

# DYE UPTAKE AND FASTNESS PROPERTIES OF COTTON FABRIC DYED WITH RED CABBAGE PIGMENT

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This study investigated the dyeing behavior and fastness properties of cotton fabric using red cabbage (RC) extract, a natural source of anthocyanin pigments. The dye solution was obtained through aqueous extraction at a mildly acidic pH. Cotton fabrics were dyed under various conditions, including pH (4-8), temperature (30-75 °C), dyeing time (30-120 minutes), and with three metallic mordants including iron sulfate, copper sulfate, and potassium aluminum sulfate. Dye uptake was quantitatively evaluated using colorimetric analysis, specifically color strength (K/S) and color difference ( $\Delta E$ ). Fastness properties were assessed according to international standards for washing. Results indicated that the dye uptake was significantly influenced by these dyeing parameters, with optimal conditions identified at pH 5-6, 45 °C, and a dyeing time of 30 minutes. Mordanting, particularly with iron sulfate, notably enhanced both color depth and fastness performance. Iron sulfate-mordanted fabrics exhibited the highest color retention after washing. This research confirms red cabbage extract as a promising and environmentally sustainable natural dye for cotton, contributing to eco-textile development and circular fashion systems.

**Keywords:** natural dye, red cabbage extract, cotton fabric, dye uptake, color fastness

## INTRODUCTION

The global textile industry ranks among the most environmentally burdensome sectors, primarily due to its extensive reliance on synthetic dyes for coloration processes. These dyes, which are predominantly derived from petrochemical sources, often contain a complex mixture of hazardous substances, including aromatic amines, heavy metals (*e.g.*, chromium, lead, and cadmium), and persistent organic pollutants.<sup>1-3</sup> Upon discharge into aquatic ecosystems during dyeing and finishing operations, these substances contribute to severe water pollution, disrupt aquatic life, and pose long-term health risks to humans through bioaccumulation and exposure to contaminated water resources.<sup>4,5</sup> In response to these environmental and health concerns, there is a growing global impetus, driven by both regulatory pressures and consumer demand, to develop and adopt environmentally benign, sustainable alternatives in textile dyeing and finishing.<sup>6,7</sup>

Natural dyes, which are extracted from renewable sources, such as plants, fungi, insects, and certain minerals, have gained increasing attention as viable eco-friendly alternatives to

synthetic dyes. These dyes are typically biodegradable, non-toxic, and free from carcinogenic or mutagenic compounds, making them inherently safer for both the environment and human health.<sup>6,8</sup> Moreover, some natural dyes exhibit additional functional properties, such as antimicrobial, UV-protective, and antioxidant effects, which can add value to textile products.<sup>9-11</sup> Despite these benefits, the practical implementation of natural dyes in industrial-scale applications remains limited due to several inherent challenges. Among these are relatively poor color fastness to washing and light, variability in dye yield due to seasonal and geographical factors, limited reproducibility of shades, and the necessity for mordants to enhance dye-fiber binding, particularly in the case of cellulosic fibers such as cotton.<sup>12,13</sup> Cotton's hydroxyl-rich yet chemically inert cellulose backbone provides limited binding sites for most natural dye molecules, making pre- or post-mordanting strategies essential for improving dye fixation and ensuring acceptable durability.<sup>14,15</sup>

Red cabbage (*Brassica oleracea* var. *capitata f. rubra*) (denoted as RC in this work) has emerged as a noteworthy source of natural dyes due to its high anthocyanin content, water-soluble flavonoid pigments responsible for its characteristic red to purple coloration.<sup>16-20</sup> Anthocyanins are notable for their sensitivity to pH, undergoing structural transformations that result in a broad spectrum of colors from red (acidic conditions) to blue or green (alkaline conditions).<sup>21,22</sup> This unique pH-dependent chromaticity not only enables versatile aesthetic applications, but also provides a basis for studying the interactions between dye chemistry and fabric properties.<sup>23,24</sup> However, the successful and reproducible use of RC extract as a textile dye requires systematic optimization of dyeing conditions and a thorough evaluation of color performance under real-world usage scenarios.<sup>25-27</sup>

