

# Dry and chemical-free chromatic homogenization of mixed-colored waste polyester textiles using supercritical CO<sub>2</sub>

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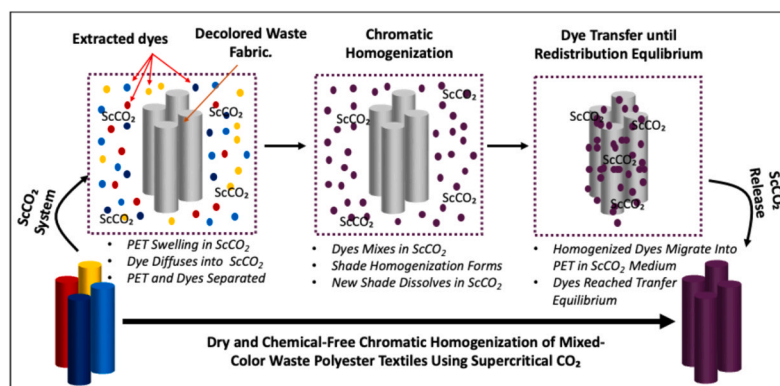
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## HIGHLIGHTS

- Chemical-free approach for sustainable repurposing and recycling of textile waste, reducing the need for re-dyeing.
- Chromatic homogenization of mixed-colored PET using supercritical CO<sub>2</sub>.
- Color consistency achieved with K/S values showing minimal variation across samples.
- High color fastness to wash and rubbing, with full strength retention post-treatment.

## GRAPHICAL ABSTRACT



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## ABSTRACT

Herein, disperse dyed mixed-colored (blue, yellow, orange) polyester textile (PET) was homogenized into a common final color using a supercritical carbon dioxide (scCO<sub>2</sub>) system following Le Chatelier's equilibrium principle and partition equilibrium between fabric–scCO<sub>2</sub>–dye phases and subtractive color mixing principles. For that, mixed-colored PET were placed together in the scCO<sub>2</sub> system at predetermined weight ratios and treated under controlled temperature and pressure conditions. Under supercritical conditions, dye molecules exhibited enhanced mobility and partial redistribution between textile substrates via the scCO<sub>2</sub> medium, enabling chromatic equilibration without the use of auxiliary chemicals or solvents. The resulting PET demonstrated a new and consistent color, confirmed by colorimetric analysis (K/S values) and visual color variance compared to the initial mixed-color feedstock. Detailed data analysis of treated PET revealed that the standard deviation of K/S values within each group ranged from 0.06 to 0.38, confirming homogenized shade across all sample, which is in line with scCO<sub>2</sub>'s unique superlevelling capacity, enabling chromatic harmonization. The samples were further analyzed for their color fastness to wash and rubbing as well as tensile strength properties. Results showed that, the color fastness of both wash and rubbing ranges from 4/5–5 with full strength retention before and after the

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treatment. The results of this study are of great importance, as it presents a new, dry and chemical-free approach for homogenization of mixed-colored waste polyester into a common color to facilitate sustainable repurposing and recycling of textile waste, reducing the need for re-dyeing.

## 1. Introduction

Polyesters represent one of the most commercially significant groups of polymers worldwide. Ranking after polyethylene and polypropylene, polyesters contribute approximately 18% of global polymer output and the dominant material utilized in textile fiber production [1,2]. According to materials market report (2024) by Textile Exchange, polyester remained the most produced fiber globally, accounting for 57% of total 124 million tonnes of global fiber production [3], meanwhile, less than 1% of the global fiber market came from pre- and postconsumer recycled textiles [3,4]. As highlighted by Periyasamy, A. P., & Harlin, A. (2025) [5] that, the major challenges for chemical recycling of textile waste involves the presence of heterogeneous and often unidentified contaminants. Among these, dyes constitute a critical class of contaminants hindering sustainable repurposing and recycling of textile waste due to their structural diversity and unknown chemical composition. Huang, T. (2025) [6] reported that, the same challenges persist repurposing and recycling of polyester textile waste dyed using disperse dyes. One of the most popular approach to tackle this challenges is removal of color from polyester textile waste prior to repurposing and recycling. Several reports have presented compelling method for removal of color of the polyester textile ranging from both chemical and physical color removal methods with varying level of success [7–10]. These observations highlight the need for integrated approaches that not only remove dyes effectively but also preserve the quality of the fibers, minimize environmental impact, and enable circular reuse.

Disperse dyes can be removed from polyester textiles using hot solutions containing chemicals such as sodium hydrosulfite with ammonium hydroxide, zinc sulphoxylate formaldehyde with formic acid, sodium chlorite with formic acid, or sodium hydroxymethanesulfinate with a carrier and acetic acid [10,11]. However, these approaches are generally unsustainable, relying on toxic or hazardous chemicals [5]. Physical color removal process based on  $scCO_2$  has also been introduced as a highly efficient sustainable color removal process replacing the chemical color removal process from polyester waste textile [6,8].

