell fibers blended with polyester, all with comparable structures and areal densities, were analyzed. Ultraviolet Protection Factor (UPF) measurements and air permeability tests were conducted to assess performance under both dry and wet conditions. The results revealed that polyester fibers provided the highest UV shielding effectiveness in blended fabrics, followed by cotton, viscose, and lyocell. Furthermore, the cross-sectional shape of polyester fibers significantly influenced UV protection, with hexa-channel fibers showing the highest UV protection, followed by micro- and circular-types. It was also observed that increasing moisture content reduced the UV protection of fabrics, while lower air permeability enhances their UV-blocking efficiency. These findings provide valuable insights for the development of UV-protective clothing, particularly for summer garments, and highlight opportunities for modeling and optimization in textile production.

**Keywords:** Cotton, viscose, lyocell, polyester, UV protection factor, moisture content, fiber cross-sectional shape.

## SELÜLOZİK-POLİESTER KARIŞIMLI KUMAŞLARIN UV KORUMA ÖZELLİKLERİ: LİF TİPİ VE NEM İÇERİĞİNİN ETKİSİ

**ÖZ:** Bu çalışma, selülozik–poliester karışım kumaşların ultraviyole (UV) koruma özellikleri üzerindeki lif türü ve nem içeriği etkilerini incelemektedir. Pamuk, viskon ve lyocell liflerinin poliester ile karıştırılmasıyla elde edilen, benzer yapı ve birim alan kütlesine sahip dimi dokuma kumaşlar analiz edilmiştir. Kumaşların kuru ve ıslak koşullardaki performansını değerlendirmek amacıyla Ultraviyole Koruma Faktörü (UPF) ölçümleri ile hava geçirgenliği testleri gerçekleştirilmiştir. Elde edilen sonuçlar, karışım kumaşlarda en yüksek UV korumasını poliester liflerinin sağladığını, bunu sırasıyla pamuk, viskon ve lyocell liflerinin izlediğini ortaya koymuştur. Ayrıca, poliester liflerinin enine kesit şeklinin UV koruma üzerinde önemli bir etkisi olduğu belirlenmiş; altı kanallı liflerin en yüksek korumayı sağladığı, bunu mikro ve dairesel kesitli liflerin izlediği görülmüştür. Nem içeriğinin artması, kumaşların UV koruma performansını azaltırken; daha düşük hava geçirgenliği, UV engelleme etkinliğini artırmaktadır. Bu bulgular, özellikle yazlık giysiler için UV koruyucu tekstil ürünlerinin geliştirilmesine katkı sağlamakta ve tekstil üretiminde modelleme ve optimizasyon çalışmaları için fırsatlar sunmaktadır.

**Anahtar Kelimeler:** Pamuk, viskon, lyocell, poliester, UV koruma faktörü, nem içeriği, lif kesit şekli.

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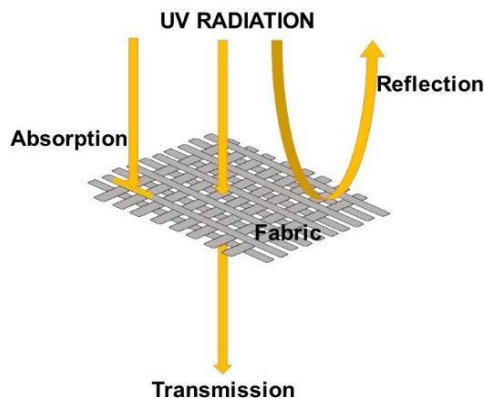
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## 1. INTRODUCTION

UV rays are a type of light energy emitted by the sun that can reach the Earth's surface. They are classified into three categories: UVA (320–400 nm), UVB (290–320 nm), and UVC (200–290 nm). Approximately 5% of the solar radiation reaching the Earth consists of UV rays. Within this range, 96–98% is UVA, while 2–4% is UVB. UVC, however, is completely absorbed by the stratospheric ozone layer before reaching the Earth's surface [1]. There are significant differences among UV rays in terms of their effects on human health. As the wavelength increases, penetration into the deeper layers of the skin also increases, while the ability to induce redness (erythema) decreases. Accordingly, UVA penetrates the skin the deepest but induces erythema only when applied at very high doses. UVA rays can generate highly reactive chemical intermediates and contribute to skin cancer by indirectly damaging DNA. In contrast, UVB rays do not penetrate as deeply as UVA rays; however, they are significantly more effective at causing erythema. UVB is considered the primary cause of sunburn, skin cancer, and cataracts [2].

The progressive thinning of the ozone layer has led to an increase in the amount of UV radiation (UVR) reaching the Earth's surface [3]. This trend is particularly concerning for children, as young children are more vulnerable to UVR than adults [4]. Additionally, the effects of UV radiation on human health vary depending on skin type [5]. Therefore, it is crucial to ensure lifelong protection from harmful solar radiation, particularly for children.

One of the simplest and most practical ways to protect against UVR is by wearing clothing. When light strikes a fabric, some rays are reflected, some are absorbed by the material, and others pass through (Figure 1) [6]. To assess how much protection the fabric provides against UVR, it is necessary to determine the amount of transmission.



**Figure 1.** Schematic illustration of UV radiation interaction with fabric

The degree of protection that a textile material offers against UVR is referred to as the 'Ultraviolet Protection Factor' (UPF). UPF is the ratio between the average effective UV rays in the atmosphere (effective dose -  $ED$ ) and the average UV rays passing through the

fabric, continuing to affect the skin (effective dose -  $ED_f$ ) (Eq. 1) [7].

$$UPF = \frac{ED}{ED_f} = \frac{\sum_{\lambda=290}^{\lambda=400} E(\lambda)S(\lambda)\Delta\lambda}{\sum_{\lambda=290}^{\lambda=400} E(\lambda)T(\lambda)S(\lambda)\Delta\lambda} \quad (1)$$

In Equation 1,  $E(\lambda)$  represents the relative redness (erythema) spectral activity,  $S(\lambda)$  denotes the spectral irradiance of the sun ( $W.m^{-2}.nm^{-1}$ ),  $\Delta(\lambda)$  indicates the wavelength range (nm),  $T(\lambda)$  refers to the spectral average transmittance of the fabric sample, and  $\lambda$  denotes the wavelength (nm).