This study addressed such gaps by investigating the dyeability and fastness properties of cotton fabrics dyed with red cabbage extract under controlled experimental conditions. The research will focus on evaluating key process variables such as initial dye bath pH, dyeing temperature, extraction concentration, and contact time. In addition, the study will assess the role of various metal mordants, specifically iron sulfate ( $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ ), copper sulfate ( $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ ), and potassium aluminum sulfate ( $\text{KAl}(\text{SO}_4)_2 \cdot 12\text{H}_2\text{O}$ ) in enhancing color strength, shade depth, and color fastness to washing. By integrating spectrophotometric analysis, fastness testing, and colorimetric evaluation, this study aims to generate scientifically grounded insights that will inform the scalable application of RC extract as a sustainable natural dye in the textile industry. The findings could facilitate the advancement of green dyeing technologies and support the broader transition towards environmentally responsible textile manufacturing practices

## EXPERIMENTAL

### Materials

The fabric used in this work was 100% plain-weave cotton, scoured and bleached, obtained from Viet Thang Textile Company (Vietnam). Fresh red cabbage was purchased from a local market in Ho Chi Minh City. The mordants applied were iron sulfate heptahydrate ( $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ ), copper sulfate pentahydrate ( $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ ), and potassium aluminum sulfate dodecahydrate ( $\text{KAl}(\text{SO}_4)_2 \cdot 12\text{H}_2\text{O}$ ), all of analytical grade. Distilled water was used throughout the entire extraction and dyeing processes.

### Methods

Red cabbage (RC) was chopped into small pieces and soaked in distilled water at a cabbage-to-water ratio of 1:5 (w/v). The mixture was gently heated to 60 °C for 30 minutes, followed by filtration using muslin cloth to remove solid residues. The resulting anthocyanin-rich extract was stored at 4 °C and used immediately to preserve pigment stability. Cotton fabric swatches (5 × 5 cm) were dyed using the exhaust dyeing method. The dye bath was prepared using red cabbage extract, with pH adjusted between 4 and 8 using acetic acid or sodium carbonate. The fabric-to-liquor ratio was maintained at 1:20.

Dyeing was conducted at different temperatures (30 °C, 45 °C, 60 °C, and 75 °C) and times (30, 60, 90, and 120 minutes). The mordant was applied using three different procedures in order to evaluate its influence on dye fixation: 1) pre-addition to the dye bath, where the mordant was first dissolved in the RC extract solution before introducing the fabric; 2) *in-situ* addition during dyeing, where the mordant was added into the dye bath after the dyeing process had started; and 3) post-dyeing treatment, where the fabric was first dyed with RC extract and subsequently immersed in a separate mordant solution.

For clarity, all sample codes used throughout the manuscript are summarized in Table 1, including their corresponding dyeing parameters and mordant application conditions.

Table 1  
Sample codes and corresponding experimental conditions

Sample code	Variable	Description
St30, St60, St90, St120	Dyeing time	30, 60, 90, 120 min
ST30, ST45, ST60, ST75	Temperature	30, 45, 60, 75 °C
SC020, SC040, SC060, SC080, SC100	Dye concentration	20:80 – 100:0 dilution ratio
SMFeB	Mordant sequence	$\text{FeSO}_4$ applied by pre-bath addition (mordant dissolved in dye bath before fabric immersion)
SMFeA		$\text{FeSO}_4$ applied by post-dyeing treatment (fabric treated in separate mordant bath after dyeing)
SMCu, SMFe, SMKAl	Mordant type	$\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ , $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ , $\text{KAl}(\text{SO}_4)_2 \cdot 12\text{H}_2\text{O}$ (in-bath addition)
SNopH5, SNopH6, SNopH7	pH effect	No mordant at pH 5, pH 6, pH 7

Dye uptake was assessed using colorimetric measurements in the CIELAB color space ( $L^*$ ,  $a^*$ ,  $b^*$ ). Color strength (K/S) values were calculated according to the Kubelka-Munk theory, and total color difference ( $\Delta E$ ) was determined relative to the undyed reference fabric. All color measurements were performed using a Datacolor spectrophotometer, and each sample was measured in triplicate with averaged values reported.