In addition to color removal, several report also highlighted the potential of color migration from a dyed polyester textile to an undyed fabric in a one batch  $scCO_2$  process. One of our previous report also heighted the potential for waste textile decolorization using  $scCO_2$  technology showing promising prospects for sustainable color migration from polyester textile waste [7]. Ren et al. (2025) [12] also reported a similar approach by treating dyed (waste) and undyed polyester textiles together in  $scCO_2$ , enabling dye migration and redistribution until equilibrium. Furthermore, Broadbent et al. (2023) [13] confirmed the superlevelling capacity of  $scCO_2$ , showing that transfer-printed polyester with calibration blocks could be homogenized into silver-grey shades through dye desorption, migration, and re-adsorption, an effect unattainable with aqueous treatment. These reports indicate that  $scCO_2$  is capable of efficient dye desorption, migration, and re-adsorption, allowing both color removal and chromatic homogenization of polyester textiles in a single process.

Significant advances have been achieved in color removal and decolorization technologies for textile recycling; however, an alternative strategy can be retaining the dyes within recycled fibers and harmonize the color across mixed textile waste streams [5]. Instead of removing dyes, this approach focuses on reusing them in the production of new textiles, either by blending or standardizing color levels. This will reduce chemical usage and environmental impact, avoids energy-intensive recycling processes, and can create economically attractive recycled textiles with consistent coloration. To the best of our

knowledge, there has been no report addressed this concept so far. The closest report to concept was published by Gong et al. (2021) [14], where they have showed that mixtures of disperse dyes can be compatibly applied in  $scCO_2$  dyeing of polyester, producing reproducible dark shades with good fastness. Specifically, a 1:1 and 1:3 ratios of Disperse Red 54 and Disperse Blue 79 generated deep black and dark blue tones, while a 1:1 mixture of Disperse Red 167 and Disperse Blue 79 yielded a stable dark purple shade.

Building on the development  $scCO_2$  technology for polyester waste textile processing, this work introduces focused on chromatic homogenization of mixed color polyester textile using  $scCO_2$  as a dry and chemical-free approach. This method is based on established  $scCO_2$  technology and will facilitate sustainable repurposing and recycling of textile waste by reducing the reliance on chemical treatments and minimizing the need for re-dyeing in downstream applications.

## 2. Experimental

### 2.1. Materials

Terasil Golden Yellow 2803, Terasil Royal Blue SC, and Colortex Corangar Orange PE-3330 dyes were obtained from Huntsman International LLC (USA) and used as received. Generic chemical structure of the dyes is provided in Fig. 1. Polyester textile with a double-jersey structure was manufactured on a Mayer & Cie OVJA 1.6 EE circular knitting machine (20-gauge, 30-inch diameter, 48 feeders). Yarns of 167 dTex/48 filaments were used for stitch formation, while 78 dTex/34 filament yarns were employed for tuck stitches on every fourth cylinder needle. Carbon dioxide ( $CO_2$ ) used in all experiments was supplied by Linde Gas AB (Sweden) with a stated purity of 99%.

### 2.2. Method of chromatic homogenization of mixed-color waste polyester textiles in $scCO_2$

Mixed-color waste polyester textiles were subjected to chromatic homogenization using  $scCO_2$  as a solvent medium. Prior to treatment, simulated textile wastes of different colors were prepared according the standard dyeing of polyester textile using  $scCO_2$  as explained elsewhere [7]. Typically, polyester textile was dyed with commercially available disperse dyes (Terasil Royal Blue SC (B), Terasil Golden Yellow 2803 (Y), and Colortex Corangar Orange PE-3330 (O)) in a batch  $scCO_2$  system at a dye concentration of 0.5% o.w.f. (on weight of fabric). Following individual dyeing, fabric samples were cut and recombined into seven experimental groups, each comprising different weight proportions of the three pre-dyed color polyester textiles, while maintaining a constant total weight of 3 g to ensure consistent mass transfer during processing (see Table 1). The ratios ranged from balanced proportions (1:1:1) to skewed combinations such as 1.5:0.5:1 thereby enabling the evaluation of how the dominance of one dyed (waste) component influences the final shade uniformity.

The experimental design was inspired by the principle of chromaticity balance, where combinations of differently colored substrates as shown in Fig. 2, are used to achieve stable compound shades [15,16].

The prepared mixed-colored fabric samples were placed in the high-pressure dyeing vessel and treated with supercritical carbon dioxide under identical processing conditions of dyeing. Typically, the  $scCO_2$  dyeing of polyester is carried out at a temperature of 120 °C and a pressure of 25 MPa for a total duration of 60 min. During the treatment, the  $scCO_2$  acted as a dye-transfer medium, promoting the diffusion, desorption, and redistribution of dyes among the differently colored

polyester textiles. This process enabled dye exchange between samples in a manner analogous to an actual dyeing operation, while ensuring consistent thermal and pressure exposure for all samples.

