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Sustainable UV-Protective Cotton Textiles Dyed With Plant-Based Extracts: A Study on Optical Behavior and Dyeing Parameters

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ABSTRACT

This study comprehensively examines the dyeing performance and UV-protective properties of cotton fabrics dyed with different natural extracts. The results affirm that the optical absorption properties of the fabrics are intrinsically linked to the chemical constituents of natural extracts, such as polyphenols and flavonoids, which act as effective UV absorbers. A strong correlation was observed between color strength (K/S) and UV-blocking efficiency: fabrics with higher dye uptake and lower lightness (L*) consistently exhibited superior UV protection, with transmittance (%T) values markedly reduced in the UV-A and UV-B regions. The application of a copper-based mordant further enhanced color depth and functional durability. Systematic optimization of dyeing parameters revealed that pH, dye concentration, and temperature play pivotal roles in determining the final quality of the textiles. The highest color strength was obtained at pH 5.8 for green tea (CS) and at pH 4.8 for butterfly pea (CT). Additionally, increasing the dye concentration noticeably improved dye fixation and optical density for both extracts, whereas elevating the dyeing temperature to 80°C enhanced color strength (K/S) for CS but caused a slight reduction in K/S for CT, while still maintaining low UV transmittance levels. By precisely controlling the dyeing process, natural extracts can be utilized to produce eco-friendly, multifunctional textiles that combine aesthetic appeal with high-performance UV protection, offering a sustainable alternative to synthetic functional agents.

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1. Introduction

The growing demand for sustainable and environmentally friendly textile processing has stimulated renewed interest in natural dyes as viable alternatives to synthetic colorants [1], [2]. Conventional dyeing processes, which rely heavily on petrochemical-based dyes, are often associated with environmental pollution, high energy consumption, and potential health risks due to the release of toxic residues [3]. In contrast, natural dyes derived from plant sources are biodegradable, renewable, and generally less harmful [4], making them attractive candidates for eco-friendly textile applications. Beyond coloration, many natural dyes possess intrinsic functional properties, including antioxidant activity and the ability to absorb ultraviolet (UV) radiation [5], [6], which can be exploited to develop multifunctional textiles.

UV radiation, particularly in the UV-A (320-400 nm) and UV-B (280-320 nm) regions, poses significant risks to human health, including skin aging, DNA damage, and increased risk of skin cancer [7], [8]. As a result, there is growing interest in textile-based UV protection as an additional layer of defense. The effectiveness of a fabric in blocking UV radiation is commonly associated with its optical properties, such as absorbance, transmittance, and color depth [9], [10]. In general, fabrics with higher optical density tend to exhibit lower UV transmittance, thereby providing better protection. Natural dyes, especially those rich in polyphenols, flavonoids, and anthocyanins, are known to exhibit strong absorption in the UV region [11], [12] due to their conjugated molecular structures. This makes them promising candidates for UV-protective textile applications. Despite these advantages, the practical application of natural dyes remains limited by challenges related to dye uptake, color consistency, and

durability, particularly washing fastness [13]. The interaction between dye molecules and cellulose fibers is often weak, resulting in partial dye loss during laundering. Mordanting is a commonly employed technique to enhance dye fixation by forming coordination complexes between dye molecules and fiber substrates [14], [15]. However, the effectiveness of mordanting depends on multiple processing parameters, including pH, dye concentration, and temperature, which influence both the chemical state of the dye and its affinity toward the fiber.

Previous works have often focused on individual factors affecting dyeing performance or have evaluated UV protection using isolated measurements. However, a systematic approach that integrates colorimetric properties, durability, and functional performance across multiple natural dye systems is still lacking. In particular, the relationship between optical characteristics and UV-blocking behavior [16], [17], as well as the influence of dyeing conditions on these properties, requires further clarification.

This present study investigates the dyeing behavior of cotton fabrics using a range of natural extracts, with an emphasis on their optical and functional performance. A comparative analysis was conducted based on colorimetric parameters (L*, a*, b*, K/S), spectral characteristics, and washing fastness to identify promising dye systems. Selected dyes were then subjected to further optimization by examining the effects of key dyeing parameters, including pH, dye concentration, and temperature. The aim is to establish a practical framework for enhancing both color performance and UV-protective functionality of naturally dyed cotton fabrics, contributing to the development of sustainable and multifunctional textile materials

2. Materials and methods

2.1. Materials

Table 1. *List of natural dyes provided by Vietnam online markets (Vegetable powder shops).*