Various standards are used to evaluate the UV protection properties of textile materials, all of which are fundamentally based on Equation 1. However, these standards differ in terms of scanning ranges, fabric positioning within the device, erythema effect spectrum, and classification criteria. Among these widely recognized standards include EN 13758 (British and European standard), AATCC Test Method 183(American standard), AS/NZS 4399:2017 (Australian/New Zealand standard), and ASTM D6603 [8]. In this study, AS/NZS 4399:2017, one of the most commonly used standards, was selected. In this standard, four key data points related to the fabric's UV protection properties are defined: mean UPF, rated UPF, and the transmittance values for UVA and UVB. The mean UPF represents the UPF value derived from averaging UV transmittance measurements taken at four different locations on the fabric. Depending on the capabilities of the measuring instrument, this value can reach up to 2000 UPF. The rated UPF is calculated as the average UPF across four test fabrics adjusted for the standard error at a 99% confidence level, and rounded down to the nearest multiple of five. If the rated UPF is lower than the lowest individual fabric measurement, it is adjusted to match the lowest measured UPF value, rounded to the nearest multiple of five. The UVA and UVB transmittance values indicate the percentage of UVA and UVB rays that penetrate the fabric [9]. According to AS/NZS 4399:2017 standard, a labeling system is established for textile materials, and UPF classification is applied as shown in Table 1 [10]. If the measured UPF value is 50 or higher, the textile material is labeled as 50+ UPF, indicating excellent protection against UV rays.

**Table 1.** Classification of UPF values according to the AS/NZS 4399:2017 standard[10]

| Classification | UV Radiation Blocking (%) | UPF Rating |
|----------------|---------------------------|------------|
| Minimum        | 93.3                      | 15         |
| Good           | 96.7                      | 30         |
| Excellent      | 98.0                      | 50, 50+    |

The UV protection properties of textile materials can vary based on multiple parameters, including fabric structure, fiber type, color, and UV protective additives. In general, for a fabric to offer

high UV protection, its structure must be tight, resulting in low porosity. UV protection properties of the fabric can also be enhanced through coloring (especially in darker shades) and the addition of UV protective additives, such as  $\text{TiO}_2$  and  $\text{ZnO}$ . The fiber types constituting the fabric exhibit varying UV protection behaviors. For instance, synthetic fibers typically provide superior UV protection compared to natural fibers [7].

In summer clothing, relatively loose, white or light-colored fabrics made from cellulosic fibers are favored for their thermal comfort. However, when considered in this context, highly porous light-colored cellulosic fabrics may not offer sufficient protection against UV radiation [11]. Additionally, incorporating UV protective additives may result in increased chemical usage and raise concerns about long-term durability. Therefore, a more sustainable approach could be to use cellulosic fibers in blends, optimizing both comfort and UV protection properties.

Studies investigating the effects of fiber type and blend ratios on UV transmittance are generally limited to specific fiber types, with a predominant focus on polyester and cellulosic fibers. Davis et al. examined the UV protection properties of fabrics with various structures composed of cotton (CO), rayon, linen, wool (WO), polyester (PES), nylon, acrylic, acetate, PES/CO, and PES/WO fibers [12]. Their findings indicated that UV protection varied with fabric structure, but PES fibers exhibited the highest UV-blocking performance. However, they noted that PES fabrics may be unsuitable for hot climates due to reduced comfort, highlighting the need for further research on the influence of different polyester blend ratios on UV protection.

Continuing the exploration of fiber types, Algaba et al. evaluated the UV protection properties of woven fabrics with varying yarn counts and thread densities composed of cotton, modal, and Modal Sun fibers—the latter incorporating a UV absorber during fiber production [13]. They also investigated the effect of optical brighteners on the UV protection performance of these fabrics in their subsequent study [14]. Their findings suggested that Modal Sun fibers exhibited superior UV protection compared to cotton and modal, demonstrating the potential of fiber-level modifications for enhancing UV-blocking performance.

In a separate study, Kursun and Ozcan reported that undyed 80% PA/20% Elastane and 80% PET/20% Elastane fabrics exhibited similar UV protection properties [15]. Karakaş et al. compared the UV protection levels of knitted fabrics made from cotton, viscose, bamboo, soybean, polyester, and cotton/polyester blends [16]. Their findings reaffirmed that polyester-based fabrics provided the highest UV protection, whereas cotton, bamboo, viscose, and soybean fabrics had insufficient UPF values.

Dai and Zhang expanded the scope of fiber comparisons by investigating the UV protection properties of woven fabrics composed of PES, cotton, silk, and hemp fibers [17]. Their study confirmed that polyester fabrics exhibited the highest UV

protection performance, followed by silk, then hemp, and finally cotton, with hemp and cotton showing similar UV protection properties. These results align with previous findings on the limited UV-blocking ability of cellulosic fibers, particularly in the absence of additional UV-absorbing treatments.

Additionally, research on fiber blends has provided further insights into the combined effects of different fiber types. Badr et al. investigated the UV protection properties of fabrics composed of cotton, Tencel, and bamboo fiber blends [18]. Their results demonstrated that blending cotton with Tencel and bamboo fibers improved UPF, with bamboo providing higher UV protection than Tencel. Similarly, Cole et al. analyzed children's T-shirts made from cotton, polyester, linen, rayon, and spandex blends from various brands [19]. They emphasized that garments with balanced fiber blends of cotton and/or polyester could provide sufficient UV protection for children.