Wash fastness was evaluated in accordance with AATCC Test Method 61-2A using a laboratory launderometer to simulate multiple domestic laundering cycles. Rubbing fastness (dry and wet) was assessed using a crockmeter following AATCC Test Method 8 and evaluated against grayscale standards.

Dyeing experiments were conducted in an infrared laboratory dyeing machine to ensure precise control of temperature, dyeing time, and liquor agitation. The pH and oxidation–reduction potential (ORP) of the dye extract solutions were measured simultaneously using a calibrated digital pH/ORP meter equipped with a combined glass pH electrode and a platinum ORP electrode with an Ag/AgCl reference system. Prior to measurement, the instrument was calibrated according to the manufacturer's instructions. The electrodes were immersed directly into the dye solution, and the pH and ORP values (mV) were recorded once the readings stabilized (approximately 30–60 s). All measurements were conducted at room temperature ( $25 \pm 1$  °C) and performed in triplicate, with average values reported.

UV-vis absorption spectra of RC extract solutions were recorded over the wavelength range of 190–700 nm using a UV-vis spectrophotometer with 1 cm quartz cuvettes. Spectral measurements were performed for the extract alone, after addition of metal salts, and for residual dye solutions collected after fabric immersion, in order to investigate anthocyanin – metal interactions and dye exhaustion behavior. Distilled water served as the blank reference. Visual assessments of dyed fabrics were conducted in a standardized color matching cabinet under D65 illumination conditions.

## RESULTS AND DISCUSSION

### Complex interaction between RC extract and metal mordants

The UV-vis spectra (Fig. 1) illustrate how different mordants affect the RC extract. The spectrum of the initial extract (NO in RC), characterized by peaks around 280–300 nm and 320–330 nm, represents the inherent absorbance of anthocyanins and phenolic compounds. The RC extract treated with copper sulfate (Cu in RC) shows a spectrum very similar to that of the initial extract, suggesting that copper has minimal impact on the electronic transitions or complexation of chromophores. In contrast, the RC extract with iron sulfate (Fe in RC) exhibits significant changes. A notable hyperchromic effect (increased

absorbance) and a bathochromic shift (red shift) occur in the 300–350 nm region, along with the appearance of a new shoulder around 400–450 nm. These changes strongly indicate complex formation between iron ions and components of the RC extract, typically leading to darker or bluer shades in dyed fabrics. The RC extract treated with aluminum potassium sulfate (Ka in RC) also shows spectral alterations, with a slight increase in absorbance around 300–350 nm and modified peak shapes compared to the initial extract. This suggests that aluminum forms complexes as well, potentially resulting in brighter shades, although its interaction appears less pronounced than that of iron. Overall, the UV-vis data clearly indicate that iron sulfate has the most significant effect on the absorption profile of the RC extract, reflecting strong complexation likely to alter the color of RC extracts. Copper sulfate has the least impact, while aluminum potassium sulfate exhibits an intermediate level of interaction. These spectral shifts are crucial for understanding how mordants influence the final color and fastness of natural dyes such as RC in textile applications. It should be emphasized that the spectral variations in Figure 1 reflect solution-phase coordination interactions between anthocyanins and metal ions rather than any fiber-related effect.