No.	Symbol	Scientific name	Common name
1	BO	*Brassica oleracea var. capitata f. rubra (L.) DC.*	Red cabbage
2	BS	*Bambusa spp.*	Bamboo charcoal
3	CS	*Camellia sinensis (L.) Kuntze*	Green tea
4	CT	*Clitoria ternatea L.*	Butterfly pea
5	GJ	*Gardenia jasminoides J. Ellis*	Cape jasmine
6	HC	*Houttuynia cordata Thunb.*	Fish mint
7	HU	*Selenicereus undatus (Haw.) D.R.Hunt*	Dragon fruit
8	IB	*Ipomoea batatas (L.) Lam.*	Sweet potato
9	MC	*Momordica cochinchinensis (Lour.) Spreng.*	Gac fruit
10	PF	*Perilla frutescens (L.) Britton*	Beefsteak plant
11	SC	*Strobilanthes cusia (Nees) Kuntze*	Indigo plant

Plain-woven cotton fabric (100%) with an areal density of 253 g/m^2 was used as the substrate. Prior to dyeing, the fabric was scoured and rinsed to remove impurities and finishing agents. A range of natural dye sources was selected (as shown in Table 1), obtained from online commercial shops. The 11 natural dye sources were selected because they are commercially available in Vietnam, represent a broad range of naturally occurring color-producing compounds (including anthocyanins, flavonoids, tannins, chlorophylls, carotenoids, and indigoids), and are known to contain UV-absorbing phytochemicals with potential ultraviolet protection properties [18]–[20]. This diverse selection enables a systematic comparison of the UV-protective performance of cotton fabrics dyed with different classes of natural dyes. All plant materials were air-dried and ground before extraction. Copper(II) sulfate pentahydrate ($CuSO_4 \cdot 5H_2O$, 1.0% owf) was used as the mordant to enhance dye fixation. All chemicals employed

were of analytical grade and used without further purification. Distilled water was used throughout the experiments.

2.2. Experimental methods

The overall experimental procedure is summarized in Figure 1. The workflow includes dye extraction, cotton dyeing under controlled conditions, colorimetric and UV-Vis characterization, washing fastness evaluation, and statistical analysis. Detailed descriptions of each step are provided in the following sections.

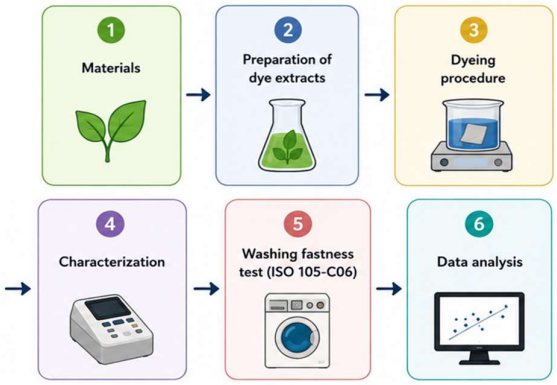


Figure 1. *Simplified workflow of experimental procedures.*

2.2.1. Preparation of dye extracts

Natural dye extracts were prepared by aqueous extraction. 25 g of plant material was mixed with 400 ml distilled water and heated at 100°C for 30 min [21]. The resulting solution was filtered to remove solid residues and used as the dye bath. The extract concentration was adjusted as required for subsequent experiments.

2.2.2. Dyeing procedure

Dyeing was carried out using a laboratory dyeing apparatus under controlled conditions. Cotton samples were dyed at a liquor ratio of 1:20 with continuous agitation. The dyeing process was performed at 80°C for 30 min. After dyeing, the samples were rinsed thoroughly and air-dried at ambient conditions. Variations in dyeing parameters, including pH of 3.8, 4.8 and 5.8, dye concentration by dilution ratio (100:00, 80:20, 60:40, 40:60, 20:80) and temperature (60 and 80°C), were applied to selected dye systems to investigate their effects on dye uptake and functional properties. The color properties of dyed fabrics were evaluated using a spectrophotometer under standard illumination conditions (D65 light source, 10° observer). The color coordinates L*, a*, and b* were recorded. The color strength (K/S) values were calculated based on the Kubelka-Munk equation [22]

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

where R is the reflectance at the wavelength of maximum absorption. Color difference (ΔE) was calculated relative to the undyed fabric.

2.2.3. UV-Vis spectral analysis

The optical properties of dyed fabrics were analyzed using a UV-Vis spectrophotometer over the wavelength range of 190-1,100 nm. Absorbance (Abs) and transmittance (%T) spectra were recorded. The average UV transmittance (%$\bar{T}$UV) was calculated over the range of 280-400 nm to evaluate UV-blocking performance.

2.2.4. Washing fastness test

Washing fastness was evaluated according to ISO 105-C06. Dyed samples were subjected to washing

under controlled conditions (40ºC, 30 minutes, liquor ratio 50:1, detergent 4 g/L). After one standard washing cycle, the samples were rinsed, dried, and re-evaluated for colorimetric properties (L*, K/S, ΔE) to assess color retention.