### 2.3. Method of color strength (K/S) measurement

The color strength of the samples after chromatic homogenization were measured by a spectrophotometer (Datacolor 500) under standard illumination conditions (D65/10° observer) with a FL40-UV filter (0% UV) to eliminate ultraviolet interference. Calibration was performed using a diagnostic tile to ensure measurement accuracy. The K/S value of fabric before and after treatment, was calculated at maximum absorption using the Kubelka-Munk equation, as signified in Eq. (1). Each sample was folded into two layers, and the K/S value was the average of four measurements taken from the fabric in the range of 400 nm – 700 nm.

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

Where: K and S are absorption and scattering coefficients of polyester textiles, respectively and R is the minimum spectral reflectance ratio.

### 2.4. Method of color fastness to washing

The color fastness to washing after chromatic homogenization was measured according to ISO 105-C06:2010 (Tests for color fastness, Part C01: Color fastness to domestic and commercial laundering). Rectangular specimens (10 cm × 4 cm) of the polyester textile were prepared and, where applicable, paired with multi-fiber adjacent fabrics (cotton, wool, polyester, acrylic, and nylon) to assess staining. Specimens were conditioned under standard testing atmosphere (20 ± 2 °C, 65 ± 4% RH) prior to testing. Washing was performed in a laboratory laundering machine with a standard reference detergent solution at 40 °C for 30 min under continuous agitation. Specimens were rinsed in cold water and air-dried. After drying, color change of the test fabrics and staining on adjacent fabrics were evaluated using the ISO gray scale (1 = very poor, 5 = excellent). At least three replicates were tested per condition, and the mean values were reported.

### 2.5. Method of color fastness to rubbing

The color fastness of polyester textiles to rubbing (crocking) after chromatic homogenization was measured according to ISO 105-X12:2016 (Tests for color fastness, Part X12: Color fastness to rubbing). Rectangular specimens were conditioned under standard atmosphere (20 ± 2 °C, 65 ± 4% RH) before testing. A white cotton rubbing cloth was used on a crockmeter under a standard applied load. Both dry and wet rubbing tests were performed, with the wet test cloth moistened with distilled water. After the specified number of rubbing cycles, the degree of color transfer to the rubbing cloth was assessed using the ISO gray scale (1 = severe staining, 5 = negligible staining). Three replicates were tested per specimen, and mean values were reported.

### 2.6. Method of tensile strength

The tensile strength of polyester textiles before and after chromatic

**Table 1**

Weight ratios of dyed waste textile in each group for chromatic homogenization.

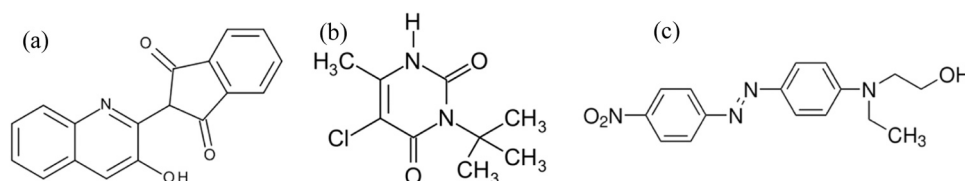
Group No.	B (g)	Y (g)	O (g)
1	1	1	1
2	1	0.5	1.5
3	1	1.5	0.5
4	0.5	1	1.5
5	0.5	1.5	1
6	1.5	1	0.5
7	1.5	0.5	1

homogenization was measured according to the ISO 13934–1:2013 (Tensile properties of fabrics, Part 1: Determination of maximum force and elongation at maximum force using the strip method). Rectangular specimens were cut in both warp and weft directions, conditioned under standard testing atmosphere (20 ± 2 °C, 65 ± 4% RH), and tested using a universal tensile testing machine (Instron). The test speed was maintained at 100 mm/min, and the maximum force (N) and elongation at break (%) were recorded. At least five replicates were performed per fabric direction, and the mean values were reported.

