QUANTITATIVE ASSESSMENT OF DYE LEACHING AND STAINING MECHANISMS IN DYED TEXTILES EXPOSED TO SIMULATED PERSPIRATION

ĐÁNH GIÁ ĐỊNH LƯỢNG CƠ CHẾ PHAI MÀU VÀ DÂY MÀU CỦA VẢI NHUỘM KHI TIẾP XÚC VỚI MỒ HÔI NHÂN TẠO

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Abstract - This study quantitatively examines dye leaching and staining behavior in 100% cotton, 100% polyester, and PE/CO blended fabrics under simulated human perspiration. Based on ISO 105-E04, AATCC 15, and JIS 0848 standards, color changes (ΔE) and leaching dynamics were evaluated using the CIELAB system and UV–Vis spectrophotometry. Results show that dye leaching is strongly affected by interactions between sweat components (NaCl, L-histidine, and lactic acid) and fiber–dye bonds. Among the tested fabrics, cotton exhibited the highest sensitivity, with the greatest color change after exposure. A dye concentration of 2% owf and a contact temperature of 45 °C were found to minimize color variation, indicating improved stability of fiber–dye interactions. These findings provide a basis for predicting colorfastness and optimizing textile finishing processes to improve color stability in performance garments.

Key words - Dye leaching; CIELAB system; color instability; perspiration fastness; quantitative assessment; dye migration; textile materials

Tóm tắt – Nghiên cứu này định lượng hiện tượng phai màu và dây màu thuốc nhuộm trên vải 100% cotton, 100% polyester và vải pha PE/CO trong mồ hôi nhân tạo. Dựa theo tiêu chuẩn ISO 105-E04, AATCC 15 và JIS 0848, sự thay đổi màu sắc (ΔE) và động học phai màu được đánh giá qua hệ CIELAB và phổ UV–Vis. Kết quả cho thấy sự phai màu chịu ảnh hưởng mạnh từ tương tác giữa các thành phần mồ hôi (NaCl, L-histidine, axit lactic) và liên kết xơ sợi - thuốc nhuộm. Vải cotton nhạy cảm nhất, với ΔE lớn nhất. Nồng độ thuốc nhuộm 2% owf và nhiệt độ 45 °C giúp giảm thiểu sự thay đổi màu, chứng minh liên kết bền vững hơn. Phát hiện này giúp dự đoán độ bền màu và tối ưu hóa quy trình hoàn tất dệt may, nâng cao độ ổn định màu cho trang phục.

Từ khóa – Sự phai màu; hệ màu CIELAB; độ không ổn định màu; độ bền màu với mồ hôi; đánh giá định lượng; sự di chuyển thuốc nhuộm; vật liệu dệt

1. Introduction

The global textile and apparel industry has consistently prioritized durability and functional longevity as essential indicators of product quality. Among various performance criteria, color fastness, particularly resistance to perspiration, remains a critical challenge for manufacturers and researchers [1-3]. In tropical climates and during intense physical activity, the human body secretes substantial amounts of sweat, which acts as a chemically active medium. Prolonged contact between dyed textiles and perspiration can result in dye migration or "dye leaching," leading to staining and aesthetic degradation [4, 5].

The complexity of dye leaching under perspiration conditions arises from the multi-component composition of sweat, which contains electrolytes (e.g., sodium chloride), organic acids (e.g., lactic acid), and amino acids such as L-histidine [6, 7]. These constituents can interact with dye–fiber bonds through multiple physicochemical mechanisms. Electrolytes influence dye aggregation and substantivity in aqueous systems, while acidic environments may promote hydrolysis or weaken hydrogen bonding in reactive and direct dye systems [8, 9]. Cotton, being hydrophilic and cellulose-based, exhibits different dye–fiber interactions compared with hydrophobic polyester fibers, which rely primarily on disperse dye diffusion and physical entrapment mechanisms [10, 11]. Related studies have shown that processing conditions significantly affect color characteristics in textiles, especially in silk fibers [12].