2.2.5. Data analysis

A comparative analysis was conducted to evaluate the relationships between the colorimetric parameters and the functional performance of fabrics dyed with different natural dye extracts. Descriptive statistical analysis was used to summarize the experimental data. Pearson correlation analysis was performed to evaluate the relationships between the UV-Vis spectral characteristics and the dyeing performance of the natural dye extracts. Since this study focused on correlation analysis rather than comparisons among independent treatment groups, ANOVA was not performed.

3. Results and discussion

3.1. Screening of natural dyes

***Table 2**. Colorimetric properties (L, a, b*, K/S, ΔE) of cotton fabrics dyed with different natural extracts before and after mordanting (referred to notations of dyes in Table 1).*

Sample	pH	L*	a*	b*	c*	h°	ΔE	K/S
SP-BO	4.22	86.28	2.27	1.67	2.81	36.28	8.29	1.07
SP-BO-M	3.47	80.66	1.54	9.48	9.60	80.90	16.76	1.15
SP-BS	10.44	89.16	-0.69	0.28	0.79	159.12	4.54	1.04
SP-BS-M	6.35	74.83	-0.17	10.06	10.06	91.10	21.72	1.28
SP-CS	4.47	68.09	3.41	18.64	18.94	79.56	30.88	1.50
SP-CS-M	3.77	54.48	4.35	17.63	18.15	76.08	43.56	**2.34**
SP-CT	4.25	71.54	0.96	-9.94	9.98	275.50	23.76	1.38
SP-CT-M	3.39	67.79	2.89	-2.82	4.10	276.90	25.84	1.52
SP-GJ	4.16	80.97	4.18	40.85	41.05	84.12	43.84	1.15
SP-GJ-M	4.07	79.30	5.37	44.93	45.25	83.16	48.34	1.18
SP-HC	3.91	82.97	-0.44	9.74	9.75	92.62	15.06	1.12
SP-HC-M	3.86	82.23	-2.41	9.96	10.24	103.58	15.84	1.13
SP-HU	4.82	89.11	-0.52	2.45	2.50	101.92	5.61	1.04
SP-HU-M	3.85	87.37	-0.71	4.38	4.44	99.34	8.18	1.06
SP-IB	4.62	89.08	0.88	0.75	1.15	40.52	5.05	1.04
SP-IB-M	3.38	85.20	1.13	4.78	4.91	76.64	10.30	1.09
SP-MC	4.59	79.59	9.69	26.78	28.47	70.10	32.54	1.17
SP-MC-M	3.49	81.53	2.25	10.08	10.33	78.46	16.30	1.14
SP-PF	5.34	77.92	0.92	13.22	13.25	85.60	16.70	1.21
SP-PF-M	4.25	63.83	2.34	14.32	14.51	80.74	33.54	**1.70**
SP-SC	7.78	76.08	1.95	-0.28	2.00	280.20	17.64	1.25
SP-SC-M	5.05	62.45	0.77	5.26	5.31	81.60	31.72	1.77

The colorimetric properties of cotton fabrics dyed with various natural extracts, both with and without mordanting, are summarized in Table 2. The results reveal significant variations in K/S, L*, and overall ΔE, reflecting differences in dye composition and affinity toward the cotton substrate. In general, unmordanted samples exhibit relatively low to moderate K/S values, indicating limited dye uptake due to the weak interaction between natural dye molecules and cellulose fibers. However, noticeable differences among dye sources are observed. Extracts such as CS, PF, and SC show comparatively higher K/S values, suggesting a greater presence of chromophoric compounds with stronger affinity for the fiber. In contrast, samples such as BO, BS, and HU display low K/S values, indicating poor coloration efficiency under the same dyeing conditions. Mordanting substantially enhances dye uptake across most dye systems. A consistent increase in K/S is observed after mordant treatment, accompanied by a decrease in L* values, indicating the formation of deeper and more saturated shades. This effect can be attributed to the formation of coordination complexes between the mordant and dye molecules, which improves dye fixation within the fiber matrix. For instance, CS and PF exhibit a marked increase in K/S after mordanting, highlighting their strong responsiveness to metal–dye interactions. The ΔE values further support these observations. Higher ΔE values are generally associated with stronger color development compared to the undyed fabric. Mordanted samples typically show greater ΔE, confirming the enhanced visual impact of dyeing. However, the magnitude of ΔE varies among dye types, reflecting differences in pigment composition and color hue. Based on these results, the studied dyes can be broadly classified into three groups: a) high color strength dyes (CS, PF, SC), b) moderate dyes (CT, GJ), and c) low-performing dyes (BO, BS, HU). This classification provides a practical basis for selecting promising candidates for further investigation. Overall, the screening results demonstrate that both dye type and mordanting treatment play critical roles in determining dye uptake and color characteristics. These findings serve as a foundation for subsequent analyses focusing on durability and functional performance, as well as for the selection of representative dye systems for process optimization.