## 3. Results and discussions

### 3.1. Analysis of chromatic homogenization of mixed-colored waste polyester textiles in scCO<sub>2</sub>

The results showed that, after treatment in supercritical carbon dioxide at 120 °C and 25 MPa for 60 min, the mixed-color polyester textile samples lost their original individual colors and developed a new shade across the mixture resulting successful chromatic homogenization. Polyester textile that initially exhibited distinct colors underwent dye desorption, diffusion through the scCO<sub>2</sub> medium, and subsequent redistribution among the textiles. Quantitative measurements, including K/S values, confirmed that the original color intensities of individual polyester textile decreased, while the interaction and combination of dyes produced a new emergent shade (see Table 2). K/S measurements taken across the polyester textile indicated convergence in color intensity and absorbance characteristics, confirming that dye migration was extensive and that the resulting color was a product of interactions among all dyes present in the mixture following Le Chatelier's equilibrium principle and partition equilibrium between fabric–scCO<sub>2</sub>–dye phases and subtractive color mixing principles [17]. This behavior could be explained by the phenomenon of dye molecules being desorbed from polyester textile and redistributed among all polyester textile in the system, consistent with dye transfer driven by chemical potential differences in the supercritical medium. Shade transformation proceeded until thermodynamic equilibrium was achieved, at which point the chemical potential of dye molecules became uniform across all fabric substrates. During this process, the original colors were effectively lost as the dyes migrated, mixed, and interacted, leading to the formation of a new emergent shade, as illustrated in Fig. 3. The behaviors of dyes in formation of new emergent shade is in line the results published by Gong et al. (2021) [14]. Nevertheless, based on the established principle, the environment of scCO<sub>2</sub> prevented hydrolytic dye loss, ensuring that the shade transformation occurred solely through dye diffusion and redistribution [18,19]. These observations are sufficient to support that



**Fig. 1.** Generic chemical structure of (a) Terasil Goldenyellow 2803, (b) Terasil Royal Blue SC, (c) Colortex Corangar Orange PE-3330.

scCO<sub>2</sub> provides a thermodynamically controlled medium for promoting complete interaction of dyes, resulting in a new color that reflects the equilibrium distribution of dye molecules across the polyester textiles.

Visual observations corroborated the quantitative findings. Prior to scCO<sub>2</sub> treatment, the polyester textiles displayed clearly distinguishable colors corresponding to their original dyeing (Fig. 4). After treatment, these distinctions disappeared, and the polyester textiles collectively exhibited a single, novel shade. Thorough analysis of the result shows that, the reference polyester textiles (B, Y, and O) exhibited distinct initial K/S values of 2.27, 8.54, and 9.77, respectively, showing that Terasil Goldenyellow 2803 and Colortex Corangar Orange PE-3330 dyed polyester textiles carried much higher color strength than Terasil Royal Blue SC (B) dyed one. After chromatic homogenization, however, mixtures of these textiles displayed intermediate shades, confirming that dye molecules migrated between textiles until equilibrium was reached. As depicted in Fig. 5, group 1 (1:1:1) yielded relatively balanced K/S values (6.64–7.39), representing a strong leveling effect and demonstrating near-uniform shade depth across all three polyester textiles. Groups 2 (1:0.5:1.5) and 3 (1:1.5:0.5) also produced closely converged values (6.42–7.29), suggesting that moderate variations in textiles proportions did not disrupt redistribution equilibrium. The deepest shades were observed in Groups 4 (0.5:1:1.5) and 5 (0.5:1.5:1), with K/S values ranging from 7.11 to 7.86. These mixtures, dominated by Terasil Goldenyellow 2803 and Colortex Corangar Orange PE-3330 dyed polyester textiles, produced warm, intense tones due to the inherently higher color strength of these textiles. Importantly, because the Terasil Royal Blue SC (B) dyed fraction was 0.5 g in these groups, the final shades shifted toward brownish hues. This outcome is consistent with subtractive color mixing theory, where orange and blue are complementary, and when combined with yellow, they yield de-saturated brown tones rather than vivid secondary colors [14]. In contrast, Groups 6 (1.5:1:0.5) and 7 (1.5:0.5:1), with blue as the dominant component (1.5 g), displayed the lowest overall K/S values (~5.42–5.92). These mixtures produced cooler, less saturated shades due to the low original K/S of the blue polyester textile, which diluted the overall color intensity. This behavior is consistent with the theory of dye mobility in scCO<sub>2</sub>. Dye molecules desorb from substrates with high surface dye concentrations, migrate through the scCO<sub>2</sub> phase, and re-adsorb onto less saturated polyester textiles until thermodynamic equilibrium is reached [12].

Detailed data analysis revealed that the standard deviation of K/S values within each group ranged from 0.06 to 0.38, confirming shade consistency across polyester textiles. The consistency achieved here mirrors reports by Broadbent et al. (2023) [13] and Elsi et al. (2024) [20], who described scCO<sub>2</sub>'s unique superlevelling capacity, enabling shade harmonization without liquid dye baths. Gong et al. (2021) [14] similarly demonstrated that varying the ratios of disperse dyes in scCO<sub>2</sub> yields reproducible compound shades of black, dark blue and purple, further confirming the compatibility and mobility of disperse dyes under these conditions. Polymer-dye interaction also plays a decisive role. As reported by Goñi et al. (2021) [21], CO<sub>2</sub> molecules penetrate polyester's amorphous regions, increasing segmental chain mobility and facilitating dynamic desorption-adsorption cycles. This mechanism explains why all mixtures, regardless of initial composition, converged toward comparable K/S values, while still reflecting the influence of initial color strength differences. Thus, the present study confirms that scCO<sub>2</sub> dyeing not only levels color intensity across textiles but also allows predictable

**Table 2**

Average K/S values of mixed dyed polyester textile under different weight ratios for chromatic homogenization.

