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# Sustainable Chemical-free Dyeing of Cotton-Polyester Blended (CVC) Fabric with *Punica Granatum* Extracts: A Green Approach

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## ABSTRACT

*Growing awareness of environmental sustainability has encouraged the search for biodegradable and eco-friendly alternatives in textile coloration. This study explores the potential of Punica granatum (pomegranate) peel extract, a tannin-rich natural dye source for dyeing cotton, polyester, and blended fabrics. The dyeing was performed using the exhaust method at 90 °C for 60 minutes under controlled conditions. The colorimetric properties of the dyed samples were then evaluated in terms of color strength (K/S values) and color difference parameters, using a precision spectrophotometer to assess the shade depth and uniformity of coloration. The CVC fabric recorded the highest K/S value of 2.1 at 420 nm, reflecting a moderate shade depth. FTIR spectroscopy was utilized to investigate the molecular interactions occurring between the dye components of Punica granatum and the CVC fabric, providing insight into the bonding mechanisms involved. It confirmed interactions between dye molecules and the fabric, with the O–H stretching band shifting from 3293.82 to 3305 cm$^{-1}$, indicating hydrogen bond formation between phenolic groups of the dye and functional groups of the fiber. The dyed fabrics exhibited satisfactory color fastness properties when evaluated against washing, water exposure, light, perspiration, and rubbing. Color fastness tests showed encouraging results, with ratings of 4-5 for washing, perspiration, and dry rubbing, 4 for wet rubbing, and 4 for light exposure. These outcomes highlight the potential of pomegranate peel extract as a sustainable substitute for chemical-free dyeing of CVC fabric, combining acceptable shade depth, good fastness, and environmental compatibility. Prog Color Colorants Coat. 19 (2026), 317-327© Institute for Color Science and Technology.*

## 1. Introduction

The textile industry, particularly the wet processing units, consumes large quantities of synthetic dyes and chemicals, generating hazardous effluents that pollute water, air, and soil [1]. Reactive, disperse, and direct dyes are widely used in modern textile industries because of their low cost and easy availability [2]. However, synthetic dyes are non-biodegradable and often toxic, creating serious environmental concerns such as water pollution, ecological imbalance, and challenges in wastewater management [3, 4]. In response to these limitations, the textile industry is gradually shifting toward eco-friendly and sustainable dyeing practices that make use of natural dyes [5].

Natural dyes are regarded as safer alternatives because they are biodegradable and environmentally compatible, particularly suitable for cellulose-based fibers in sustainable textile processing [6]. These colorants are easily obtained from a variety of plant sources and frequently provide additional functional

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benefits, such as antimicrobial, antioxidant, and ultraviolet (UV) protection [7, 8]. Plant-derived colorants are especially promising, as they can be obtained from leaves, flowers, bark, seeds, fruits, and other biomasses. Previous studies have investigated various botanical sources, including *Ocimum sanctum* (tulsi leaves) [9], *Oryza sativa* (black rice) [10], *Azadirachta indica* (neem leaves) [11], *Camellia sinensis var. assamica* (green tea), and *Hylocereus polyrhizus* (dragon fruit) [12]. Despite their benefits, natural dyes frequently encounter challenges, including higher costs, uneven shade uniformity, and comparatively lower color fastness [13].

Among various natural dye sources, *Punica granatum* (pomegranate) peel extract has gained attention due to its rich composition of polyphenolic compounds, particularly tannins, flavonoids, gallic acid, and ellagic acid, which not only impart vibrant coloration but also offer additional functional properties [14, 15]. In addition to their dyeing capabilities, pomegranate peel extracts demonstrate antimicrobial and UV-protective properties, broa-dening their potential use in multifunctional textile applications [16]. Recent research has shown enhanced dyeing perfor-mance of pomegranate peel extract on natural fibers, including silk, cotton, viscose, Tencel, wool, and polyamide [14, 16-20]. Various approaches, including microwave irradiation, plasma pretreatment, and different mordanting techniques (pre, post, and simul-taneous), have been explored to enhance dye uptake and improve fastness properties. However, most of these studies rely heavily on metallic mordants such as copper sulfate, potassium dichromate, ferrous sulfate, and chrome, which present significant environmental concerns. These substances are often difficult to eliminate from wastewater and can compromise the sustainability objectives of natural dyeing practices. Recent research highlights the growing significance of biological mordants like chitosan and plant-based polyphenols, as they enhance the bonding between pomegranate extracts and textile fibers, leading to improved dye fixation and durability [21]. These bio-mordants enhance both the color strength and fastness of the dyed fabric while providing an eco-friendly alternative to conventional toxic metal salts [22]. Mordants act by forming stable dye–mordant–fiber complexes, which contribute to improved resistance against washing, light, and perspiration. For CVC fabrics, plasma surface activation further enhances fiber wettability, facilitating better dye absorption on the polyester portion of the blend [23]. Furthermore, radiation-assisted methods such as UV, microwave, ultrasound, and gamma irradiation have been reported to enhance dye fixation, increase color strength (K/S values), and minimize both processing time and resource use, thereby providing a more sustainable approach to natural dyeing [24]. In response to these challenges, chemical-free dyeing has become an important area of research, with the goal of minimizing environmental risks while preserving color quality. Among the promising natural resources, pomegranate peel extract stands out. Rich in phenolic compounds, pomegranate peel can form hydrogen bonds with the hydroxyl groups of cellulose, enabling effective dye–fiber interactions [15].