Figure 2 shows UV-vis spectra of RC extracts with mordants, after the introduction of fabric, showing notable differences compared to the corresponding solutions without fabric. Although dye adsorption onto cotton is expected to reduce the overall dye concentration in solution, the absorbance intensity in some cases appears comparable to or even higher than that observed before dyeing (Fig. 1). This apparent inconsistency does not directly indicate an increase in dye concentration, but rather reflects ongoing complexation reactions and structural transformations occurring during the dyeing process. In general, the absorbance peaks for all samples (No, Cu, Fe, Ka in RC+FB) appear slightly lower in intensity and potentially broader, particularly in the 300–350 nm region. This reduction in absorbance suggests that the colorant compounds from the RC extract, whether with or without mordants, have been adsorbed onto the fabric. The changes in peak shape and intensity across the different mordanted samples further indicate that the mordants enhance the exhaustion and binding of the dye onto the fabric. Therefore, the UV-vis spectra shown in Figure 2 should be interpreted as a combined result of dye exhaustion

and metal – anthocyanin complex evolution in the residual solution, rather than as a direct quantitative indicator of dye concentration alone. Among them, the iron complex continues to

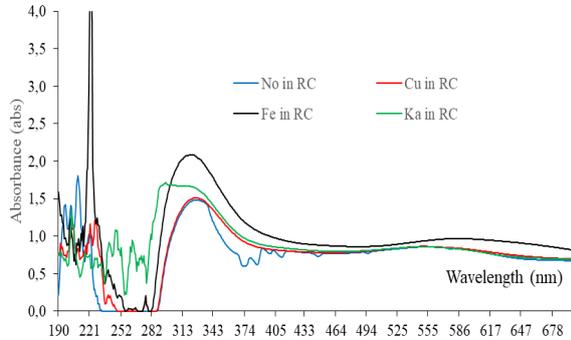


Figure 1: UV-vis spectra of RC extract without (No in RC) and with different mordants –  $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$  (Cu in RC),  $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$  (Fe in RC), and  $\text{KAl}(\text{SO}_4)_2 \cdot 12\text{H}_2\text{O}$  (Ka in RC)

exhibit the highest absorbance, implying a strong interaction even after dye uptake by the textile. This comparison supports the occurrence of dye transfer from the solution to the fabric.

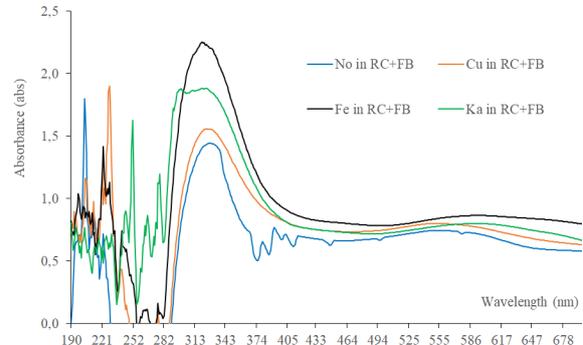


Figure 2: UV-vis spectra of residual RC dye solutions after cotton immersion (FB: fabric bath) under *in-situ* (simultaneous) mordanting conditions

**Effect of pH and ORP values on dye uptake**

Figure 3 and Table 2 clearly demonstrate the critical influence of pH on the dyeability of cotton fabric using unmordanted RC extract. Figure 3 shows that both the K/S value and total  $\Delta E$  are maximized under slightly acidic conditions. Specifically, the highest K/S value (0.9717) and  $\Delta E$  (43.56) are observed for SpH5 (initial pH  $\sim 5.05$ ). Dyeing at  $\sim \text{pH } 3.99$  (SpH4) and  $\sim \text{pH } 6.00$  (SpH6) also yields high dyeing efficacy. However, as the pH shifts toward neutral and alkaline ranges (SpH7,  $\sim \text{pH } 7.04$ ; SpH8,  $\sim \text{pH } 7.99$ ), there is a noticeable decrease in both K/S and  $\Delta E$  values, indicating reduced color uptake and intensity. For example, for SpH8, the K/S value decreases to 0.7932 and  $\Delta E$  to 38.58. This behavior is characteristic of anthocyanins, the main

chromophores in RC extract, which are most stable and exhibit more intense coloration in acidic environments. As pH increases, anthocyanins undergo structural transformations, often resulting in diminished color and reduced dyeing efficiency. It confirms that the pH of the dye bath remains relatively stable after dyeing, highlighting the importance of setting the correct initial pH. The ORP values reported in Table 2 were directly measured using a combined pH/ORP electrode system, and reflect the redox environment of the dye bath. The observed decrease in ORP with increasing pH indicates a progressively less oxidative medium, which may influence anthocyanin stability.