Although standardized test methods such as ISO 105-E04, AATCC TM15, and JIS L 0848 are widely adopted in industry, evaluation often relies on grayscale visual ratings for color change and staining [3, 13]. While practical, this qualitative approach limits mechanistic understanding and may lack sufficient precision for advanced material optimization. Recent advances advocate the use of instrumental colorimetry, particularly the CIELAB system, to quantify color difference (ΔE) and provide objective evaluation of textile performance [14, 15].

In response to these limitations, this study applies CIELAB colorimetric analysis combined with UV-Vis spectrophotometry to systematically investigate dye release behavior in 100% cotton, 100% polyester, and PE/CO blended fabrics under simulated perspiration conditions. Beyond pass/fail grading, the work evaluates the effects of dye concentration, immersion time, temperature, and pH on dye-fiber stability. By identifying critical thresholds such as saturation dye loading and temperature-dependent stability regions, this research establishes an empirical framework for predicting dye migration behavior. The findings contribute to optimizing dye–fiber selection and finishing strategies aimed at

minimizing color bleeding and enhancing the functional lifespan of textile products.

2. Materials and Methods

2.1. Materials and Sample Preparation

In this study, three textile substrates (100% cotton, 100% polyester, and PE/CO blend) were used. Prior to dyeing, all fabrics were subjected to a standard pre-treatment process to remove impurities, including desizing, scouring, and rinsing. Specifically, cotton and blended fabrics were scoured in an alkaline solution containing NaOH (2 g/L) and a non-ionic detergent at 80°C for 30 minutes, followed by thorough rinsing and air drying. Polyester fabrics were washed with a mild detergent at 60°C to remove surface contaminants. Dyeing was carried out using direct dyes (Lurazol, BASF) for cotton-based fabrics and disperse dyes (Dianix®, DyStar) for polyester. The dye concentrations were set at 1%, 2%, and 4% owf. The dyeing process was performed at a liquor ratio of 1:20. For cotton, dyeing was conducted at 90°C for 60 minutes, while polyester samples were dyed at 130°C for 45 minutes under high-temperature conditions. After dyeing, all samples were rinsed thoroughly and subjected to a post-treatment process, including soaping at 60°C for 15 minutes to remove unfixed dyes, followed by rinsing and air drying at room temperature. Prior to testing, all samples were conditioned in a standard atmospheric environment (20 ± 2°C and 65 ± 2% relative humidity) for 24 hours using a controlled climate chamber to ensure moisture equilibrium.

2.2. Preparation of simulated perspiration

To ensure reproducibility, simulated perspiration solutions were prepared following international standards primarily based on ISO 105-E04 with additional reference AATCC TM15 (acidic condition: pH 4.3 ± 0.2). The acidic solution (pH 5.5, pH 5.5 ± 0.2, according to ISO 105-E04) was formulated using L-histidine monohydrochloride monohydrate (0.5 g/L), sodium chloride (5 g/L), and sodium dihydrogen orthophosphate dihydrate (2.2 g/L), with pH adjusted using dilute acetic acid (CH_3COOH). The alkaline variant (pH 8.0) was also utilized to compare the pH-dependent leaching mechanisms, with pH adjusted using sodium hydroxide (NaOH). Lactic acid was incorporated as a representative organic acid component of human perspiration to evaluate its influence on dye-fiber interactions, and its concentration was varied between 1 g/L and 5 g/L to observe its specific role in promoting dye desorption and potential hydrolytic weakening of fiber-dye bonds.