Recent studies have also explored the impact of fiber composition on UV protection in dyed fabrics. Duru et al. examined fabrics composed of dyed cotton, hemp, viscose, and Refibra blends [20]. They reported that an increased proportion of cotton, viscose, and Refibra fibers in the yarns led to reduced UV protection, whereas the amount of hemp fiber had no significant effect. This finding highlights the continued challenges associated with UV protection in cellulosic-based fabrics, particularly in dyed and blended fabric structures.

Overall, existing research consistently shows that polyester-based fabrics provide the highest UV protection, while cellulosic fibers such as cotton, viscose, and hemp typically exhibit lower UPF values. However, studies that examine the effect of fiber type while controlling for other fabric parameters like structure, color, and additives remain limited. Further research is needed to better understand how fiber composition and blend ratios influence UV-blocking performance, particularly in multi-fiber fabric systems. Notably, there is a lack of comprehensive data on the UV protection properties of polyester fibers with different cross-sectional structures—circular (CPES), hexachannel (HPES), and microfiber (MPES)—when blended with natural and regenerated fibers.

This study aims to address these gaps by investigating the influence of fiber composition and fabric moisture content on UV protection. By comparing the UV protection values of fabrics in both dry and wet conditions based on fiber type, it seeks to contribute to the existing body of knowledge and enhance understanding of UV shielding in blended fabrics.

Blends of cotton, viscose, lyocell, and various forms of PES (round-section PES, hexachannel PES, and microfiber PES) with the same fabric construction were examined in both dry and wet conditions. The obtained data were then analyzed to assess the impact of fiber type and blend ratio on UV protection performance.

## 2. MATERIALS AND METHODS

### 2.1 Materials

18 pre-treated fabrics were used, including 100% cotton, 100% viscose, and 100% lyocell fabrics, as well as blends of these fibers with each other and with various types of PES fibers (circular-cross-section PES (CPES), hexa-channel PES (HPES), and microfiber PES (MPES)). All fabrics were constructed with a 3/1 twill weave pattern, and the blend ratio was set at 65/35. The yarn counts were standardized across all fabric types, with Ne 36 for cellulosic yarns and 167 dtex for synthetic yarns. Similarly, the yarn twist coefficient was maintained at  $\alpha_c$  3.7. The fabric density was kept uniform, with 48 ends/cm for warp yarns and 31 picks/cm for weft yarns. The fabrics were washed with a non-ionic washing agent, and polyester-containing blends were thermofixed in a stenter at 180 °C after washing.

### 2.2 Method

The mass per unit area was determined in accordance with EN 12127. The fabric thickness was measured using a Digital Thickness Tester (SDL Atlas, USA), following EN ISO 5084 standard.

Total porosity of the fabrics was calculated using Equation 2.

$$\varepsilon = 1 - \frac{\rho_a}{\rho_b} \quad (2)$$

where  $\rho_a$  is the fabric density (g/cm<sup>3</sup>),  $\rho_b$  is the fiber density (g/cm<sup>3</sup>), and  $\varepsilon$  is the porosity. Fabric density was calculated by dividing the fabric mass per unit area by fabric thickness. The mean densities of cotton, viscose, lyocell, and polyester fibers were accepted as 1.54 g/cm<sup>3</sup>, 1.50 g/cm<sup>3</sup>, 1.52 g/cm<sup>3</sup>, and 1.38 g/cm<sup>3</sup>, respectively [21, 22].

The air permeability of the fabrics was measured in accordance with the EN ISO 9237 standard, using an FX3300 air permeability tester (Textest, Switzerland). The measurements were conducted with a 20-cm<sup>2</sup> test area and a pressure differential of 100 Pa.

The UVR blocking/transmission properties and the UV protection factor (UPF) were determined using a Labsphere UV 2000F device, in accordance with the AS/NZS 4399:2017 standard.

Whiteness (WI CIE) values of the fabrics were obtained using a HunterLabUltraScan Pro spectrophotometer at absorbance wavelengths of 400 to 700 nm, with a D<sub>65</sub> light source and an observation angle of 10°.

To investigate the effect of moisture on UV protection, the fabrics were impregnated with deionized water at 50% and 100% pick-up ratios, using a laboratory-scale padder (ATAÇ, Türkiye) to achieve the specified pick-up levels. After the impregnation process, UVR transmittance tests were immediately conducted on the fabrics.

Test results were statistically analyzed using one-way analysis of variance (ANOVA) in SPSS 25 software, with differences at  $p < 0.05$  regarded as statistically significant.

## 3. RESULTS AND DISCUSSIONS

### 3.1 Effect of Fiber Type on the UV Protection of Fabrics

Figures 2 and 3 illustrate the UPF values of 100% cotton (CO), 100% viscose (CV), and 100% lyocell (CLY) fabrics, as well as the UPF values of their blends with each other and with various PES fiber types (CPES, HPES, and MPES). Additionally, the UVA and UVB blocking percentage values of these fabrics are presented in Figures 4–6.

Overall, the findings indicate that 100% cotton and 65% cotton blend fabrics, except for lyocell blends, exhibit excellent UV protection properties in the dry state, as classified by UPF values according to the AS/NZS 4399:2017 standard (Table 1), while demonstrating varying degrees of UV protection (Figure 2). However, viscose and lyocell fabrics achieved high UV protection levels only when blended with PES (Figure 3). The UVA and UVB blocking effects of PES-blended fabrics were also significantly higher than those of cellulosic fibers and their blends with each other (Figures 4–6), resulting in higher UPF values ( $p < 0.05$ ). The fabrics showed similar results in the wet state. This performance can be attributed to the UVR absorption ability of PES fibers, which results from their molecular structure. The presence of aromatic rings in PES fibers and their higher crystallinity compared to cellulosic fibers contribute to their enhanced UV protection performance. In this context, cellulosic/PES blends may be considered suitable for applications that require both improved comfort and handle properties, as well as improved UV protection.