Most previous studies on dyeing with pomegranate peel extract have primarily focused on single-fiber substrates such as 100 % cotton, silk, polyester, viscose, or Tencel. [25-27]. In contrast, compre-hensive studies on cotton–polyester (CVC) blends remain limited, making this substrate relatively underexplored for sustainable dyeing applications. Although some research has utilized mordants or cationization techniques, systematic investigations on auxiliary-free dyeing of CVC fabrics supported by quantified K/S values and standardized fastness data are still largely lacking [28]. By examining CVC fabrics, this study provides valuable insights into the dual-phase dye uptake and fastness behavior of both the cellulose-rich and polyester-rich components [29]. In reported studies on pomegranate-based dyeing, the use of mordants or fixatives has generally resulted in deeper shades and improved fastness properties [30]. This study bridges that research gap by demonstrating auxiliary-free dyeing of CVC fabrics using pome-granate peel extract. The findings offer new data-driven insights that support sustainable coloration approaches. Moreover, given polyester's global prominence for its durability, versatility, and cost-effectiveness, developing scalable and eco-friendly dyeing techniques for polyester-cotton blends has become an important industrial priority [31].

The use of pomegranate peel extract for dyeing cotton-polyester blended fabrics has been only minimally explored to date. Polyester, one of the most widely used synthetic fibers, is valued for its versatility, durability, and cost-effective production [32]. Blending polyester with natural fibers like cotton results in fabrics that combine improved performance with unique functional properties. However, the hydrophobic nature and crystalline structure of polyester restrict its dye absorption, posing particular challenges for natural dyeing. Therefore, this study focuses on the extraction and application of *Punica granatum* peel dye for coloring cotton–polyester blended (CVC) fabrics. By adopting eco-friendly and chemical-free dyeing approaches, and by assessing both color intensity and fastness properties, the research seeks to provide new insights into the sustainable use of pomegranate peel extracts on blended textiles. The outcomes are expected to support the development of greener alternatives to synthetic dyes, offering the textile industry a practical pathway toward eco-sustainable processing.

## 2. Experimental

### 2.1. Fabric

Commercially available single jersey knitted fabrics composed of 100 % cotton, 100 % polyester, and 60 % cotton and 40 % polyester (CVC) with a GSM of 150 were used in this study. Before testing, all fabric samples were conditioned for 24 hours under standard atmospheric conditions, maintained at 20 ± 2 °C and 65 % relative humidity (RH).

### 2.2. Chemicals

The experimental work involved the use of distilled water as the medium for dye extraction and a soaping agent (INDOCLEAN MFD), which was applied during the post-dyeing washing process.

### 2.3. Extraction of natural dye from *Punica granatum* peel

Pomegranate peels were thoroughly rinsed with tap water and then cut into small pieces. The prepared material was immersed in distilled water at a material-to-liquor ratio of 1:30 in a stainless-steel container. The mixture was heated to 100 °C and maintained for 60 minutes for extraction [30]. The aqueous extract of pomegranate peel was boiled for one hour at an elevated temperature, as the primary coloring compound, tannin, remains stable and retains its dyeing potential even under high-temperature extraction conditions. After cooling, the pulp was separated using a metal strainer, and the obtained extract was collected and preserved in sufficient quantity for subsequent dyeing applications [14].