3.2. Color fastness performance

The washing fastness of cotton fabrics dyed with different natural extracts was evaluated by comparing colorimetric properties before and after washing, as summarized in Table 3. The results reveal noticeable variations in color retention depending on dye type and mordanting treatment. In general, a decrease in K/S is observed after washing for most samples, indicating partial dye removal due to weak dye–fiber interactions. However, the extent of this reduction varies markedly among the dye systems. Mordanted samples retained higher absolute K/S values after washing compared to their unmordanted counterparts, although their percentage color retention (K/S retention) was not consistently higher. This suggests that mordanting enhances overall dye deposition by promoting stronger interactions between dye molecules and the cellulose matrix, even though loosely bound surface complexes may still be partially removed during laundering. Among the tested samples, SP-CS-M maintained the highest post-washing color strength (K/S = 2.06), despite showing the lowest percentage retention (88.03% vs. 96.67% for unmordanted SP-CS) due to its high initial dye uptake. A similar pattern was observed for SP-PF-M (91.76% vs. 104.13% for SP-PF) and SP-SC-M (92.66% vs. 112.80% for SP-SC). In contrast, SP-CT-M shows stable behavior (94.08% retention, K/S decreasing slightly from 1.52 to 1.43), suggesting effective incorporation of dye molecules within the fiber structure. Meanwhile, samples with lower initial K/S values, such as SP-BO and SP-BS, exhibit minimal relative changes after washing (larger than 99% retention) but remain limited in overall color performance, indicating weak dye uptake from the beginning. Variations in total ΔE before and after washing further reflect these trends, where mordanted fabrics generally maintain more pronounced visual color depth than unmordanted ones. Overall, the washing fastness results highlight a trade-off between high initial color intensity and percentage durability. While some dyes achieve high initial color strength, their resistance to washing depends strongly on the effectiveness of dye fixation. These findings emphasize the importance of optimizing dyeing conditions to enhance both color performance and durability. The observed stability trends also provide a basis for selecting representative dye systems for further investigation.

Table 3. *Colorimetric properties and color strength (K/S) of dyed cotton fabrics before and after washing.*

Sample	Unwashed		Washed		K/S Retention (%)
	ΔE	K/S	ΔE	K/S	
SP-BO	8.29	1.07	8.64	1.08	100.93
SP-BO-M	16.76	1.15	15.86	1.14	99.13
SP-BS	4.54	1.04	4.96	1.05	100.96
SP-BS-M	21.72	1.28	20.24	1.24	96.88
SP-CS	30.88	1.50	31.10	1.45	96.67
SP-CS-M	43.56	2.34	40.78	2.06	**88.03**
SP-CT	23.76	1.38	21.92	1.33	96.38
SP-CT-M	25.84	1.52	23.76	1.43	**94.08**
SP-GJ	43.84	1.15	43.88	1.14	99.13
SP-GJ-M	48.34	1.18	47.94	1.17	99.15
SP-HC	15.06	1.12	13.10	1.08	96.43
SP-HC-M	15.84	1.13	14.08	1.10	97.35
SP-HU	5.61	1.02	6.09	1.05	102.94
SP-HU-M	8.18	1.04	7.84	1.06	101.92
SP-IB	5.05	1.07	5.00	1.04	97.20
SP-IB-M	10.30	1.09	10.64	1.11	101.83
SP-MC	32.54	1.17	28.38	1.15	98.29
SP-MC-M	16.30	1.14	17.34	1.18	103.51
SP-PF	16.70	1.21	23.84	1.26	104.13
SP-PF-M	33.54	1.70	30.52	1.56	91.76
SP-SC	17.64	1.25	23.08	1.41	112.80
SP-SC-M	31.72	1.77	29.16	1.64	92.66