2.3. Experimental design and controlled variables

A multi-factorial experimental design was implemented to analyze the staining mechanisms. The primary independent variables included: Temperature (controlled using a thermostatic water bath at 25°C, 35°C, 45°C, 55°C, and 65°C), selected to cover both standard testing conditions (around 37°C) and extended conditions to evaluate temperature-dependent behavior beyond physiological limits, immersion duration (ranging from 0.5 to 24 hours to track the kinetics of dye release, including standard durations of 4-6 h as well as prolonged exposure for kinetic analysis), mechanical agitation applied using a laboratory shaker at a constant speed of 100 rpm (samples were subjected to controlled stirring to simulate the friction between skin and fabric). All experiments were conducted in sealed containers with a liquor ratio of 1:20 to ensure consistent contact conditions between fabric and solution. To ensure clarity and consistency throughout this work, the abbreviations and sample codes used are summarized in Table 1.

Table 1. *Abbreviations and sample codes used in this study*

Code	Description
PE100	100% polyester fabric
CO100	100% cotton fabric
PE/CO	Polyester/cotton blended fabric
ST25, ST35, ST45, ST55, ST65	Samples tested at different temperatures (25°C, 35°C, 45°C, 55°C, 65°C)
SP30, SP120, SP360, SP720, SP1440	Samples tested at different contact times (30, 120, 360, 720, 1440 minutes)
SDC1.0, SDC2.0, SDC3.0, SDC4.0	Samples tested at dye concentrations of 1%, 2%, 3%, and 4% owf

All experiments were conducted in triplicate. The results are expressed as mean ± standard deviation. Statistical analysis was performed to ensure data reliability.

2.4. Quantitative analytical techniques

The degree of dye leaching and subsequent staining was quantified using two primary methods: 1) Spectrophotometric measurement: A Konica Minolta CM-3600A spectrophotometer was employed to measure the reflectance values of the samples before and after exposure. Color coordinates (L^*, a^*, b^*) were recorded under D65 illuminant and 10° standard observer. 2) Color difference calculation: The total color difference (ΔE) was calculated using the CIELAB 1976 formula.

$$\Delta E = \sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2} \quad (1)$$

where ΔE, Δa, and Δb represent the differences in lightness, redness-greenness, and yellowness-blueness, respectively. Higher ΔE values correlate with a greater magnitude of dye leaching and staining.

In addition, chroma (C^*) was calculated to represent color saturation, defined as

$$C^* = \sqrt{a^{*2} + b^{*2}} \quad (2)$$

while the hue angle (h°) describes the color tone and is given by arctan (a^*/b^*). The total color difference (ΔE) was used to quantify the magnitude of color change after treatment, where higher ΔE values indicate greater perceptible differences.

A spectrophotometer was used to scan the artificial perspiration solutions in the ultraviolet range (190-400 nm) to characterize their baseline absorption behavior. UV-Vis spectra were recorded under different pH conditions.

2.5. Staining assessment on multi-fiber adjacent fabrics

To assess the staining mechanism on secondary surfaces, dyed samples were placed in contact with multi-fiber adjacent fabrics (containing wool, acrylic, polyester,

nylon, cotton, and acetate) under a pressure of 12.5 kPa. The pressure was applied using a standard perspirometer in accordance with ISO 105-E04, which ensures uniform and controlled loading during testing. The fabric specimens (test and adjacent fabrics) were assembled in a sandwich structure and subjected to the specified pressure for a fixed duration (4 h) at controlled temperature conditions (37 ± 2°C), following standard testing procedures. The migration of leached dye molecules onto these specific fibers was then quantitatively evaluated based on color change (ΔE) and staining assessment using instrumental colorimetry, to identify which fiber types are most susceptible to cross-contamination. The staining behavior on adjacent fabrics is evaluated, and the results are presented in Section 3.