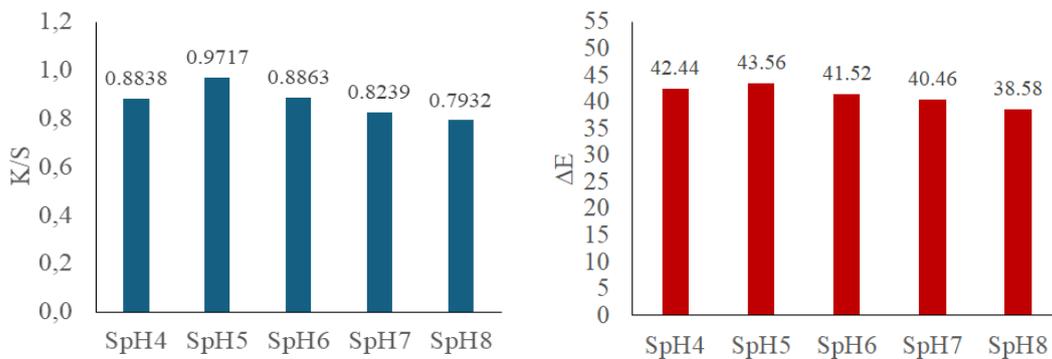


Figure 3: Changes in K/S and  $\Delta E$  value of cotton fabric dyed with RC extracts (without mordant) at pH 4 (SpH4), 5 (SpH5), 6 (SpH6), 7 (SpH7), and 8 (SpH8)

Table 2  
pH and ORP values of RC dye bath before and after cotton immersion (without mordant)

Sample	Pre-bath addition		After dyeing	
	pH	ORP	pH	ORP
SpH4	3.99	177.3	3.95	180.7
SpH5	5.05	115.6	5.09	113.3
SpH6	6.00	59.4	6.08	54.7
SpH7	7.04	-2.4	6.87	7.4
SpH8	7.99	-58.4	7.66	-39.3

### Roles of metallic mordants

The results presented in Table 3 and illustrated in the corresponding photos highlight the significant impact of both pH and mordant type on the dyeing performance of cotton fabric with RC extract. In the absence of mordants, the highest K/S value (0.7964) and  $\Delta E$  (38.22) were observed at pH 5, confirming that slightly acidic conditions favor anthocyanin stability and color intensity. As pH increases to 6 and 7, K/S and  $\Delta E$  values decrease or fluctuate slightly, indicating diminished dye uptake in neutral to weakly alkaline environments. In the presence of mordants, dye absorption and color strength significantly improve.  $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$  exhibited the strongest effect, particularly at pH 7, with the highest K/S (2.1677) and  $\Delta E$  (52.02), resulting in deep bluish shades. This supports previous UV-vis findings that iron forms strong complexes with anthocyanins, enhancing color depth and stability.  $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$  also improved dye uptake, especially at pH 7 (K/S: 1.1361;  $\Delta E$ : 43.18), but to a lesser extent than iron.  $\text{KAl}(\text{SO}_4)_2 \cdot 12\text{H}_2\text{O}$  showed intermediate performance, with optimal results at pH 7 (K/S: 1.2443;  $\Delta E$ : 44.76), suggesting moderate complexation and color enhancement. Overall, both dye uptake (K/S) and color difference ( $\Delta E$ ) were highest under slightly acidic to neutral pH, and the presence of mordants, especially iron, greatly boosted color strength. These results reaffirm the importance of pH control and mordant selection in optimizing natural dyeing processes for improved textile coloration.