### 2.4. Dyeing procedure

The dye bath was prepared by immersing the cotton, polyester, and blended fabrics in 150 mL of dye solution at a liquor ratio of 1:30. The process was carried out in a laboratory dyeing machine (Eco Dyer, Xiamen Rapid Precision Machinery Co. Ltd., Taiwan) at an initial temperature of 30 °C [30]. The temperature was gradually raised to 90 °C at a controlled rate of 3 °C per minute for all fabric samples, and the dyeing process was maintained at this temperature for 60 minutes [30, 33]. Commercially, cotton fabrics are typically dyed at around 80 °C. However, in this study, the dyeing temperature was increased to enhance dye penetration, as no auxiliary agents were employed. It is also noteworthy that polyester fabrics are conventionally dyed at higher temperatures, approximately 130 °C [25]. In this study, the dyeing temperature for polyester and CVC fabrics was optimized at 90 °C to prevent potential dye degradation at higher temperatures, since no additional chemicals were used to promote dye exhaustion or fixation. Therefore, all fabric samples were dyed at a uniform temperature of 90 °C [33, 34], followed by cooling and drying. The temperature was lowered to 70°C for soaping [35]. The steps involved in dyeing fabric using pomegranate peel extract are illustrated in Figure 1.

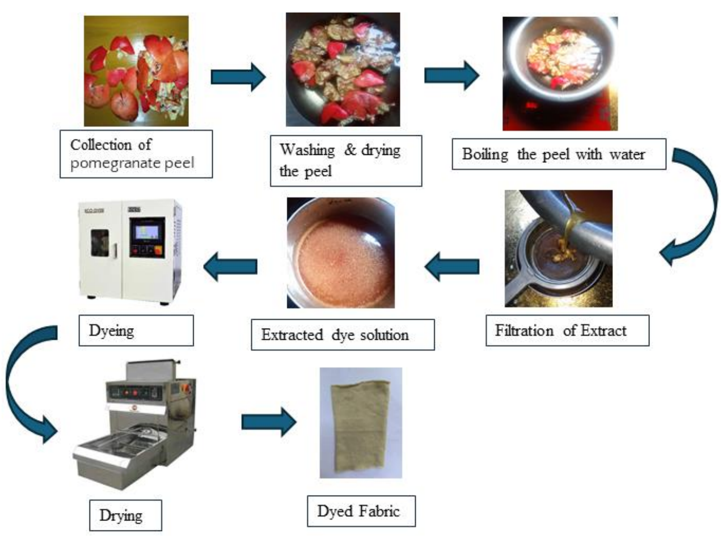


**Figure 1:** Pictorial depiction of the dyeing procedure of cotton, polyester, and CVC fabric using pomegranate peel extract.

The soaping bath was prepared by mixing 80 mL of water with 20 mL of a 2% soaping agent solution. The treatment was carried out at the set temperature for 15 minutes, after which the bath was cooled and drained. Finally, the fabrics were dried at 80 °C for 5 minutes using a laboratory mini dryer (Xiamen Rapid Precision Machinery Co. Ltd., Taiwan).

## 2.5. Characterizations

### 2.5.1. FTIR spectroscopy analysis

Fourier-transform infrared (FTIR) spectroscopy was performed using an FT/IR-4700 spectrometer (JASCO Corporation, Japan) to examine the interactions between the fabric and the dye molecules [36]. Each fabric sample was securely mounted by opening the machine clamp before analysis. Infrared radiation was then passed through the dyed fabrics, and absorbance spectra were recorded in the range of 500–4000 $cm^{-1}$ to identify characteristic chemical groups. The results showed that IR absorption varied with dye intensity: fabrics with deeper or more saturated shades exhibited stronger absorption peaks, whereas lighter shades produced lower peak intensities. These findings suggest that greater color saturation enhances the infrared absorption of the fabric, which may also be associated with improved color fastness properties [37].

### 2.5.2. Color strength (K/S value)

Color strength is a key parameter in evaluating dyed fabrics. In this study, the color strength of the samples was assessed using the Kubelka–Munk theory. The K/S values were calculated according to the following equation 1.

$$K/S=\frac{(1-R)^2}{2R} \quad (1)$$

In this equation, R denotes the fraction of light reflected by the fabric, K represents the absorption coefficient, indicating the extent of light absorbed, and S refers to the scattering coefficient, which describes the amount of light dispersed by the fabric [36].