3. Results and discussion

3.1. UV-Vis spectral characteristics of artificial sweat solutions at different pH

To characterize the baseline absorption behavior of the artificial perspiration solutions, UV-Vis spectra were recorded at different pH conditions. The results are shown in Figure 1

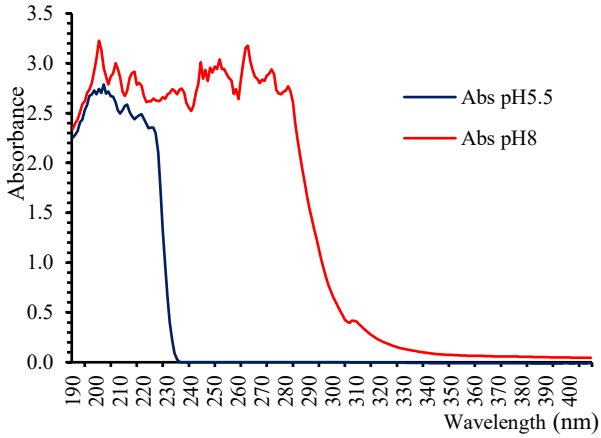


Figure 1. *UV-Vis absorption spectra of artificial sweat solutions at pH 5.5 and pH 8 according to ISO 105-E04*

The UV-Vis spectra reveal a clear difference between artificial sweat solutions with acidic properties (pH 5.5) and alkaline properties (pH 8) according to ISO 105-E04, presented as baseline references to characterize the intrinsic absorption of the testing media. It should be noted that the spectra exhibit minor noise in the deep UV region due to the low absorbance of the solution and instrumental limitations; however, this does not affect their role as reference data. At pH 5.5, the absorption spectrum is strictly concentrated in the deep UV region (approximately 190–225 nm, with high intensity that decreases rapidly beyond 230 nm, suggesting that the primary absorbing components are simple functional groups like organic acids and inorganic salts. In contrast, at pH 8, the spectrum extends to around 280-300 nm and exhibits a more pronounced shoulder region, indicating potential changes in the ionization state of the solution components. These baseline characteristics provide a reference for interpreting subsequent UV-Vis measurements of dye-containing solutions after fabric exposure, which are directly related to dye leaching behavior.

3.2. Effect of fiber composition

The colorimetric parameters of dyed fabrics with different fiber compositions after exposure to artificial perspiration are summarized in Table 2.

Table 2. *Colorimetric parameters (L^*, a^*, b^*, C^*, h°, ΔE) of dyed fabrics with different fiber compositions after contact with artificial perspiration (see Table 1 for sample codes)*

Sample	L^*	a^*	b^*	C^*	h°	ΔE ± SD
PE100	40.65	-0.12	-6.57	6.57	268.86	**0.48**±0.03
PE/CO	43.22	0.72	-8.57	8.60	274.50	**1.13**±0.06
CO100	44.34	0.76	-9.46	9.48	274.20	**2.26**±0.12

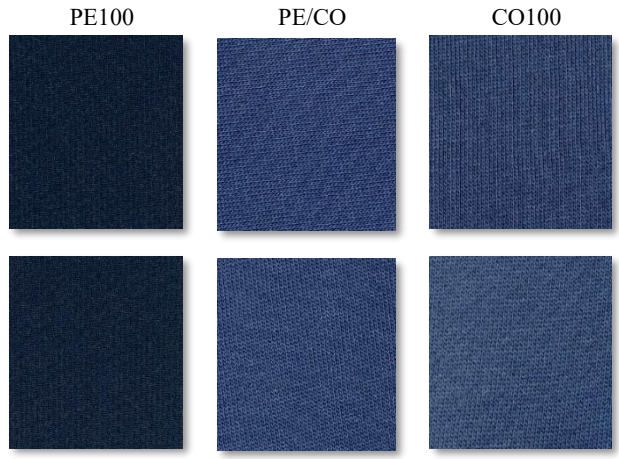


Figure 2. *Visual appearance of dyed fabrics (PE100, PE/CO, and CO100) before (top row) and after (bottom row) exposure to artificial perspiration*