When the UV protection measurement results of PES blended fabrics were analyzed in detail, it was found that the fiber cross-section influenced the UV protection properties (Figure 3). Hexa-channel PES fibers (HPES) exhibited the highest UPF and UVR blocking values, followed by micro-PES fibers (MPES) and circular cross-section PES fibers (CPES). This can be attributed to changes in the microstructure and the interaction of fibers with UVR. HPES fibers have a relatively larger surface area compared to CPES, which allows them to scatter and absorb more UVR. As a result, HPES fibers have higher UPF values than the other PES fiber types. Similar to HPES, MPES fibers also offer relatively higher UV protection than CPES fibers. The smaller diameter of MPES fibers allows a greater number of fibers to be packed together, increasing the total surface area (Figure 7). This leads to more UVR scattering and absorption. On the other hand, CPES fibers, with their more uniform structure, allow more UVR to pass through, leading to lower UPF values.

When the UV protection properties of cellulosic fibers were examined, it was observed that 100% cotton and cotton blends had relatively higher UPF values than 100% viscose, 100% lyocell,

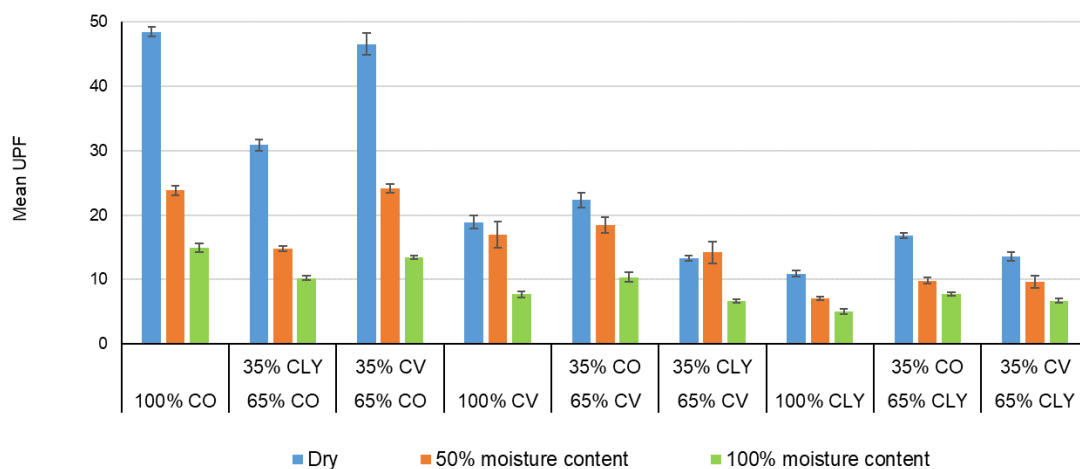
and their blends (Figure 2). This can be attributed to the relatively denser structure of cotton compared to regenerated cellulosic fibers, its lower total pore volume, and therefore its greater ability to block UVR [23].

From another perspective, cotton fiber, which is a natural fiber, has an irregular and wrinkled structure. This irregular surface can cause UV rays to scatter multiple times in different directions, leading to more changes in their path on the fiber surface and ultimately reducing their penetration through the fabric. Regenerated fibers, such as viscose and lyocell, have a relatively more regular and round cross-section [24]. These fibers are produced through an extrusion process that allows for controlled shaping, resulting in much smoother fiber surfaces. As a result, on these smooth surfaces, UV rays scatter less and penetrate deeper into the fabric more easily. In addition, when viscose and lyocell fibers are compared, viscose fibers have a relatively more irregular cross-section and surface, while lyocell fibers exhibit an approximately circular cross-section with a smooth and regular morphology [25]. This suggests that UVR is scattered in multiple directions on the surface of viscose fibers, potentially enhancing UV protection performance compared to lyocell fibers.

Gambichler et al. stated that the UV protection property of a fabric depends on the amount of UVA and UVB radiation it blocks, with UVB radiation having a greater influence on this property [26]. In this context, the authors indicated that fabrics with strong UVB absorption tend to have higher UPF values compared to those with strong UVA absorption. Similarly, in the present study, comparable results were obtained. For example, in the dry state, the UVA blocking of the 35% HPES / 65% CLY fabric was 92.8%, while that of the 35% MPES / 65% CLY fabric was

93.83% (Figure 4). Although the 35% MPES / 65% CLY fabric, which has higher UVA blocking, would be expected to exhibit a higher UPF value (49 UPF), the 35% HPES / 65% CLY fabric actually recorded a higher UPF value (54 UPF). Examining the UVB blocking values of these fabrics reveals that the 35% HPES / 65% CLY fabric (98.79%) had a slightly higher UVB blocking value than the 35% MPES / 65% CLY fabric (98.47%) (Figure 4). These results further confirm that even small increases in UVB blocking play a significant role in enhancing UPF values. This situation is clearly observed in the graphs presented in Figures 4–6. In these graphs, fabrics in the dry state are ranked according to their increasing UPF values. For a clearer comparison, the graphs of fabrics containing 50% and 100% moisture (Figures 5–6) are also based on the rankings of dry-state fabrics. Additionally, the relationship between the UPF values of the fabrics and their UVA/UVB blocking effects is distinctly visible.

An analysis of UPF values and UVB blocking effects revealed a statistically significant correlation ( $p < 0.05$ ). However, despite a decrease in the UVA blocking effect, an increase in UPF values was observed in some fabrics (e.g., 35%CPES / 65% CLY, 35%HPES / 65% CLY, 35%HPES / 65% CV). This can be attributed to the increase in UVB blocking properties. A similar phenomenon was also reported by Kocic et al., and is linked to the varying biological activity (or harmfulness) of different types of UVR [27]. The biological activity in the UVB range, which corresponds to shorter wavelengths, is significantly higher than that in the UVA range. Accordingly, even minimal UVB transmission through a textile material can significantly influence the UPF value. In this context, fabrics with relatively low UVA blocking effects can achieve higher UPF rankings due to their enhanced UVB blocking capability.