Figure 4 clearly illustrates the significant positive impact of increasing  $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$  mordant content on the dyeability of cotton fabric with RC extract. Both K/S and total  $\Delta E$  consistently increase as the mordant content rises from 1 wt% (SMFe1) to 5 wt% (SMFe5). At 1 wt% mordant, K/S is 1.1952 and  $\Delta E$  is 42.84. These values progressively improve, reaching K/S of

1.3826 and  $\Delta E$  of 44.96 at 3 wt% (SMFe3), and peaking at K/S of 1.8103 and  $\Delta E$  of 50.06 at 5 wt% (SMFe5). This trend indicates that higher concentrations of the iron mordant facilitate greater dye uptake and stronger color intensity on the cotton fabric. Iron ions act as a crucial link, forming stable complexes with the anthocyanin pigments in the red cabbage extract and subsequently enhancing their affinity for the cellulosic cotton fibers. More mordant implies a greater number of available binding sites or more robust dye-mordant complexes, leading to more efficient dye adsorption and fixation. Thus, to achieve deeper and more vibrant colors when dyeing cotton with red cabbage extract, increasing the iron sulfate mordant concentration is highly effective.

Figure 5 presents the total  $\Delta E$  values of cotton fabrics dyed with RC extract under two different mordant application sequences: pre-bath addition, in which the mordant was introduced into the dye solution before fabric immersion (SMFeB), and post-dyeing mordant treatment where the dyed fabric was subsequently treated in a separate mordant bath (SMFeA). The results clearly demonstrate that pre-bath addition yields a significantly higher  $\Delta E$  value (42.24) compared to post-dyeing treatment (37.52). This indicates that incorporating iron sulfate into the dye bath prior to fabric introduction enhances color development and produces a deeper, more intense shade. The improved performance observed with pre-bath addition suggests that the presence of iron ions during the dyeing stage suggesting improved dye-mordant-fiber interaction during dyeing. In contrast, applying the mordant after dyeing may limit coordination efficiency, as part of the dye has already been loosely adsorbed onto the fiber surface, resulting in comparatively lower color intensity.

Table 3  
K/S and  $\Delta E$  values of cotton fabric dyed with RC at pH 5, 6, and 7 in the absence or presence of  $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ ,  $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ , and  $\text{KAl}(\text{SO}_4)_2 \cdot 12\text{H}_2\text{O}$

Mordants	Sample	pH	K/S	$\Delta E$	Photo
None	SNopH5	5	0.7964	38.22	
	SNopH6	6	0.6010	34.72	
	SNopH7	7	0.7500	38.4	
$\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$	SMCupH5	5	0.9169	39.50	
	SMCupH6	6	0.8804	39.76	
	SMCupH7	7	1.1361	43.18	
$\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$	SMFepH5	5	1.5335	46.48	
	SMFepH6	6	1.2758	44.04	
	SMFepH7	7	2.1677	52.02	
$\text{KAl}(\text{SO}_4)_2 \cdot 12\text{H}_2\text{O}$	SMKapH5	5	0.9810	41.58	
	SMKapH6	6	0.7741	38.38	
	SMKapH7	7	1.2443	44.76	