### 2.5.3. Color differences (CMC) analysis

A spectrophotometer was employed to evaluate the color differences among the dyed samples. In the CMC test, the analysis typically reports values for ΔE*, ΔL*, Δa*, Δb*, Δc*, and ΔH*. Among these parameters, ΔE* represents the total color difference, while ΔL* indicates the degree of lightness or darkness, with positive values denoting lighter shades and negative values denoting darker shades. Similarly, Δa* expresses the red–green axis, where positive values correspond to redder tones and negative values to greener tones, and Δb* reflects the yellow–blue axis, with positive values indicating more yellow and negative values indicating more blue. The parameter Δc* describes differences in chroma or brightness, with positive values representing brighter and negative values representing duller shades, whereas ΔH* accounts for variations in hue. The overall color difference of the dyed fabrics was then determined according to the following equation 2 [39].

$$(\Delta E^*)^2=(\Delta L^*)^2+(\Delta a^*)^2+(\Delta b^*)^2 \quad (2)$$

### 2.5.4 Color fastness to wash

Wash fastness was assessed in accordance with the ISO 105-C06 standard method. A multifiber fabric measuring (100 ± 2) mm × (40 ± 2) mm was attached to cotton, CVC, and polyester fabrics of the same dimensions. The specimens were then washed in a laboratory washing machine with 25 steel balls, using ISO standard detergent at a liquor ratio of 1:50, maintained at 60 °C for 30 minutes [40, 41]. After washing, the samples were rinsed in cold water and subsequently dried at 60 °C. Color staining on all fabric samples was then assessed using the gray scale.

### 2.5.5. Color fastness to perspiration

The color fastness to perspiration test was carried out to assess the resistance of dyed textiles to color change or staining caused by exposure to sweat. All fabric samples were tested in accordance with the ISO 105-E04:201 standard [42]. It examines the effect of both acidic and alkaline sweat on dyed fabrics.

### 2.5.6. Color fastness to water

Color fastness to water evaluates the ability of a fabric to retain its color when in contact with water. This test was conducted in accordance with the ISO 105-E01:2010 standard method [43].

### 2.5.7. Color fastness to rubbing

The rubbing fastness test was conducted to evaluate the extent of color transfer from the surface of dyed fabrics to a standard test cloth during rubbing. The procedure followed the ISO 105-X12:2016 standard using a crock meter. Dyed fabric specimens measuring 14 × 5 cm were mounted on the apparatus, while a 5 × 5 cm cotton cloth was fixed to the rubbing finger of the device. The finger was then moved across the fabric surface with 10 strokes. For wet rubbing, the same procedure was repeated using a wetted crocking cloth [41]. After the test, color transfer was evaluated for both dry and wet rubbing using a grey scale.

### 2.5.8. Color fastness to light

Color fastness to light was evaluated according to the ISO 105-B02:2013 standard. Fabric specimens measuring (100 ± 2) mm × (40 ± 2) mm were mounted flat on a sample holder to ensure uniform exposure. The samples were then exposed to a xenon arc lamp with a color temperature ranging from 5500 K to 6500 K for 72 hours. Following exposure, color changes were assessed using the gray scale [43].

## 3. Result and Discussion

### 3.1. FTIR analysis

FTIR analysis (Figure 2) was conducted to confirm the interaction between the phenolic groups present in the pomegranate peel extract dye molecules and the functional groups present in the fabric. This technique also provides evidence of successful dye fixation by identifying characteristic shifts in absorption peaks associated with specific functional groups. A previous study by Otaviano et al. supported the presence of polyphenolic compounds in pomegranate peel through ATR-FTIR analysis, confirming that these constituents play a key role in defining the extract's characteristic chromatic properties [44]. Pomegranate rind is rich in polyphenolic compounds, including phenolic acids, tannins, flavonoids, and anthocyanins [30]. Tannins are the major chemical constituents of the aqueous extract obtained from pomegranate rind. The peels primarily contain hydrolyzable tannins, which belong to one of the two main classes of tannins. The functional groups present in the aqueous pomegranate peel extract were identified using FTIR analysis, as shown in Figure 2 c. The spectrum exhibited characteristic peaks corresponding to aromatic ring vibrations at 1616 $cm^{-1}$, C–H bond vibrations at 2337 $cm^{-1}$, and stretching of phenolic –OH groups around 3586 $cm^{-1}$ [45]. Additionally, the spectrum displayed a bending vibration of the C–H bond at 965 $cm^{-1}$, an asymmetric C–O–C stretching band at 1025 $cm^{-1}$, and an –OH deformation vibration of phenolic groups at 1276 $cm^{-1}$ [30].

The interaction between the phenolic group and the CVC fabric was also examined using FTIR spectroscopy. In Figure 2 b, the O-H stretching peak shifted from 3293.82 to 3305 $cm^{-1}$, indicating the dye interacts with cotton fibers primarily via hydrogen bonding, either between its phenolic groups and the hydroxyl groups of cellulose [15]. For polyester fiber, it may create hydrogen bonding between the ester groups in polyester and the carbonyl groups of phenolic compounds [38].