**Figure 2.** UPF values of cellulosic fabrics at different moisture contents (dry, 50%, and 100% moisture content)

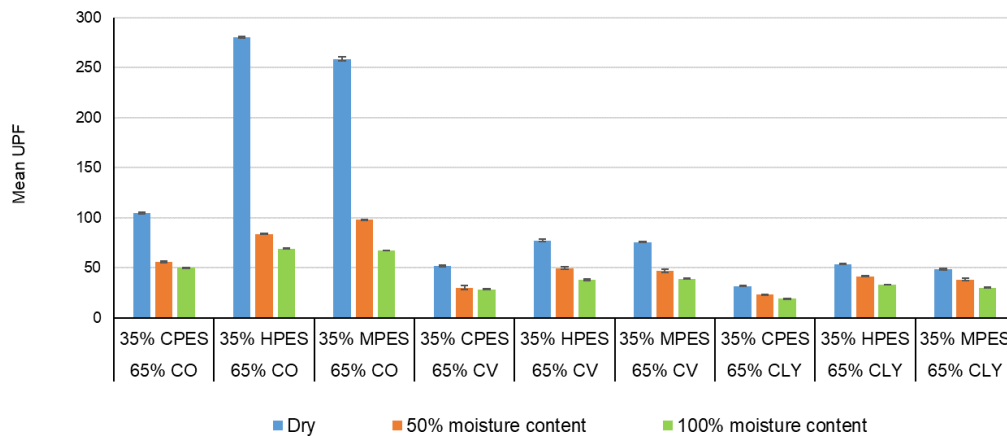


Figure 3. UPF values of PES/cellulosic blend fabrics at different moisture contents (dry, 50%, and 100% moisture content)

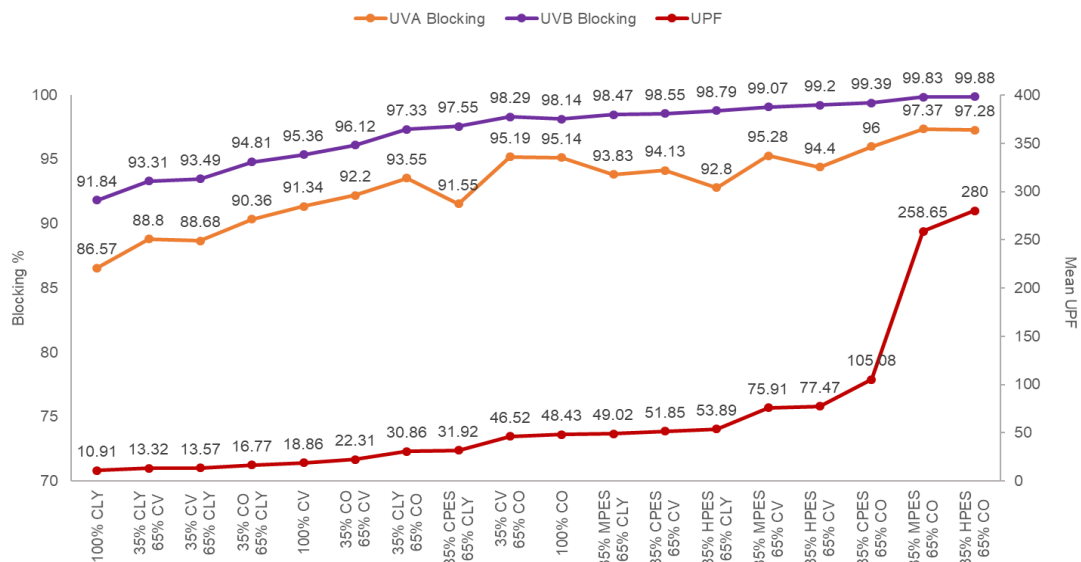


Figure 4. UVA and UVB blocking percentages and their relationship with the UPF values of the fabrics in the dry condition

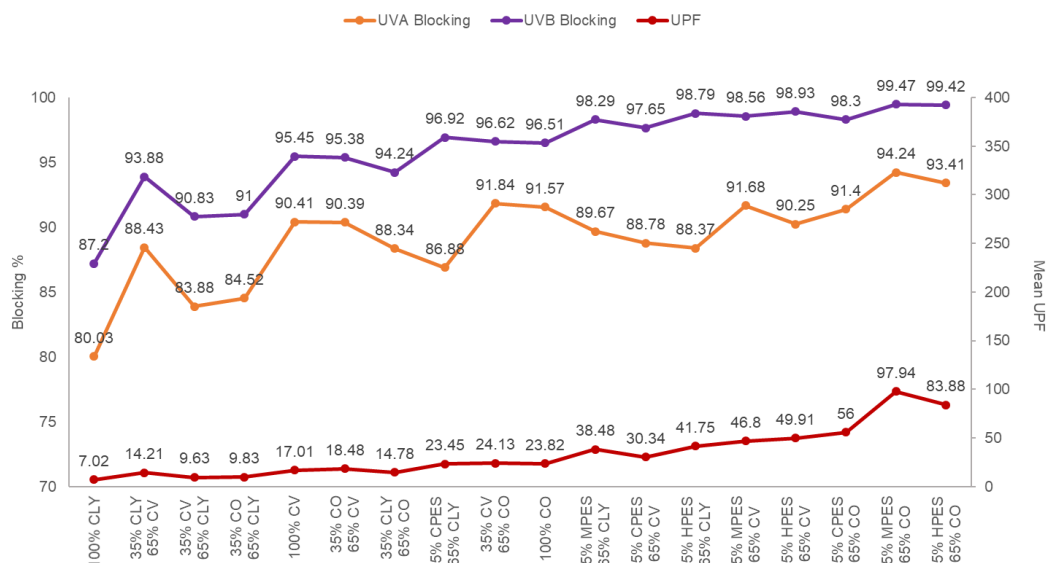


Figure 5. UVA and UVB blocking percentages and their relationship with the UPF values of the fabrics at 50% moisture content