Group	Fabric Weight Proportions (g)			Average K/S		
	B	Y	O	B	Y	O
Ref	-	-	-	2.27	8.54	9.77
1	1.0	1.0	1.0	6.64	7.39	7.00
2	1.0	0.5	1.5	6.42	6.61	6.59
3	1.0	1.5	0.5	7.09	7.29	6.85
4	0.5	1.0	1.5	7.86	7.42	7.66
5	0.5	1.5	1.0	7.28	7.33	7.11
6	1.5	1.0	0.5	5.85	5.53	5.92
7	1.5	0.5	1.0	5.51	5.53	5.42

shade modulation by tailoring the weight proportions of dyed (waste) polyester textile.

### 3.2. Analysis of color fastness to washing, rubbing and fabric strength before and after chromatic homogenization of mixed-colored waste polyester textiles

The polyester textiles exhibited excellent color fastness to washing (see Table 3), reflecting minimal color change and negligible staining on adjacent multi-fiber fabrics both before and after chromatic homogenization. This superior performance is a direct consequence of the supercritical CO<sub>2</sub> dyeing mechanism involving several interrelated factors. Dye molecules in supercritical CO<sub>2</sub> diffuse efficiently into the amorphous regions of polyester fibers, resulting in deep and uniform internal fixation rather than superficial adsorption. The hydrophobic nature of both the polymer and disperse dyes promotes thermodynamically favorable interactions, enhancing dye retention and minimizing desorption during washing. Being a waterless process, scCO<sub>2</sub> dyeing eliminates hydrolytic degradation and uncontrolled dye migration, which are common in aqueous dyeing systems. In mixed-colored fabric systems, chromatic homogenization occurs as dye molecules redistribute until thermodynamic equilibrium is reached, ensuring uniform color distribution and stabilized dye-fiber bonding while reducing localized over- or under-dyed regions that could otherwise leach dye. Collectively, these factors explain the minimal color change and negligible staining observed on adjacent multi-fiber fabrics, confirming the output of color-stable polyester textiles, while enabling predictable chromatic homogenization in mixed-colored fabric recycling and repurposing applications.

Similarly, the polyester textiles demonstrated very good color fastness to dry and wet rubbing (see Tables 4–5), indicating limited color transfer under both dry and wet friction conditions. This high rubbing fastness can be attributed to the strong dye-fiber interactions achieved in scCO<sub>2</sub>, where dyes are not merely adsorbed on the fiber surface but diffused and fixed within the polymer matrix. The absence of water prevents dye bleeding during friction, while the uniform redistribution of dye in mixed polyester textiles further stabilizes color on the fiber surface.

It appears that the chromatic homogenization process in scCO<sub>2</sub> does not adversely affect the fastness properties of the dyes, as the strong dye-fiber interactions and uniform internal dye fixation remain intact even during redistribution among mixed polyester textiles. Consequently, shade harmonization through controlled dye transfer can be achieved without compromising wash or rubbing fastness, representing a

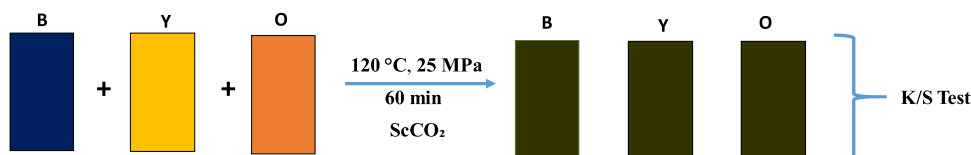


Fig. 2. Concept of chromatic homogenization in dyed (waste) polyester textile.