3.3. Optical absorption properties

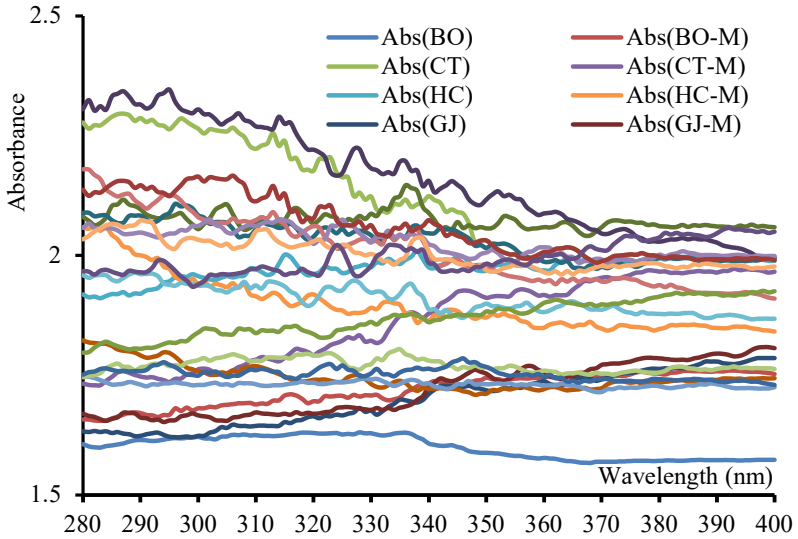


Figure 2. *UV-Vis spectra of 1) BO, 2) BS, 3) CS, 4) CT, 5) GJ, 6) HC, 7) HU, 8) IB, 9) MC, 10) PF and 11) SC extracts in the wavelength range from 280 to 400 nm (the presence and absence of a mordant (M) (1.0 % owf $CuSO_4.5H_2O$).*

Figure 2 analyzes the optical absorption properties of cotton fabrics dyed with 11 different natural extracts, highlighting the critical relationship between spectral behavior and functional performance. The UV-Vis spectra, recorded across the 280-400 nm range, reveal that natural pigments, particularly those rich in polyphenols, flavonoids, and anthocyanins, exhibit substantial absorption peaks in the ultraviolet region. This inherent capability is attributed to their conjugated molecular structures, which effectively intercept and dissipate high-energy UV-A and UV-B radiation. The results reveal a clear disparity in absorption intensity among the various extracts; samples such as CS, PF, and SC show noticeably higher absorbance levels compared to others like BO or HU. A pivotal finding in this section is the impact of mordanting on the optical density of dyed fabrics. The application of a copper-based mordant (1.0% owf $CuSO_4 \cdot 5H_2O$) consistently enhances the spectral absorbance across the entire measured range. This phenomenon is driven by the formation of coordination complexes between the metallic ions and the natural dye molecules, which not only deepens the visual color but also increases the density of chromophores capable of absorbing UV light. Consequently, mordanted fabrics typically exhibit lower transmittance values, providing a superior protective barrier. Furthermore, the comparative analysis of these optical profiles serves as a foundational step for predicting UV-blocking efficiency. There is a strong correlation between the K/S and the spectral absorbance: fabrics with higher dye uptake consistently display more robust absorption characteristics. These results underscore the potential of specific natural dyes as eco-friendly UV absorbers. By identifying extracts with optimal absorption spectra, such as CS and CT, the study provides a scientific basis for selecting the most effective candidates for subsequent process optimization aimed at maximizing the multifunctional properties of sustainable textiles

3.4. UV-Blocking performance

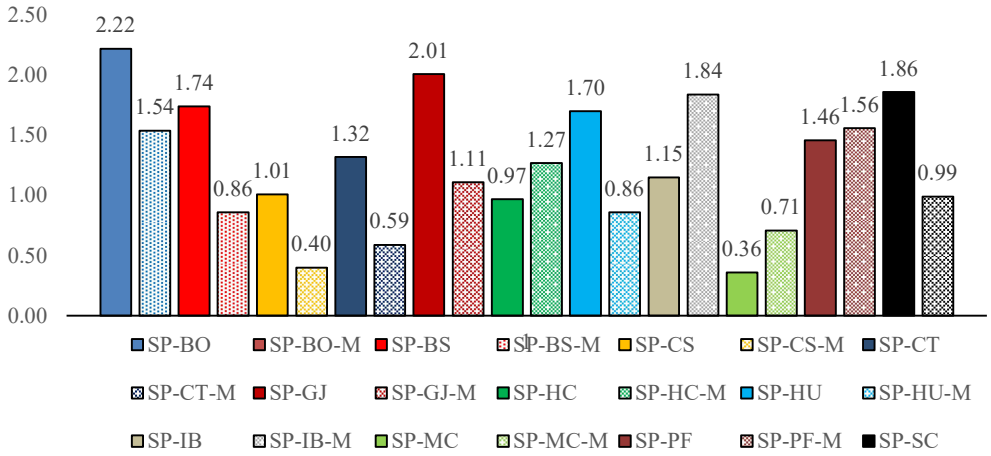


Figure 3. *UV-Blocking properties of cotton fabrics dyed with 1) BO, 2) BS, 3) CS, 4) CT, 5) GJ, 6) HC, 7) HU, 8) IB, 9) MC, 10) PF and 11) SC extracts in the presence and absence of a mordant (M) (1.0 % owf $CuSO_4.5H_2O$).*