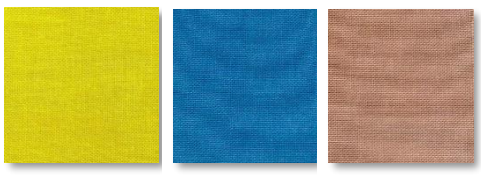
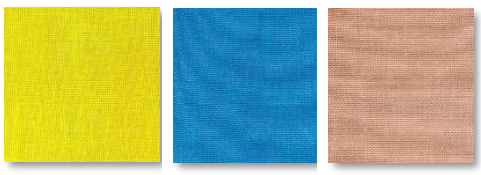
The colorimetric parameters of dyed fabrics before and after exposure to artificial perspiration are summarized in Table 2. For each fabric type, noticeable changes were observed after treatment. The L^* values slightly increased, indicating a general lightening effect, while variations in a^* and b^* suggest minor chromatic shifts. In particular, the decrease in b^* values reflects a tendency toward a stronger blue tone. Changes in chroma (C^*) indicate slight variations in color saturation, whereas the hue angle (h°) remains within the blue region, suggesting no significant hue shift. Notably, the total ΔE increases with cotton content: 0.48 (PE100), 1.13 (PE/CO), and 2.26 (CO100). The lowest ΔE for PE100 indicates superior color stability, likely due to the hydrophobic nature of polyester, which limits interaction with perspiration components. In contrast, the higher ΔE of CO100 suggests stronger fiber-solution interactions associated with the hydrophilic structure of cellulose, promoting dye migration or partial desorption. Overall, increasing cotton content reduces color stability under artificial perspiration. Leaching and staining are interrelated, as dye released from the fabric (leaching) may subsequently transfer to adjacent materials (staining). In this study, the analysis focuses on leaching, while staining is only briefly discussed as a complementary aspect.

3.3. Effect of dyes on color fastness

A comparison of color change for different dyed fabrics after perspiration exposure is presented in Table 3. The data specifically illustrates a visual comparison of yellow,

blue, and brown fabrics dyed with synthetic colorants before and after exposure to artificial perspiration following AATCC TM15. Among the three shades, brown exhibits the highest total color difference (ΔE = 10.94), indicating significant color alteration and relatively poor perspiration fastness. Blue shows a moderate color change (ΔE = 5.42), while yellow demonstrates the lowest ΔE (1.65), suggesting comparatively better color stability under acidic perspiration conditions. The larger color change observed in darker shades (especially brown) may be attributed to higher dye loading or differences in dye–fiber interaction mechanisms, which can influence dye migration or partial desorption during testing. The increase in L^* values indicates a general lightening effect after treatment. Meanwhile, the reduction in a^* and b^* values, particularly in brown fabric, suggests a loss of redness and yellowness, contributing to the overall color difference. These changes confirm that color variation arises from both lightness increase and chromatic shifts.

Table 3. *Visual and colorimetric comparison of synthetic-dyed fabrics (Yellow, Blue, Brown) before and after artificial perspiration exposure according to AATCC TM15*

	Yellow	Blue	Brown
Untreated			
L^*	80.34	66.22	76.70
a^*	-4.65	-28.11	16.62
b^*	74.09	-16.67	17.71
Treated			
L^*	81.56	70.89	81.08
a^*	-5.27	-26.82	10.29
b^*	73.16	-19.16	10.94
ΔE	**1.65**±0.12	**5.42**±0.14	**10.94**±0.24

The effect of dye concentration on color difference is shown in Figure 3, which further examines the influence of yellow dye concentration (1-4% owf) on perspiration-induced color change. The ΔE value is highest at 1% owf (5.96), decreases markedly at 2% owf (2.49), then increases again at 3% owf (3.26) and 4% owf (4.28). This non-linear trend suggests that moderate dye concentration (2% owf) provides optimal dye fixation and color stability. At low concentration (1% owf), insufficient dye–fiber interaction may result in higher susceptibility to color change. Conversely, at higher concentrations (3-4% owf), dye aggregation or incomplete fixation may occur, leading to increased dye migration under perspiration conditions.