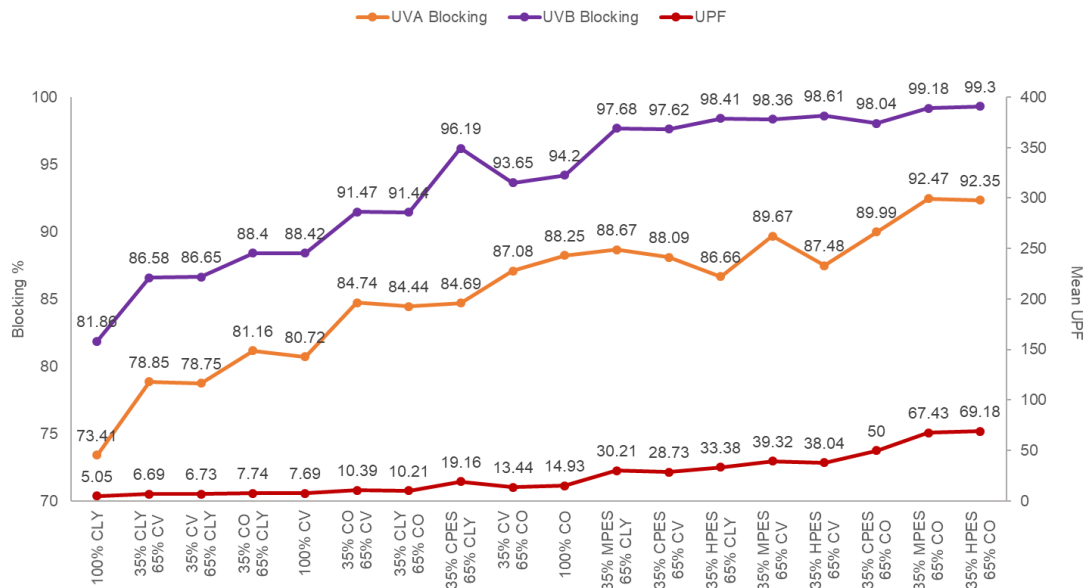


Figure 6. UVA and UVB blocking percentages and their relationship with the UPF values of the fabrics at 100% moisture content

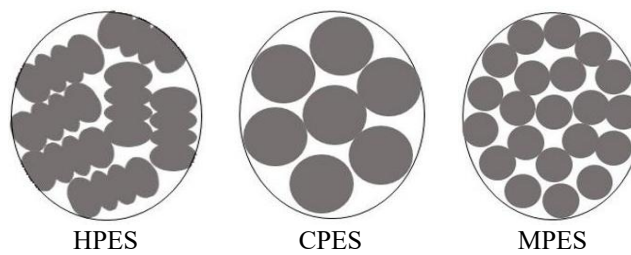


Figure 7. Schematic cross-sectional view of PES fibers[28, 29]

### 3.2 Effect of Moisture Content on the UV Protection of Fabrics

The UPF values for the fabrics at dry, 50%, and 100% moisture content are presented in Figures 2 and 3. Additionally, the relationships between their UVA and UVB blocking percentages and UPF values are shown in Figures 4–6.

The results showed that the UPF values and UVR blocking percentages of the fabrics decreased as the moisture content increased. Additionally, wet PES-blended fabrics exhibited higher UPF values compared to both dry and wet cellulosic-blended fabrics. This finding indicates that PES-blended fabrics offer superior UV protection compared to cellulosic fabrics, even in wet conditions.

A portion of the UVR directed at a 'dry' fabric passes directly through it, while a portion is absorbed by the fibers it encounters, and another portion is scattered by the surface (Figure 1). When a fabric becomes wet, the number and size of the direct paths through which light can pass may change. Fabrics made of hydrophilic fibers, such as cellulosic fibers, are more likely to have fewer direct paths for light to pass through, as they swell

when wet. In contrast, hydrophobic fibers, like polyester, may exhibit little to no change in porosity when they absorb moisture. In these fabrics, water does not swell the fibers but instead tends to remain in the interstices.

However, regardless of whether the fibers swell and consequently change the fabric's porosity, wetting the fabric alters the scattering of UVR directed at it. The scattering of light on wet fabric tends to decrease, resulting in increased UVR penetration and reduced UV protection [15].

When examining the results in Figures 2 and 3, in cotton blended fabrics, a greater decrease in UPF value was observed with the increase in moisture content, while a relatively lesser decrease was observed in viscose and lyocell blended fabrics. Especially when PES/cellulosic blended fabrics are examined (Figure 3), cotton blended fabrics show a higher decrease in UPF values when wet compared to their dry state, while viscose and lyocell blended fabrics show a relatively less decrease in UPF values when dry. This situation was attributed to the fact that cotton fibers have lower swelling compared to man-made cellulosic fibers [30, 31]. Viscose and lyocell fibers, which have a higher swelling property

compared to cotton, swell more with an increase in moisture content and porosity decreases. Thus, the UV transmittance rate also decreases. That being said, if fiber swelling were the main factor, one would expect that UPF values would increase when cellulosic blended fabrics are wetted, as cellulosic fibers tend to swell, which would reduce the fabric's porosity. Similarly, no change should be observed in UPF values when polyester blended fabrics are wetted, as PES fibers do not swell with water, and thus there would be no change in pore size.

In this context, the decrease in UPF values of fabrics with increasing moisture content can also be attributed to the fact that the scattering of light reaching the surface of the moist fabric is relatively less compared to that of dry fabric, resulting in increased UVR penetration. Moreover, when the UVR penetration characteristics of dry and moist fabrics are examined in terms of UVA and UVB radiation, a relatively greater decrease in UVA blocking than in UVB blocking is observed (Figures 4-6). This phenomenon is attributed to the greater penetration of UVA radiation through water compared to UVB radiation, as stated by Salo et al. [32].