Figure 3 evaluates the UV-blocking performance of the dyed cotton fabrics, establishing a critical link between colorimetric characteristics and functional protection against ultraviolet radiation. The findings indicate that the effectiveness of the fabrics in mitigating UV transmission is strongly dependent on the dye uptake and the inherent chemical properties of the natural extracts. A consistent trend-based analysis reveals that samples with higher K/S values and lower L* values exhibit noticeably reduced UV transmittance across the 280-400 nm range. This suggests that a higher density of chromophores on the fiber surface enhances the material's ability to absorb and scatter harmful UV-A and UV-B rays, thereby providing a robust protective barrier for the wearer. The performance varies markedly across the different dye systems. High-performing extracts such as CS, PF, and SC demonstrate superior UV-blocking capabilities compared to low-performing ones like BO or BS. This superiority is attributed to the high concentration of bioactive compounds, specifically polyphenols and flavonoids, which possess natural UV-absorbing properties due to their conjugated structures. Furthermore, the results highlight

the transformative role of mordanting in enhancing functional performance. For instance, SP-CS-M and SP-PF-M show markedly improved UV-blocking efficiency relative to their unmordanted counterparts. This enhancement is linked to the formation of stable coordination complexes between the metal ions and dye molecules, which not only improves dye fixation but also increases the optical density of the fabric. Consequently, these findings validate the potential of using optimized natural dyeing processes to develop sustainable, high-performance multifunctional textiles with exceptional UV-protective properties

3.5. Selection of potential natural dyes

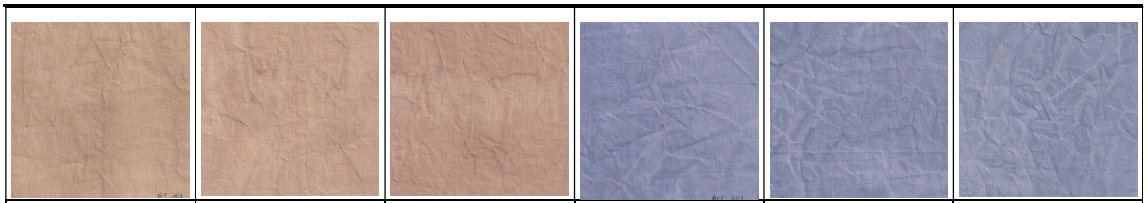
Based on the comparative evaluation of colorimetric parameters, a ranking-based approach was adopted to elucidate the relationship between dye uptake and functional performance across different dye systems. The samples were categorized into high, medium, and low color strength groups according to their K/S values. It was consistently observed that samples with higher K/S values exhibited more pronounced color development (higher ΔE) and darker shades (lower L*), indicating greater dye deposition on the fabric surface. Notably, mordanted samples generally shifted from medium to high K/S levels, confirming the significant role of mordanting in enhancing dye fixation. For instance, SP-CS-M and SP-PF-M displayed markedly higher K/S values compared to their unmordanted counterparts, accompanied by substantial increases in ΔE, reflecting improved color depth. In contrast, samples such as SP-BO and SP-BS remained in the low K/S range, showing limited color development and weaker dye–fiber interactions. A representative comparison further supports this trend. SP-CS-M, which exhibited one of the highest K/S values, also maintained relatively high color strength after washing (2.34 to 2.06), maintaining superior post-wash color depth despite a 11.97% relative reduction. Similarly, SP-CT-M showed stable behavior with only a slight decrease in K/S after washing (1.52 to 1.43), suggesting effective fixation within the fiber matrix. On the other hand, samples with lower initial K/S values, such as SP-BO and SP-BS, showed minimal changes after washing but remained limited in overall color performance. These observations demonstrate that K/S can serve as a practical indicator of both dye uptake and durability. The consistent improvement in K/S and ΔE after mordanting, together with acceptable washing stability in selected samples, suggests that optimizing dyeing conditions is essential to further enhance functional performance. Therefore, selected dyes such as CS and CT were chosen for subsequent investigations focusing on the effects of pH, dye concentration, and temperature on dye fixation and related properties.

3.6. Effect of dyeing parameters

3.6.1. Effect of pH

Table 4. *Colorimetric parameters, ORP values, and UV-blocking performance of dyed fabrics under various pH conditions.*

Sample	pH	ORP	L*	a*	b*	ΔE	K/S	Abs			%T		
								365	320	254	365	320	254
CSpH38	3.8	165.63	65.88	4.28	20.96	31.47	2.73	1.80	1.83	1.92	1.62	1.50	1.24
CTpH38	3.8	172.32	59.31	2.35	-14.83	33.93	3.71	2.03	1.93	1.72	0.96	1.18	1.92
CSpH48	4.8	107.33	66.01	5.26	19.53	30.62	2.71	1.78	1.79	1.75	1.66	1.64	1.78
CTpH48	4.8	113.71	59.07	1.53	-14.38	33.87	3.75	1.92	1.81	1.90	1.22	1.56	1.24
CSpH58	5.8	49.02	63.67	6.68	18.39	32.42	3.02	2.01	2.04	1.32	0.98	0.98	1.32
CTpH58	5.8	56.54	60.84	0.31	-12.52	31.40	3.45	1.91	1.77	1.81	1.22	1.72	1.56