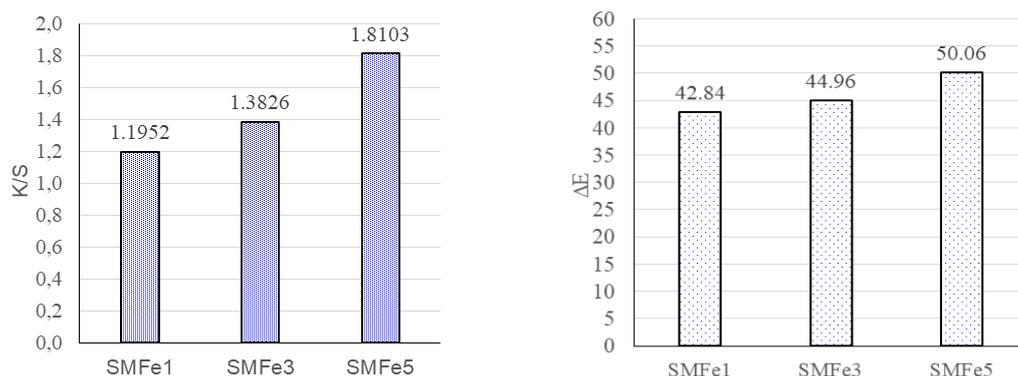


Figure 4: Dyeability of cotton fabric dyed with RC extract in the presence of 1 wt%, 3 wt%, and 5 wt%  $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$  (denoted as SMFe1, SMFe3, and SMFe5, respectively)

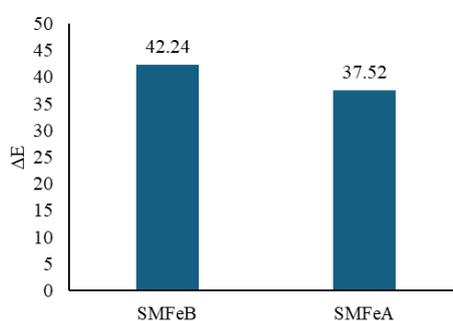


Figure 5: Total  $\Delta E$  values of cotton fabrics dyed with RC extract under different mordant application sequences: pre-bath addition (SMFeB) and post-dyeing treatment (SMFeA)

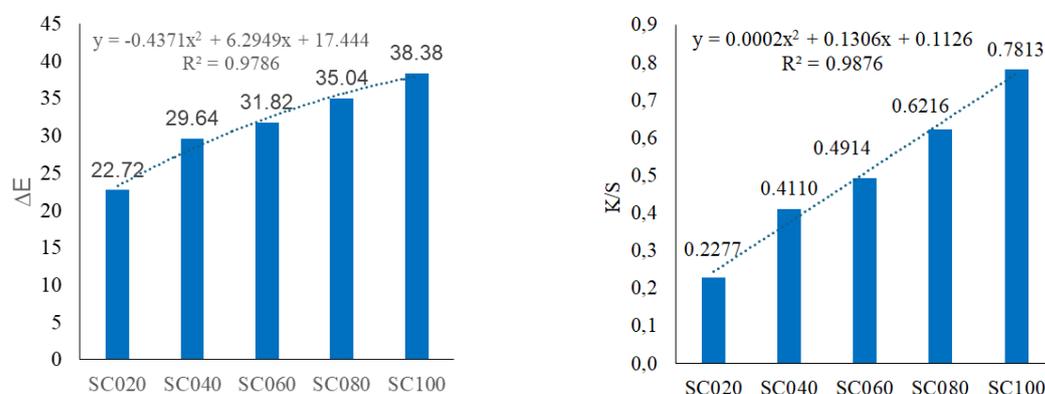


Figure 6: K/S and  $\Delta E$  values of cotton fabric dyed with RC extracts at dilution ratios of 20:80, 40:60, 60:40, 80:20, and 100:0 (denoted as SC020, SC040, SC060, SC080, and SC100, respectively)

### Dye concentration

Figure 6 effectively describes the profound influence of the dilution ratio of RC extract on the dyeability of cotton fabric. Both the total  $\Delta E$  and K/S exhibit a clear and consistent increasing trend as the concentration of the RC extract in the dye bath increases (*i.e.*, as the dilution ratio decreases from 20:80 to 100:0). For instance, the  $\Delta E$  value escalates from 22.72 at a 20:80 dilution (SC020) to

38.38 for the undiluted extract (SC100). Similarly, the K/S value rises from 0.2272 to 0.7813 across the same range. This strong positive correlation signifies that a higher concentration of the RC extract provides more dye molecules available for adsorption onto the cotton fibers, leading to a greater dye uptake and consequently, a deeper and more intense color on the fabric. The quadratic regression equations provided with high  $R^2$  values

further confirm this non-linear relationship. Therefore, for achieving maximum color intensity when dyeing cotton with red cabbage extract, minimizing the dilution of the dye bath is essential.