### 3.2. Color strength (K/S value) analysis

Table 1 shows the color strength value of cotton, polyester, and CVC fabric after dyeing with pomegranate peel extract. This assessment determines how effectively the blended fabric absorbs phenolic compounds, indicating the level of dye uptake. It also helps evaluate how dark or light the final dyed fabric appears, which is crucial for shade consistency and visual appeal. The color strength (K/S values) of all the fabrics dyed with pomegranate extract was measured at a wavelength of 420 nm. Higher K/S values are indicative of a greater color depth (darker) shade, while a lower value shows a lighter shade [36]. As shown in Table 1, among the tested samples, the 100 % cotton fabric exhibited the lowest color strength (K/S = 1.15), while the polyester fabric showed a slightly higher value of 1.35. The pomegranate peel contains several tannin-based pigments, including mucoepidene, ellagic acid, amphiregulin, and pomegranate pithin A and B. However, these compounds have relatively low affinity toward natural fibers and high solubility in water, which often necessitates the use of mordants or fixing agents to improve dye fixation and color fastness [30]. Therefore, the cotton fabric exhibited the lowest K/S value, while the CVC fabric dyed with pomegranate peel extract recorded the highest K/S value of 2.1, indicating a moderate color strength. This finding suggests that pomegranate peel extract shows greater dye affinity toward cellulose-rich blended fibers, resulting in enhanced color intensity in CVC fabrics [26]. The K/S value of the polyester fabric was lower than that of the CVC fabric, which can be attributed to the higher crystallinity of polyester fibers. This structural characteristic limits dye penetration, leading to reduced dye uptake compared to the less crystalline CVC fabric [19].