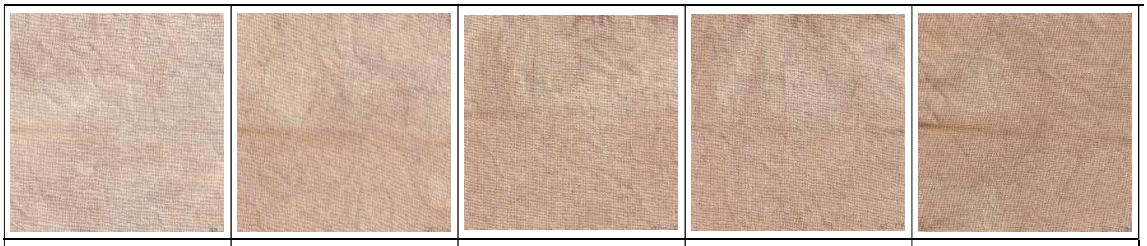
CSpH38	CSpH48	CSpH58	CTpH38	CTpH48	CTpH58

Table 4 examines the influence of dye bath pH on the colorimetric and functional properties of cotton fabrics dyed with CS and CT extracts. The results demonstrate that pH markedly modulates dye uptake, as evidenced by the variations in K/S and ORP. For CS, the highest K/S value of 3.02 is achieved at pH 5.8, whereas CT exhibits optimal coloration at pH 4.8 with a K/S of 3.75. These variations indicate that the chemical stability and affinity of natural pigments, such as polyphenols and anthocyanins, are highly sensitive to the ionic environment of the dye bath. Furthermore, the optical data indicates a strong correlation between pH-driven dye fixation and UV-blocking efficiency; samples with optimized pH levels show higher spectral absorbance and lower UV transmittance. Consequently, selecting an appropriate pH is crucial not only for achieving desired aesthetic shades but also for maximizing the UV-protective functionality of the treated textiles

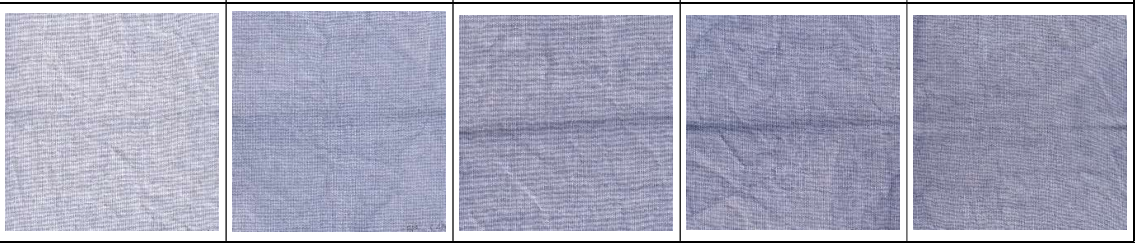
3.6.2. Effect of dye concentration

Table 5. *Colorimetric coordinates and UV-blocking parameters of dyed fabrics at different extract concentrations.*

Sample	Dilution ratio	ORP	L*	a*	b*	ΔE	K/S	Abs			%T		
								365	320	254	365	320	254
CSC100	100:00	101.92	64.50	4.98	20.46	30.38	2.91	1.68	1.95	1.53	1.78	1.12	0.76
CTC100	100:00	97.61	61.65	1.26	-11.63	28.78	3.32	2.17	2.09	2.03	0.70	0.84	0.94
CSC080	80:20	104.63	68.76	4.07	17.19	24.88	2.40	2.12	1.82	1.65	1.67	1.50	2.38
CTC080	80:20	102.01	60.07	1.66	-13.42	31.02	3.57	1.80	2.05	1.73	1.66	0.90	1.86
CSC060	60:40	105.50	70.11	4.01	17.85	24.34	2.26	2.10	1.62	1.75	1.68	2.38	1.82
CTC060	60:40	104.42	62.29	1.67	-12.27	28.48	3.22	1.74	1.94	1.99	1.80	1.18	1.10
CSC040	40:60	111.31	67.33	3.98	16.47	22.38	2.56	1.68	1.54	1.65	2.10	2.92	2.26
CTC040	40:60	107.93	71.62	1.43	-11.64	23.82	2.12	1.67	1.81	1.97	2.14	1.58	1.08
CSC020	20:80	121.14	75.91	2.30	14.92	19.28	1.76	1.52	1.47	1.53	3.03	3.34	2.96
CTC020	20:80	113.72	74.08	0.67	-5.82	13.44	1.90	1.57	1.80	1.91	2.66	1.58	1.26