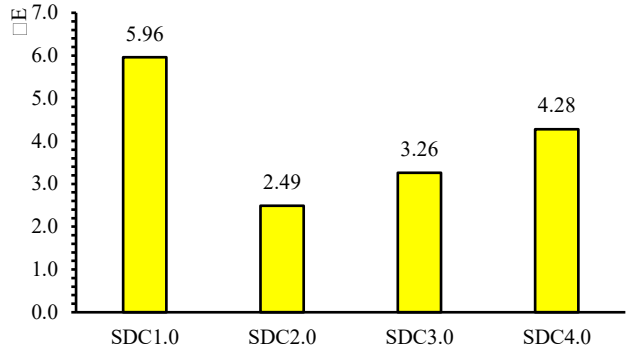


Figure 3. *Effect of yellow dye concentration (1-4% owf) on color difference (ΔE) after artificial perspiration testing (AATCC TM15) (see Table 1 for sample codes)*

3.4. Effect of temperature

The effect of contact temperature on color difference and lightness is illustrated in Figure 4. The results show the variation in total color difference (ΔE) of PE/CO fabric after contact with artificial perspiration at different temperatures (25-65°C), compared with the original (untreated) sample. The ΔE decreases from 1.35 at 25°C (ST25) to 1.22 at 35°C (ST35), reaching the lowest value of 0.52 at 45°C (ST45). This indicates the presence of an intermediate temperature at which color change is minimized, suggesting an optimal balance between dye-fiber fixation and dye mobility. Such non-linear behavior has been reported in previous studies [16], where increasing temperature can initially enhance dye-fiber interactions and stability, but further temperature increase promotes dye diffusion and desorption. However, when the temperature increases further, ΔE rises to 0.68 at 55°C (ST55) and sharply to 1.51 at 65°C (ST65), the highest value among all samples. This trend suggests that elevated temperature accelerates dye–fiber interaction with perspiration components, possibly promoting dye migration or partial desorption. Therefore, high temperature significantly reduces the color stability of the blue-dyed PE/CO fabric. Overall, the results confirm that temperature affects color stability in a non-linear manner, with moderate temperature (45°C) providing the most stable condition, whereas excessive thermal exposure negatively affects perspiration fastness.

Figure 4b illustrates the evolution of lightness (L) as a function of contact temperature. A non-linear behavior is observed: the L value decreases markedly from 45.35 (25°C) to a minimum of 41.81 (35°C), indicating a significant darkening of the fabric. This phenomenon can be attributed to the initial swelling of fibers and enhanced dye migration toward the fiber surface at near-physiological temperatures, which increases light absorption. As the temperature rises to 45°C and 55°C increases to 43.25 and 44.42, respectively, suggesting a partial stripping of the dye into the perspiration solution. However, at 65°C, a slight decrease to 43.01 is noted, likely due to complex dye-fiber re-equilibrium or thermal degradation of the dye molecules.

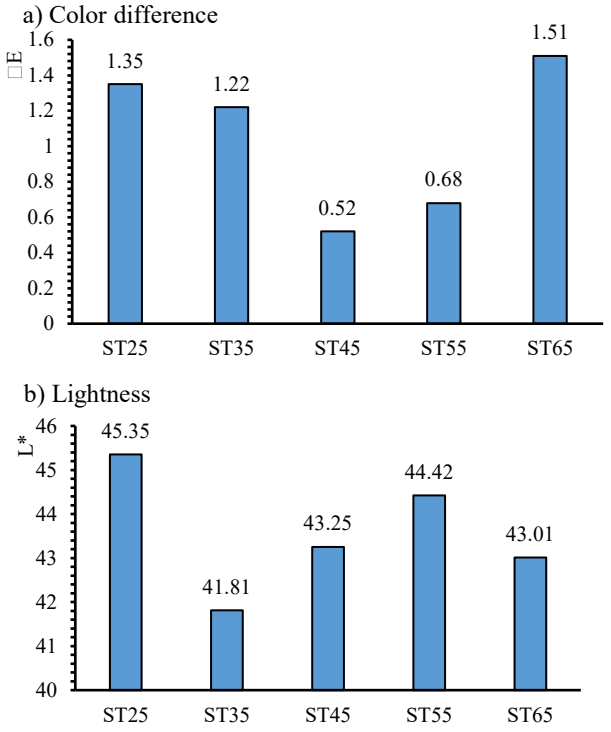


Figure 4. *Effect of contact temperature (25-65°C) on (a) Color difference (ΔE) and (b) lightness (L*) of blue-dyed PE/CO fabric after artificial perspiration exposure (ΔE compared with the untreated reference sample) (see Table 1 for sample codes)*