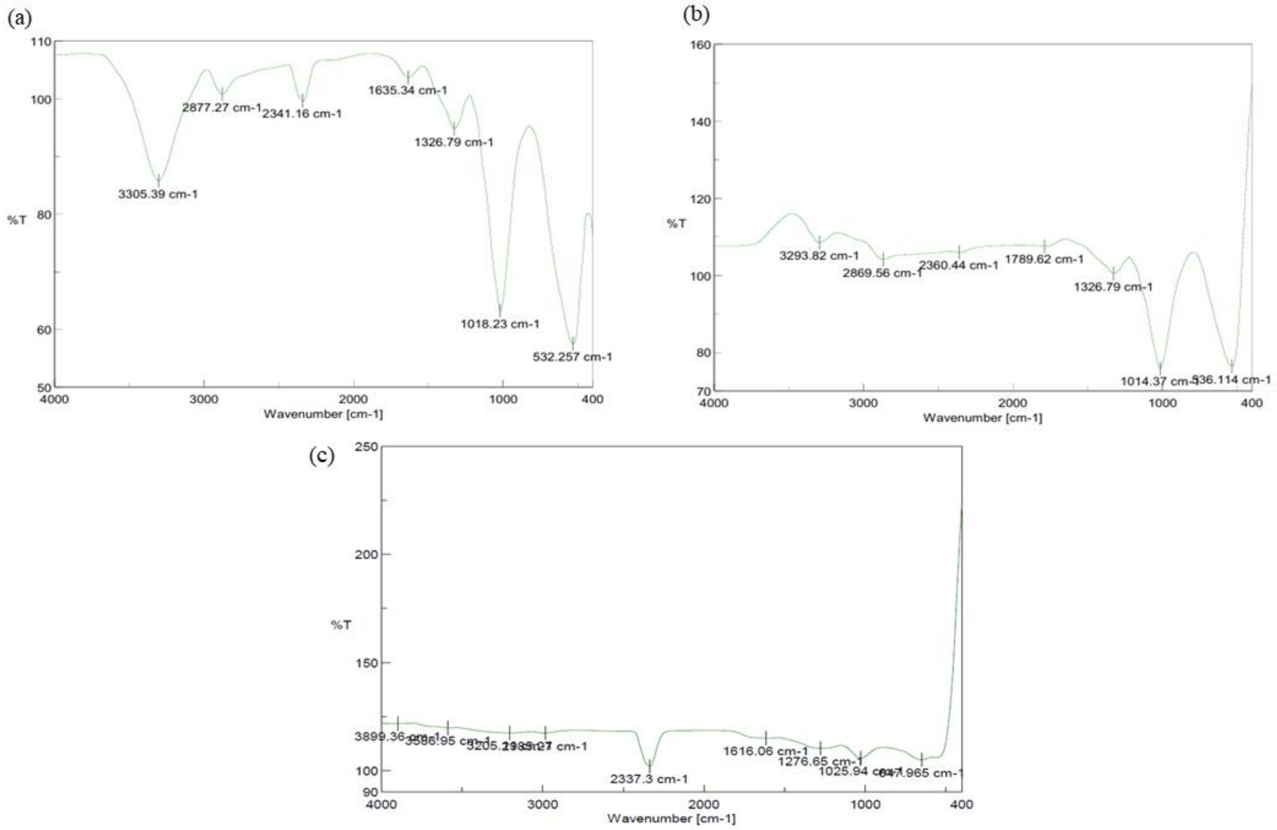


**Figure 2:** FTIR spectra of (a) undyed CVC fabric, (b) dyed CVC fabric, and (c) pomegranate peel dye extract.

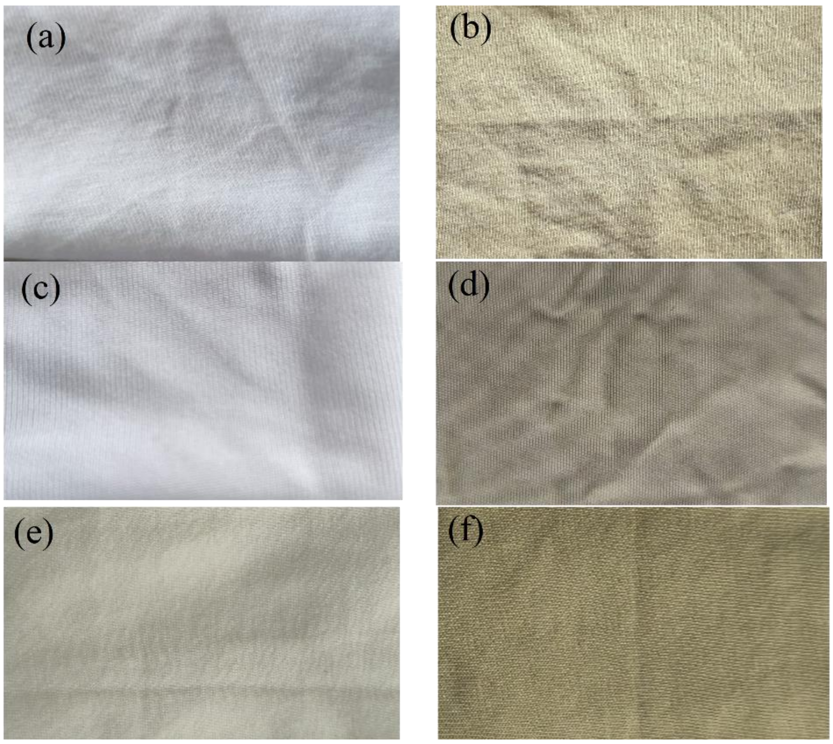


**Figure 3:** Sample images of (a) undyed cotton fabric, (b) dyed cotton fabric, (c) undyed polyester fabric, (d) dyed polyester fabric, (e) undyed CVC fabric, and (f) dyed CVC fabric with pomegranate peel extract.

### 3.3. CMC (Color measurement committee) value analysis

Table 1 shows the color difference analysis of cotton, polyester, and CVC fabric dyed with pomegranate peel extract exhibited a total color difference (ΔE*) of 14.04, 13.87, and 15.68, respectively, indicating a visibly perceivable variation in shade compared to the standard reference. The negative ΔL* value for all the samples signifies that the dyed samples appeared considerably darker, a common outcome when natural dyes with strong tannin content penetrate the fibers. A positive shift in Δa* suggests a minor inclination towards the red region of the color axis, while the Δb* value indicates a pronounced shift towards yellow tones. The corresponding increase in chroma confirms enhanced color saturation, attributed to the high phenolic content of pomegranate peel extract. Meanwhile, the Δh* value demonstrates a negligible change in hue angle, signifying that the overall color tone remained consistent but deepened in intensity [37]. As illustrated in Figure 3, all dyed fabric samples exhibited color shades ranging from light to medium yellowish-brown. Among them, the cotton fabric dyed with pomegranate rind extract showed the lowest lightness (ΔL*=−18.27), along with moderate greenness (Δa*=2.90) and pronounced yellowness (Δb*=10.95), compared to the polyester and CVC fabrics. The CVC fabric displayed higher chroma and hue values (ΔC*=10.60 and Δh*= −1.20) than the 100 % polyester fabric (ΔC*=9.27 and Δh* = −2.20), suggesting that the CVC samples produced more vivid and visually appealing shades [19].