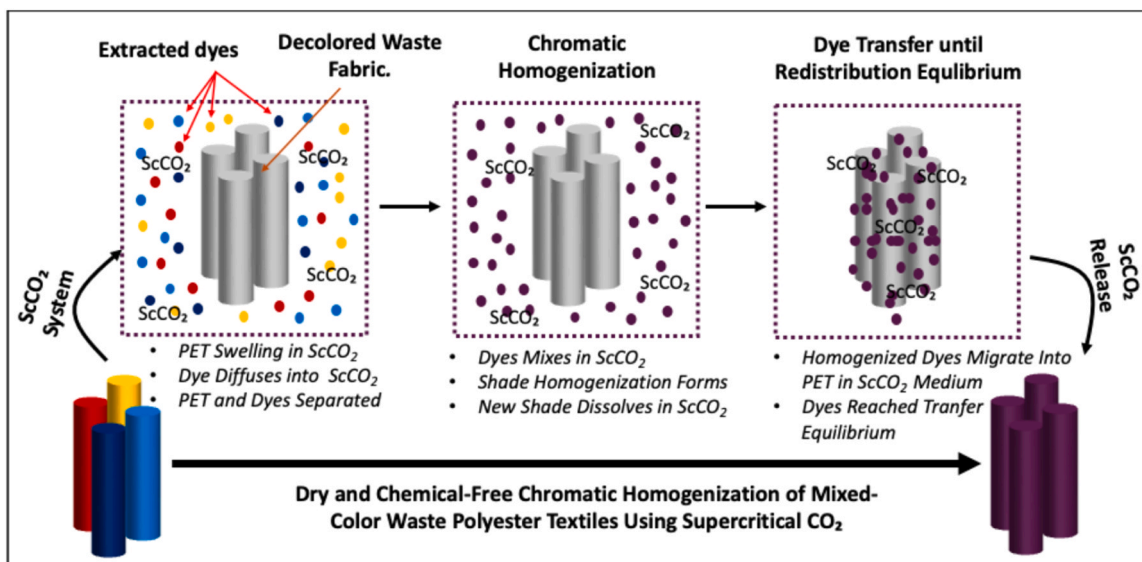


Fig. 3. Schematic Illustration of chromatic homogenization of mixed-colored waste polyester textiles using supercritical CO<sub>2</sub>.

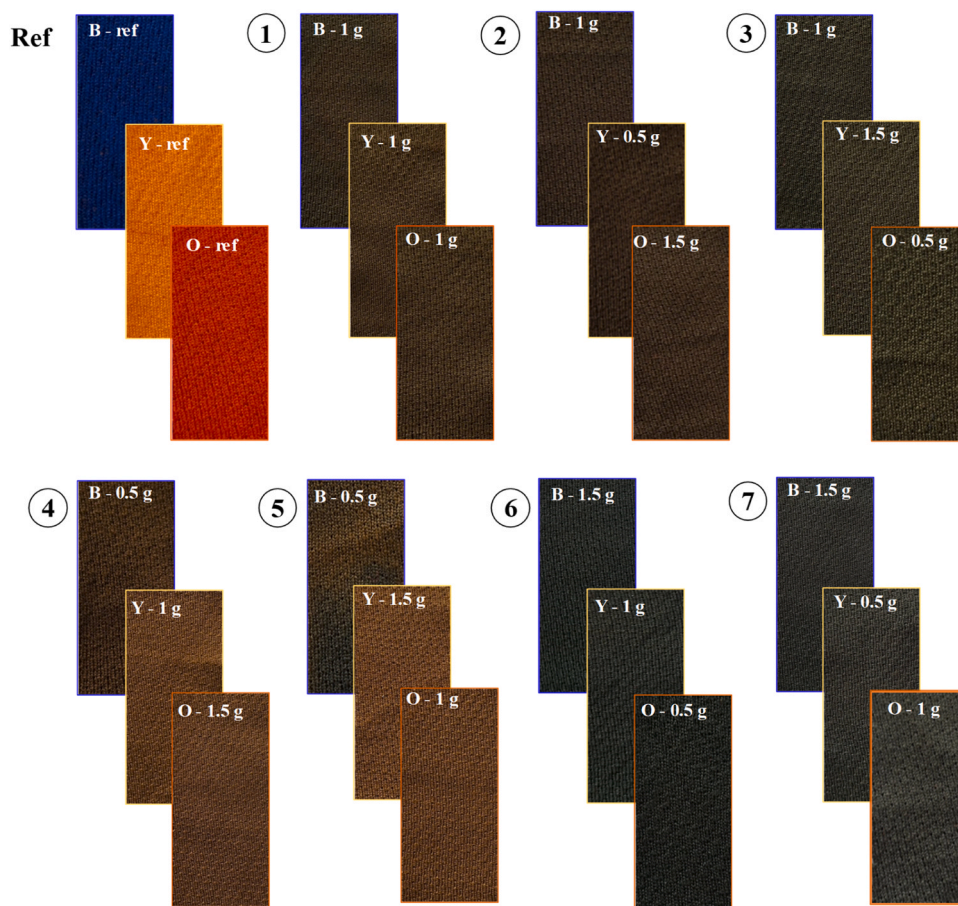


Fig. 4. Photographs of polyester textiles showing color uniformity under varying weight proportions.

significant step toward establishing scCO<sub>2</sub> dyeing as a potential alternative to conventional re-dyeing and de-dyeing processes for the repurposing and recycling of polyester textiles. This approach not only ensures predictable and uniform color outcomes but also contributes to sustainable and efficient textile management in circular economy applications.