CSC020	CSC040	CSC060	CSC080	CSC100



CTC020	CTC040	CTC060	CTC080	CTC100

Table 5 investigates the impact of dye concentration, varied through different dilution ratios, on the colorimetric and UV-protective properties of cotton fabrics. The experimental data indicates a direct correlation between extract concentration and K/S, where the highest concentration (100:00) yields the most intensive shades for both CS (K/S = 2.91) and CT (K/S = 3.32) và 1.78% for CS and 0.70% for

CT at 365 nm. As the concentration decreases, the reduced density of chromophores on the fiber surface results in higher L* and diminished color depth. Crucially, the UV-blocking efficiency is markedly enhanced at higher concentrations, with UV transmittance (%T) reaching its minimum values, 0.70% for CS and 1.78% for CT at 365 nm. This demonstrates that a sufficient concentration of natural pigments is essential to form an effective absorptive barrier against UV radiation. Therefore, optimizing the dye concentration is vital for balancing aesthetic requirements with maximum functional performance in sustainable textiles.

3.6.3. Effect of temperature

Table 6. *Comparison of colorimetric coordinates and UV-blocking performance of fabrics dyed at different temperatures (60°C vs 80°C).*

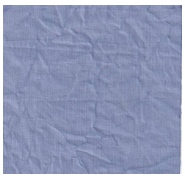
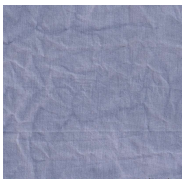
Sample	Temp	L*	a*	b*	ΔE	K/S	Abs			%T			Photo
							365	320	254	365	320	254	
CST60	60	72.29	0.84	23.35	27.93	2.06	2.22	2.05	1.90	0.64	0.90	1.26	
CST80	80	61.17	5.27	20.83	30.90	2.95	2.17	2.09	2.03	0.70	0.84	0.94	
CTT60	60	59.86	2.92	-15.70	33.17	3.61	1.75	1.79	2.05	1.80	1.58	0.90	
CTT80	80	61.36	1.23	-11.62	29.03	3.36	1.99	1.95	2.13	1.06	1.12	0.76	

Table 6 evaluates the influence of dyeing temperature on the colorimetric and UV-protective properties of the treated cotton fabrics. The experimental data reveals distinct thermal responses between the two natural dye systems. For CS, increasing the temperature from 60°C to 80°C significantly enhances dye uptake, as indicated by the increase in K/S from 2.06 to 2.95, accompanied by a decrease in lightness (L* from 72.29 to 61.17) and a more saturated shade. This improvement is attributed to the thermal swelling of cotton fibers and increased kinetic energy of the polyphenolic molecules, facilitating deeper diffusion into the fiber matrix. Conversely, CT exhibits a slight decrease in K/S when the temperature rises from 60°C to 80°C (from 3.61 to 3.36), accompanied by a minor increase in L* (from 59.86 to 61.36), likely due to partial thermal degradation or reduced affinity of anthocyanin pigments at elevated temperatures. Nevertheless, both dye systems achieved lower UV transmittance (%T) at 80°C across the measured wavelengths (e.g., decreasing from 0.90% to 0.84% at 320 nm for CS, and from 1.80% to 1.06% at 365 nm for CT), demonstrating that 80°C remains effective for maximizing UV-blocking performance, particularly for CS.

4. Conclusions

This work successfully demonstrates the potential of natural extracts as sustainable alternatives for developing multifunctional cotton fabrics with enhanced UV-protective properties. The experimental results reveal that the synergistic effect between bioactive compounds, such as polyphenols, and copper-based mordants creates an effective optical barrier that substantially mitigates the transmission of harmful UV-A and UV-B radiation. The systematic optimization of dyeing parameters established that pH, extract concentration, and dyeing temperature are critical factors influencing both color strength (K/S) and functional performance. Specifically, high extract concentrations maximized pigment density on the fibers for both dyes, while a dyeing temperature of 80°C further enhanced color strength for CS and achieved minimal UV transmittance across both systems. Moreover, the strong correlation between colorimetric data and spectral absorbance provides a reliable framework for predicting the protective capabilities of naturally dyed textiles. In conclusion, this research offers a viable and eco-friendly methodology for the textile industry to produce high-performance, health-protective garments while reducing reliance on synthetic chemicals. These findings not only contribute to the advancement of sustainable fashion but also validate the integration of traditional natural dyeing with modern functional requirements for protective textiles.

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Conflict of Interest

The authors declare no conflict of interest

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT for English language editing. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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