### 3.4. Color fastness to wash

As presented in Table 2, all fabrics dyed with pomegranate peel extract exhibited wash fastness ratings of 4-5, demonstrating strong resistance to color loss during laundering. This level of performance is particularly remarkable for an auxiliary-free, plant-based dyeing process. Comparable studies have reported similar or slightly lower wash fastness values for pomegranate-derived dyes applied to cotton and polyamide fabrics, with noticeable improvements achieved through the use of eco-friendly mordants or fiber pretreatments such as mercerization [16, 30]. These findings confirm that the tannin-rich poly-phenolic compounds in pomegranate peel significantly contribute to strengthening dye–fiber interactions, primarily through hydrogen bonding and secondary molecular forces with cellulose, thereby minimizing dye desorption under aqueous conditions [16]. Overall, the performance observed in this study falls within the higher range of natural dye systems, highlighting the potential of pomegranate peel as a sustainable and durable alternative for eco-friendly textile coloration.

### 3.5. Color fastness to perspiration

As shown in Table 2, the dyed cotton, polyester, and CVC fabrics exhibited perspiration fastness ratings of 4–5 under both acidic and alkaline conditions, indicating strong resistance to color change and staining. This level of performance is particularly noteworthy for an auxiliary-free dyeing process and can be attributed to the tannin-rich polyphenolic compounds present in pomegranate peel, which form hydrogen bonds and micro-entrapments with the fiber surfaces, effectively minimizing dye desorption and improving overall fastness [18]. These results emphasize the potential of pomegranate peel extract as a sustainable natural dye that can deliver durable coloration even under perspiration conditions. Further improvements may be achieved through the application of eco-friendly pretreatment or finishing techniques to enhance its overall performance.

**Table 1:** Color strength and color differences of dyed cotton, polyester, and CVC fabric.

| Fabric Type | K/S value | ΔE* | ΔL* | Δa* | Δb* | Δc* | Δh* |
|---|---|---|---|---|---|---|---|
| 100 % Cotton | 1.14 | 14.04 | -18.27 | 2.90 | 10.95 | 11.19 | -1.73 |
| 100 % Polyester | 1.35 | 13.87 | -23.51 | 3.33 | 8.92 | 9.27 | -2.20 |
| CVC | 2.1 | 15.68 | -24.33 | 1.89 | 10.50 | 10.60 | -1.20 |

### 3.6. Color fastness to water

The samples were assessed for their colorfastness to water, and as presented in Table 2, they attained high ratings of 4-5, indicating strong resistance to color fading. These results indicate that all fiber types in the multifiber fabric, namely acetate, cotton, nylon, polyester, acrylic, and wool, exhibited good resistance to color change upon exposure to water. The findings suggest that the fabrics retained their color effectively under wet conditions; this enhanced water resistance is likely due to strong interactions between polyphenolic constituents of the pomegranate-peel extract and the fiber surface [14, 15].

### 3.7. Color fastness to rubbing

As shown in Table 3, all dyed fabrics exhibited excellent dry rubbing fastness, with ratings between 4 and 5, indicating strong resistance to color transfer under mechanical friction. Although the wet rubbing fastness was slightly lower-recording a rating of 4 for both cotton and CVC fabrics-the polyester sample demonstrated comparatively better performance in this regard. This behavior can be attributed to the presence of tannins and phenolic compounds in pomegranate peel, which form hydrogen bonds with cellulose, thereby enhancing the dye-fiber interaction and improving overall color retention [27]. Similar results have been reported in previous studies, where pomegranate-based dyes generally exhibited better rubbing fastness compared to other natural colorants, although a slight reduction in wet rubbing performance remains a common limitation [39]. The present results position this dyeing system among the higher-performing examples of auxiliary-free natural dye applications, demonstrating the strong potential of tannin-rich extracts to form durable dye–fiber bonds. However, further enhancement in wet rubbing resistance may be achieved through sustainable post-treatment processes or the incorporation of bio-mordants.