The lack of a strictly linear trend implies that temperature exerts a dual influence on both dye diffusion kinetics and fiber - solution equilibrium. Correlating these findings with Figure 4a, the minimum ΔE observed at 45ºC coincides with a moderate L value, identifying this as the stability threshold for blue-dyed PE/CO fabric. Conversely, the high ΔE and fluctuating L at 65ºC confirm that elevated thermal energy destabilizes the dye-fiber system, accelerating color fading. In conclusion, a moderate contact temperature of approximately 45ºC represents the optimal stability point, whereas temperatures exceeding 55ºC significantly compromise color fastness.

3.5. Effect of contacting times

Table 4. *Influence of contact time (30, 120, 360, 720, 1440 minutes) on the colorimetric properties (L*, a*, b*, C*, h° and ΔE) of PE/CO fabrics after exposure to artificial perspiration (see Table 1 for sample codes)*

Sample	L*	a*	b*	C*	h°	ΔE±SD
SP30	42.68	-6.53	-5.50	8.61	219.9	**1.93**±0.19
SP120	42.63	-6.68	-5.44	8.61	219.00	**1.89**±0.21
SP360	42.30	-6.19	-5.15	8.10	219.68	**2.04**±0.18
SP720	41.33	-5.90	-5.35	7.95	222.16	**2.98**±0.31
SP1440	42.15	-6.50	-5.63	8.60	220.84	**2.27**±0.23

In contrast to the trend-focused analysis in Section 3.3, all colorimetric parameters across various contact times are detailed in Table 4. This tabular format captures subtle color variations more precisely than graphical plots, including the untreated fabric's coordinates as baseline values for comparison. The lightness (L^*) values show only minor fluctuations, decreasing slightly from 42.68 (30 min) to 41.33 (720 min) before recovering to 42.15 at 1440 min. This indicates that prolonged exposure does not cause substantial lightness variation.

The a^* and b^* coordinates remain consistently negative throughout the test, confirming that the fabric maintains a bluish-green tone. The a^* values vary slightly between -6.68 and -5.90, while b^* values range from -5.63 to -5.15, suggesting limited chromatic shift over time. Chroma (C^*) also exhibits small changes (7.95-8.61), indicating relatively stable color saturation. The hue angle (h°) varies within a narrow range (219.0-222.16°), confirming that the overall hue remains essentially unchanged during exposure. In contrast, the total ΔE shows a more noticeable time-dependent trend. ΔE increases from 1.93 (30 min) to 2.04 (360 min) and reaches a maximum of 2.98 at 720 min, indicating that extended contact enhances color alteration. Interestingly, ΔE decreases to 2.27 after 1440 min, suggesting partial stabilization or equilibrium between dye, fiber, and perspiration components. On the other hand, while the fundamental hue and saturation remain relatively stable, prolonged exposure to artificial perspiration increases perceptible color change, particularly after 720 minutes. This behavior reflects gradual dye migration or interaction with perspiration constituents over time.