The result of tensile strength of the polyester textiles before and after chromatic homogenization in scCO<sub>2</sub> is presented in Table 6. The tensile strength of the polyester textiles was fully retained following scCO<sub>2</sub> chromatic homogenization, with warp strength values before treatment ranging from 238 N to 245 N and remaining essentially unchanged after treatment (240 N – 245 N). Examination of all seven sample groups and

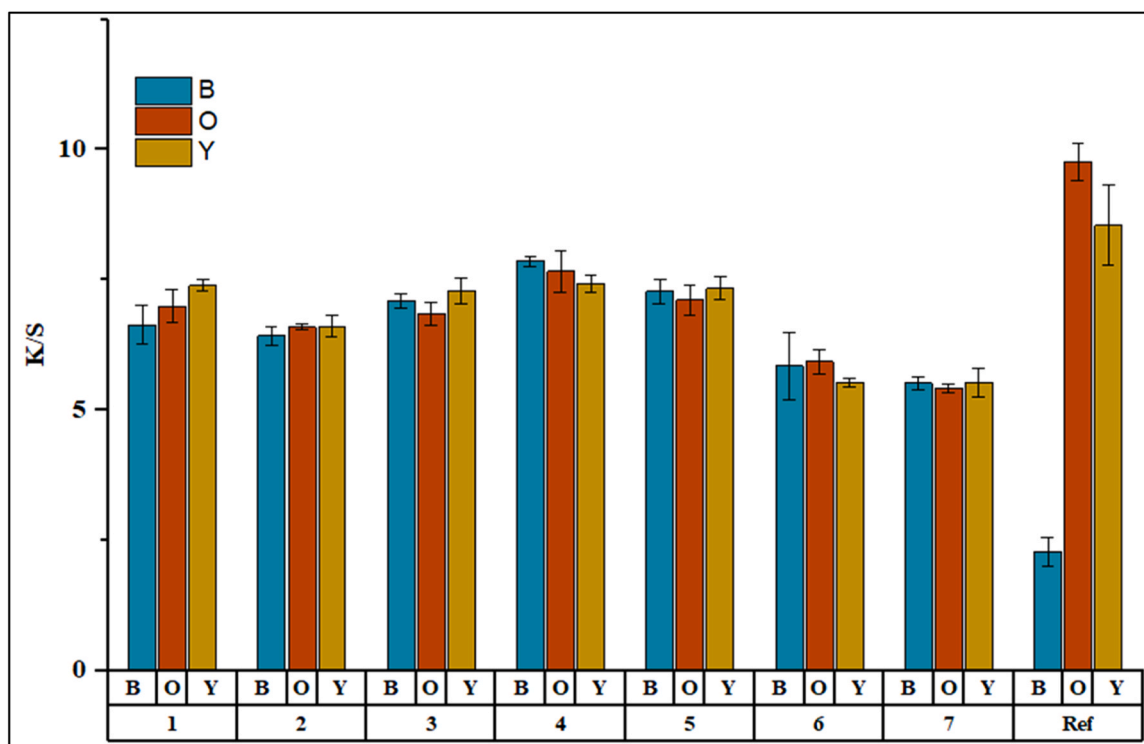


Fig. 5. K/S value comparison for each color across different mixture groups.

Table 3

Average color fastness to washing of polyester textile before and after chromatic homogenization in scCO<sub>2</sub>.

Group	Average color fastness to washing of polyester textile before chromatic homogenization			Average color fastness to washing of polyester textile after chromatic homogenization		
	B	Y	O	B	Y	O
1	5	5	5	5	5	5
2	5	5	5	5	5	5
3	5	5	5	5	5	5
4	5	5	5	5	5	5
5	5	5	5	5	5	5
6	4/5	5	5	4/5	5	5
7	4/5	5	5	4/5	5	5

Table 4

Average color fastness to dry rubbing of polyester textile before and after chromatic homogenization in scCO<sub>2</sub>.

Group	Average color fastness to rubbing (dry) of polyester textile before chromatic homogenization			Average color fastness to rubbing (dry) of polyester textile after chromatic homogenization		
	B	Y	O	B	Y	O
1	4/5	4/5	4/5	4/5	4/5	4/5
2	4/5	4/5	4/5	4/5	4/5	4/5
3	4/5	4/5	4/5	4/5	4/5	4/5
4	4/5	4/5	4/5	4/5	4/5	4/5
5	4/5	4/5	4/5	4/5	4/5	4/5
6	4/5	4/5	4/5	4/5	4/5	4/5
7	4	4/5	4/5	4	4/5	4/5

three fabric colors (blue, yellow, and orange) shows that the maximum variation between pre- and post-treatment values was within 2 N – 3 N, indicating negligible change and 100% preservation of mechanical performance. Notably, in several instances, the post-treatment strength was slightly higher than the initial value, likely reflecting normal

Table 5

Average color fastness to wet rubbing of polyester textile before and after chromatic homogenization in scCO<sub>2</sub>.