### 3.8. Color fastness to light

As presented in Table 3, the CVC fabrics dyed with pomegranate peel extract exhibited a light fastness rating of 4 on the grey scale, while the 100 % cotton and 100 % polyester fabrics showed slightly lower ratings of 3. These results indicate good resistance to light exposure, as ratings between 4 and 5 are generally considered satisfactory for apparel and interior textile applications. This performance can be attributed to the presence of polyphenols and tannins in pomegranate peel, which form hydrogen bonds with cellulose and impart UV-screening properties, thereby minimizing chromophore degradation during light exposure [19]. Comparable observations were reported by Botteri et al., who found that cotton fabrics dyed with pomegranate extract exhibited similar or even higher light fastness values than those dyed with other natural colorants. The study also noted significant improvements in light fastness when mordants or pretreatment methods were employed [30]. Although the auxiliary-free approach used in this study demonstrates performance consistent with typical natural dye systems, further improvements toward the highest grey-scale rating of 5 could be achieved through environmentally friendly strategies such as the use of bio-mordants, fiber surface pretreatments, or the incorporation of UV-absorbing finishes.

**Table 2:** Color fastness to wash, perspiration, and water test results of dyed fabrics.

| Fiber name | Color fastness to wash | | | Color fastness to perspiration | | | | | | Color fastness to water | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Alkaline | | | Acidic | | | | | |
| | 100 % Cotton | 100 % Polyester | CVC | 100 % Cotton | 100 % Polyester | CVC | 100 % Cotton | 100 % Polyester | CVC | 100 % Cotton | 100 % Polyester | CVC |
| Acetate | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 |
| Cotton | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 |
| Nylon | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 |
| Polyester | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 |
| Acrylic | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 |
| Wool | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 | 4-5 |

**Table 3:** Color fastness to rubbing and light test results of dyed fabric.

| Fabric type | Color fastness to rubbing | | Color fastness to light |
|---|---|---|---|
| | Dry | Wet | |
| 100 % Cotton | 4-5 | 4 | 3 |
| 100 % Polyester | 4-5 | 4-5 | 3 |
| CVC | 4-5 | 4 | 4 |

## 4. Conclusion

This study investigated a clean, eco-friendly, and chemical-free approach for dyeing 100 % cotton, 100 % polyester, and cotton–polyester (CVC) blended fabrics using *Punica granatum* (pomegranate) peel extract. The dyeing was conducted without the use of any auxiliary chemicals. Evaluation of the dyed samples showed satisfactory coloration performance, particularly in terms of color strength (K/S value). Among the tested fabrics, the CVC sample exhibited the highest K/S value of 2.1 at a wavelength of 420 nm, indicating a moderate shade depth compared to the control cotton and polyester samples. FTIR analysis confirmed the formation of hydrogen bonds between the phenolic groups of the dye and the hydroxyl groups of cellulose in cotton, indicating successful binding of the dye molecules to the fabric substrate. In polyester fabric, hydrogen bonding may occur between the ester groups of polyester and the carbonyl groups of phenolic compounds. These results suggest that the tannins and other phenolic compounds present in pomegranate peel enhance the dye's affinity, thereby improving color intensity even in the presence of polyester's crystalline structure. Colorfastness tests were performed to evaluate the resistance of the dyed fabrics to washing, perspiration, rubbing, and light exposure. The results demonstrated satisfactory performance, confirming that all dyed samples exhibited adequate durability under these conditions. Overall, pomegranate peel extract proved to be an effective chemical-free dyeing agent, providing moderate color depth, acceptable fastness properties, and notable environmental benefits, underscoring its potential as a sustainable alternative for textile coloration. Nonetheless, there remains scope for optimization. The dye extraction and dyeing parameters can be further refined to increase the concentration of dye compounds and enhance color performance. As this work adopted a chemical-free approach, microwave-assisted extraction could be a promising strategy to improve dye yield and efficiency. Although high temperature was employed during extraction, this may raise energy consumption concerns; therefore, future studies could explore low-temperature extraction methods to achieve similar outcomes more sustainably. In this research, a single material-to-liquor ratio was applied for both dye extraction and dyeing, which could be varied in subsequent investigations to determine its influence on color yield and uniformity. Moreover, previous studies have shown that certain natural mordants can strengthen dye–fiber interactions across different natural dyes and fiber types. Their application in pomegranate-based dyeing of CVC fabrics should be explored in future work. Additionally, further research may focus on enhancing dye uptake and fastness performance while preserving the auxiliary-free and environmentally friendly nature of the process. As a readily available agricultural by-product, pomegranate peel not only serves as an effective natural dyeing agent for blended textiles but also represents a promising step toward integrating bio-based colorants into sustainable textile manufacturing and circular economy models. To further advance its application, large-scale pilot trials and comprehensive life-cycle assessments are recommended to evaluate its industrial feasibility, cost-effectiveness, and long-term environmental benefits in sustainable textile production.


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