A detailed examination of the results at different moisture contents once again revealed a pattern consistent with the findings of Gambichler et al. [26]. At 100% moisture content, the 35% HPES / 65% CLY fabric exhibited a UVA blocking rate of 86.66%, whereas the 35% MPES / 65% CLY fabric showed a slightly higher value of 88.67% (Figure 6). Despite its greater UVA blocking ability, the 35% MPES / 65% CLY fabric would be expected to achieve a higher UPF value (30 UPF); however, the 35% HPES / 65% CLY fabric actually recorded a higher UPF of 34. A detailed assessment of the UVB blocking values reinforced this pattern, revealing that the 35% HPES / 65% CLY fabric had a superior UVB blocking rate (98.41%) compared to the 35% MPES / 65% CLY fabric (97.68%). These results once again

emphasize that even small improvements in UVB blocking can significantly impact a fabric's UPF value, regardless of the moisture content.

### 3.3 Effect of Physical Properties on the UV Protection of Fabrics

The main aim of this study was to determine the effect of fiber type on UPF. Therefore, the physical properties of all samples were kept constant, and their effect on UPF was eliminated. In this section, analyses were conducted to indicate that the changes in UPF properties were not due to changes in the physical properties of the samples. The values for mass per unit area, fabric thickness, and total porosity of the fabrics are presented in Table 2. The effect of the whiteness index was also analyzed.

The fabrics used in this study were pre-treated fabrics made from different cellulosic fiber blends, resulting in varying whiteness values. It is well known that the color properties of fabrics significantly influence their UV protection properties [7]. Therefore, the effect of the whiteness indexes of the fabrics on UV protection was examined, but no statistically significant effect was found ( $p > 0.05$ ).

The mass per unit area of the fabrics was also found to have no significant effect on the fabric's ability to block UVR in the present study ( $p > 0.05$ ), although it contributes to the overall structure and bulkiness of the fabric. This suggests that the weight alone does not play a crucial role in UV protection, as factors such as the composition of the fibers and the fabric's microstructure may have a more direct influence. On the other hand, fabric thickness had a statistically significant effect on UPF ( $p < 0.05$ ), despite the minor differences between the fabrics. Thicker fabrics generally provide higher UV protection by creating a denser structure that blocks more UVR from penetrating the material, thereby offering enhanced protection.

**Table 2.**Physical properties of the fabrics

| Fabric type        | Whiteness Index CIE | Mass per unit area (g/m <sup>2</sup> ) | Thickness (mm) | Total Porosity (%) |
|--------------------|---------------------|----------------------------------------|----------------|--------------------|
| 100% Co            | 35.05 ± 0.63        | 152 ± 1.52                             | 0.38 ± 0.013   | 74 ± 0.52          |
| 35% CLY / 65% Co   | 35.51 ± 0.47        | 151 ± 1.48                             | 0.39 ± 0.006   | 75 ± 0.16          |
| 35% CV / 65% Co    | 31.42 ± 0.38        | 155 ± 1.63                             | 0.38 ± 0.010   | 73 ± 0.36          |
| 35% CPES / 65% Co  | 42.66 ± 0.87        | 160 ± 1.14                             | 0.37 ± 0.009   | 72 ± 0.94          |
| 35% HPES / 65% Co  | 40.95 ± 0.71        | 165 ± 1.02                             | 0.38 ± 0.012   | 71 ± 0.71          |
| 35% MPES / 65% Co  | 44.82 ± 0.80        | 166 ± 1.21                             | 0.36 ± 0.011   | 70 ± 0.96          |
| 100% CV            | 59.01 ± 0.86        | 160 ± 1.12                             | 0.28 ± 0.009   | 63 ± 0.36          |
| 35% Co / 65% CV    | 39.61 ± 0.74        | 151 ± 1.44                             | 0.38 ± 0.012   | 75 ± 0.57          |
| 35% CLY / 65% CV   | 53.88 ± 0.92        | 149 ± 1.79                             | 0.29 ± 0.008   | 67 ± 0.48          |
| 35% CPES / 65% CV  | 44.96 ± 0.87        | 166 ± 1.55                             | 0.27 ± 0.012   | 61 ± 0.87          |
| 35% HPES / 65% CV  | 57.34 ± 0.73        | 168 ± 1.33                             | 0.27 ± 0.006   | 60 ± 0.93          |
| 35% MPES / 65% CV  | 60.17 ± 0.59        | 166 ± 1.07                             | 0.26 ± 0.005   | 59 ± 0.94          |
| 100% CLY           | 43.12 ± 0.57        | 155 ± 1.33                             | 0.34 ± 0.009   | 70 ± 0.47          |
| 35% Co / 65% CLY   | 38.45 ± 0.94        | 155 ± 1.11                             | 0.37 ± 0.012   | 73 ± 0.66          |
| 35% CV / 65% CLY   | 37.48 ± 0.69        | 160 ± 1.09                             | 0.31 ± 0.004   | 66 ± 0.72          |
| 35% CPES / 65% CLY | 37.19 ± 0.71        | 163 ± 1.38                             | 0.29 ± 0.006   | 64 ± 0.38          |
| 35% HPES / 65% CLY | 46.82 ± 0.77        | 162 ± 1.27                             | 0.30 ± 0.005   | 66 ± 0.37          |
| 35% MPES / 65% CLY | 51.41 ± 0.92        | 163 ± 0.97                             | 0.30 ± 0.007   | 65 ± 0.22          |



The total porosity values of the fabrics were found to vary between 60% and 75% (Table 2). For fabric porosity to change, parameters such as fabric density, yarn count, thickness, and mass per unit area must vary. In this study, weaving parameters were kept as constant as possible to examine the effect of fiber type on UV protection. All fabrics had the same warp and weft densities. Additionally, their yarn counts, fiber densities, mass per unit area, and thickness values were also similar. Therefore, the porosity values calculated according to Equation 1 were also close to each other. Accordingly, in this study, total porosity did not have a statistically significant effect on the UV protection properties of the fabrics ( $p > 0.05$ ). However, the total porosity of a fabric consists of three components: intra-fiber, intra-yarn (inter-fiber), and inter-yarn porosity. Intra-fiber porosity refers to the voids within the fiber itself, intra-yarn porosity refers to the empty spaces between fibers within a yarn, and inter-yarn porosity refers to the gaps formed at the intersections of yarns within the fabric. The 'effective porosity' in a fabric is primarily determined by inter-yarn and inter-fiber porosity [33]. In fabrics with similar structural characteristics, such as those in this study, inter-yarn porosity remains relatively constant; thus, inter-fiber porosity becomes the key component of porosity influencing permeability. As stated by Militky et al., a relationship exists between inter-fiber porosity and air permeability in woven fabrics [34]. Therefore, the air permeability properties of the fabrics were measured and used as an indicator of the inter-fiber porosity in the fabrics examined in this study.