Group	Average color fastness to rubbing (wet) of polyester textile before chromatic homogenization			Average color fastness to rubbing (wet) of polyester textile after chromatic homogenization		
	B	Y	O	B	Y	O
1	4/5	4/5	4/5	4/5	4/5	4/5
2	4/5	4/5	4/5	4/5	4/5	4/5
3	4/5	4/5	4/5	4/5	4/5	4/5
4	4/5	4/5	4/5	4/5	4/5	4/5
5	4/5	4/5	4/5	4/5	4/5	4/5
6	4/5	4/5	4/5	4/5	4/5	4/5
7	4	4/5	4/5	4	4/5	4/5

Table 6

Average tensile strength of polyester textile before and after chromatic homogenization in scCO<sub>2</sub>.

Group	Average tensile strength (N) of polyester textile before chromatic homogenization			Average tensile strength (N) of polyester textile after chromatic homogenization		
	B	Y	O	B	Y	O
1	243 ± 5	245 ± 8	244 ± 9	242 ± 7	245 ± 5	243 ± 4
2	242 ± 5	245 ± 6	242 ± 3	243 ± 3	244 ± 5	241 ± 5
3	240 ± 3	242 ± 8	244 ± 7	240 ± 5	240 ± 4	242 ± 8
4	243 ± 5	245 ± 4	244 ± 2	244 ± 4	245 ± 8	245 ± 7
5	239 ± 9	241 ± 5	240 ± 4	240 ± 5	240 ± 8	242 ± 4
6	245 ± 3	243 ± 2	240 ± 5	242 ± 4	241 ± 5	240 ± 2
7	238 ± 7	245 ± 5	241 ± 4	240 ± 4	241 ± 5	242 ± 5

experimental variation rather than any material reinforcement. These observations demonstrate that the scCO<sub>2</sub> dyeing and shade transformation process does not induce fiber degradation, chain scission, or weakening of the polyester polymer matrix. Preservation of tensile strength alongside effective dye migration highlights the unique

advantage of supercritical CO<sub>2</sub> as a medium: it enables complete chromatic transformation and dynamic dye redistribution without exposing fibers to water, high shear, or chemical stress that can occur in conventional aqueous dyeing methods. Overall, the data confirm that this approach allows the formation of new shades through dye desorption, diffusion, and equilibrium-driven redistribution while maintaining the structural and mechanical integrity of polyester fabrics, making it highly suitable for textile recycling, upcycling, and high-performance applications where both color transformation and material strength are essential.

#### 4. Conclusion

This study demonstrates that scCO<sub>2</sub> processing is an effective, dry method for achieving chromatic homogenization and color transformation of mixed-colored polyester textiles. Treatment at 120 °C and 25 MPa for 60 min facilitated complete dye desorption, diffusion, and redistribution, resulting in the loss of original individual colors and the formation of new emergent shades across all mixtures. Quantitative K/S measurements confirmed extensive dye migration, with convergence of color intensity values across fabrics, and demonstrated that final shades could be modulated by varying the initial weight proportions of each dyed textile. Observed color shifts were consistent with subtractive color mixing principles, with yellow- and orange-dominated mixtures producing warmer, more saturated tones, and blue-dominated mixtures producing cooler, less intense shades. The shade transformation process is thermodynamically controlled, proceeding until chemical potential equilibrium is reached between the dye molecules, polyester substrates, and the scCO<sub>2</sub> medium. The anhydrous supercritical environment prevents hydrolytic dye loss, ensuring that color redistribution occurs exclusively through diffusion and adsorption-desorption cycles within the polymer matrix. Visual and instrumental evaluations confirmed excellent color fastness to washing, as well as dry and wet rubbing, indicating stable dye-fiber interactions even after redistribution. Importantly, tensile strength measurements demonstrated full retention of mechanical integrity, with warp strength values remaining essentially unchanged across all sample groups. This confirms that the scCO<sub>2</sub> process does not induce fiber degradation or polymer weakening. Collectively, these findings establish scCO<sub>2</sub> as a sustainable, efficient, and versatile approach for recoloring, harmonizing, and recycling polyester textiles, enabling predictable shade formation, minimal resource consumption, and high-quality, structurally intact fabrics suitable for circular economy applications.

#### Author's contribution

Mohammad Neaz Morshed, Annah Tayebwa and Hui Deng carried out all the experimental works. All authors were involved in conceptualization, data analysis, writing and revising of the manuscript.

#### CRedit authorship contribution statement

**Vincent Nierstrasz:** Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Michael Rauch:** Writing – original draft, Formal analysis, Data curation. **Molla Tadesse Abate:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Veronica Malm:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation, Conceptualization. **Hui Deng:** Investigation, Conceptualization. **Annah Tayebwa:** Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Mohammad Neaz Morshed:** Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

#### Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used artificial intelligence in order to language improvement of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

#### Declaration of Competing Interest

The authors have declared no conflict of interest.

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#### Data Availability

Data will be made available on request.

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