3.6. Effect of testing standards on fastness evaluation

A comparison of major testing standards for color fastness to perspiration is provided in Table 5, highlighting both similarities and differences in solution composition and testing conditions. ISO 105-E04 and JIS L 0848 employ nearly identical testing conditions (including similar compositions of artificial perspiration containing histidine, sodium chloride, and phosphate buffer, pH 5.5 ± 0.2 for acid, 8.0 ± 0.2 for alkaline, 37 ± 2°C, 4 h), which is reflected in their very similar colorimetric results. The a^* values are identical (-6.53), while b^* and L^* values differ only slightly (L^* = 42.68 for ISO and 42.99 for JIS), indicating negligible variation in hue and lightness. Correspondingly, the total color difference (ΔE) remains close (2.11 for ISO and 2.00 for JIS), confirming that both standards provide comparable evaluation outcomes for the dyed PE/CO fabric.

Although AATCC TM15 applies a more acidic condition (pH 4.3 ± 0.2) and a longer duration (6 h), and involves slight differences in solution formulation and exposure severity, the resulting color coordinates (a^* = -6.81, b^* = -5.40, L^* = 42.94) remain within a narrow range compared with ISO and JIS. Interestingly, the ΔE value under AATCC (1.71) is slightly lower, which may be attributed to differences in pH-dependent dye–fiber interactions and possible stabilization effects under the specific test conditions, rather than a simple increase in dye desorption.

Overall, the observed differences in color change (ΔE) can be explained by variations in pH, exposure duration, and solution composition among the standards; however, these factors do not lead to significant differences in the overall staining mechanism. The results demonstrate consistent perspiration fastness performance across the three major standards, with only minor variations attributable to differences in testing conditions.

Table 5. *Comparison of major standards for color fastness to artificial perspiration of dyed PE/CO fabric*

Item	ISO 105-E04	JIS L 0848	AATCC TM15
Full name	Textiles - Tests for color fastness - Part E04: Color fastness to perspiration	Test method for color fastness to perspiration	Colorfastness to Perspiration
Organization	ISO (International Organization for Standardization)	JIS (Japanese Industrial Standards)	AATCC (USA)
Test solutions	Acid and alkaline artificial perspiration	Acid and alkaline artificial perspiration	Acid and alkaline artificial perspiration
Typical pH (acid)	5.5 ± 0.2	5.5 ± 0.2	4.3 ± 0.2
Typical pH (alkaline)	8.0 ± 0.2	8.0 ± 0.2	8.0 ± 0.2
Temperature	37 ± 2 °C	37 ± 2 °C	37 ± 2 °C
Duration	4 hours	4 hours	6 hours
Evaluation method	Gray scale for color change and staining	Gray scale for color change and staining	Gray scale for color change and staining
Adjacent fabric	Multifiber adjacent fabric	Multifiber adjacent fabric	Multifiber test fabric
Application scope	International trade, research	Japanese market	North American market
a^*	**-6.53±0.21**	**-6.53±0.12**	**-6.81±0.05**
b^*	**-5.49±0.13**	**-5.20±0.18**	**-5.40±0.16**
Lightness L^*	**42.68±0.35**	**42.99±0.73**	**42.94±0.28**
Color change ΔE	**2.11±0.20**	**2.00±0.19**	**1.71±0.09**

4. Conclusion

This research has provided a systematic and quantitative assessment of dye leaching mechanisms in simulated perspiration environments. Experimental results demonstrate that fiber composition is a primary determinant of colorfastness; while hydrophobic polyester fibers exhibited superior color stability (with ΔE as low as 0.48), hydrophilic cotton fibers showed the most significant color variation (ΔE reaching 2.26) due to intense interaction with the aqueous perspiration solution.

Regarding thermal influence, the study identified 45°C as the critical threshold for maintaining color stability in PE/CO fabrics, where the competing mechanisms of dye fixation and desorption reach a localized equilibrium. Conversely, elevated temperatures (65°C) were found to accelerate dye migration and release due to the dominance of the desorption process, significantly increasing the color difference. These quantitative findings underscore that controlling dye concentration (optimally at 2% owf within the investigated range) and environmental conditions is essential for enhancing textile quality. The data obtained not only assists textile engineers in selecting compatible fiber-dye combinations but also establishes a robust foundation for future research into specialized anti-leaching finishing agents.

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