Air permeability refers to the rate at which air passes through a specified surface area under a defined pressure difference between two sides of the fabric. During the test, air is drawn through the fabric specimen into a sealed chamber and exits through an orifice, where the airflow rate is measured [35]. Air permeability, which indicates how easily air passes through the fabric, can affect the fabric's UV protection by influencing UVR transmission. Within the scope of this study, the relationship between air permeability and the UV protection properties of the fabrics was investigated, and air permeability ( $p < 0.05$ ) was found to significantly affect the UVR transmission of the fabrics (Figure 8). Fabrics with lower air permeability tend to have a more compact structure, limiting the exposure of the fabric's fibers to UVR, thus enhancing the UV protection performance. This result suggests that fabrics with both higher density and lower air permeability can provide more effective shielding from UVR. However, UPF is influenced not only by inter-fiber porosity but also by variations in UVR absorption properties depending on fiber type, particularly in PES fibers. In other words, the UV protection properties of fabrics depend not only on their UVR transmittance but also on their UVR absorption characteristics. As a result, it has been shown that there is a significant relationship between the air permeability of the fabrics and their UV protection properties, in addition to which the UVR absorption properties of the fibers should also be taken into account.

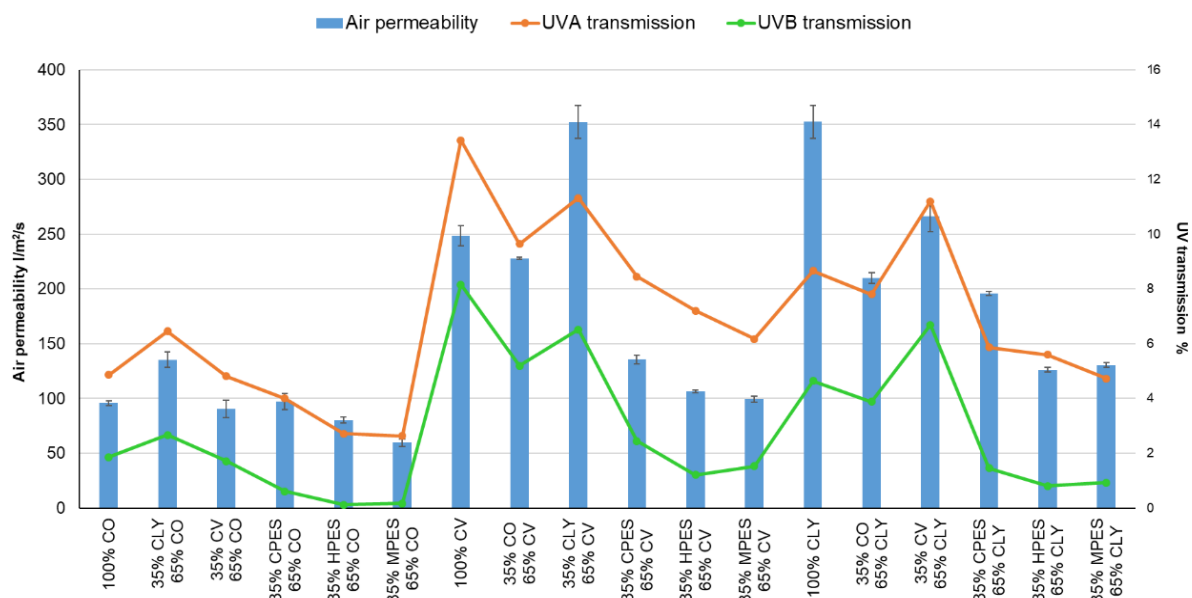


Figure 8. Relationship between air permeability and UV radiation transmission properties of fabrics

#### 4. CONCLUSION

This study provides a systematic evaluation of the UV protection properties of fabrics composed of different fibers (cotton, viscose, lyocell, and PES fiber blends) with the same weaving structure under dry and wet conditions. The results confirmed that PES fibers provide superior UV protection compared to cellulosic fibers, with their cross-sectional structure playing a critical role in UPF performance. Among the cellulosic fibers, cotton exhibited the highest UV protection, followed by viscose and lyocell.

A significant contribution of this study is the demonstration that fiber morphology and polymer composition are key determinants of UV protection in textiles. The findings indicate that UPF assessments should incorporate both UVA and UVB transmittance for a comprehensive evaluation. Moreover, moisture content was found to reduce UV protection across all fiber types, with PES-based fabrics maintaining higher performance even in wet conditions. In addition, the relationship between the air permeability properties of the fabrics and UPF was also examined. It was observed that fabrics with low air permeability could provide higher UV protection.

These insights have direct implications for the development of high-performance UV-protective fibers and textiles, particularly for summer clothes. Understanding the role of fiber morphology in UV blocking efficiency provides a pathway for optimizing fiber design and polymer modifications to enhance protective performance.

Future research could build upon these findings by employing predictive modeling approaches—such as machine learning or advanced regression analysis—to quantitatively estimate UV protection based on fiber type and blend ratio. Further studies may also expand the scope to include additional fiber compositions, fabric structures, finishing techniques, and real-world environmental conditions.

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