### Dyeing temperature and time

The data provided in Table 4 illustrates the effect of dyeing time on the K/S and  $\Delta E$  values of cotton fabric dyed with RC extracts. The most striking observation is that the shortest dyeing time, 30 minutes (St30), yields the highest dyeability compared to longer durations. At 30 minutes (St30), the fabric exhibits the maximum K/S value of 0.8625 and the highest  $\Delta E$  of 42.62. The sample photo for St30 also visually appears to have the deepest color among the tested samples. However, as the dyeing time extends beyond 30 minutes, both K/S and  $\Delta E$  values noticeably decrease. At 60 minutes (St60), K/S drops to 0.7606 and  $\Delta E$  to 38.92. This trend continues, with K/S slightly decreasing further to 0.7451 at 90 minutes (St90), although  $\Delta E$  shows a minor rebound to 39.28. At 120 minutes (St120), K/S slightly increases to 0.7859, while  $\Delta E$  slightly drops to 38.18, neither of which recovers to the initial 30-minute levels. This unexpected decline in dyeability after an initial short period suggests potential degradation of the dye molecules or saturation of the fabric. Anthocyanins, the primary colorants in red cabbage, are known to be sensitive to prolonged exposure to heat and light, which are typically present during dyeing processes. Extended dyeing times could lead to thermal or oxidative decomposition of the dye in the bath, reducing its availability for binding to the fabric. Alternatively, the cotton fibers might reach their saturation point within the first 30 minutes, and further exposure could even lead to some desorption or leaching of loosely bound dye, or degradation of the absorbed dye itself. Such results indicate that for dyeing cotton fabric with red cabbage extracts, an optimal dyeing time is relatively short, around 30 minutes, to achieve maximum color strength and difference. Longer dyeing times appear to be detrimental to the dyeing efficiency, highlighting the importance of time optimization for natural dyeing processes to preserve dye integrity and achieve desired color yields.

Figure 7 indicates the impact of dyeing temperature on the K/S of cotton fabric dyed with RC extracts. The results indicate a clear optimal temperature for achieving maximum dyeability. At 30 °C (ST30), the K/S value is 0.5852. As the

temperature increases to 45 °C (ST45), the K/S significantly rises to its peak at 0.7092. This improvement suggests that elevated temperature enhances the kinetic energy of the dye molecules, facilitating better diffusion and adsorption onto the cotton fibers. It likely also aids in opening up the fiber structure for more efficient dye penetration. However, beyond 45 °C, the K/S value starts to decline. At 60 °C (ST60), the K/S drops to 0.5956, which is notably lower than the peak. Even at 75 °C (ST75), while the K/S value slightly recovers to 0.6495, it still remains below the optimum achieved at 45 °C. This decrease at higher temperatures is typically attributed to the thermal instability of natural dyes like anthocyanins present in red cabbage. Prolonged exposure to excessive heat can cause these dye molecules to degrade, leading to a loss of their chromophoric properties and reduced ability to effectively color the fabric.

### Color fastness performance to washing condition

Table 5 presents the significant impact of different mordants on the initial color and, more importantly, the wash fastness of cotton fabric dyed with RC extracts. The data presents  $\Delta E$  values and corresponding visual samples after 0, 1, and 5 washing cycles for fabric dyed without mordant (SMNo) and with copper (SMCu), iron (SMFe), and aluminum (SMKa) mordants. Initially, at 0 washing cycles, the fabrics display distinct colors and  $\Delta E$  values. SMNo shows a purplish-pink hue with a  $\Delta E$  of 39.65. Both SMCu (39.76) and SMKa (38.38) exhibit similar initial color differences, though with subtle hue shifts. Notably, SMFe stands out with the highest initial  $\Delta E$  of 44.04 and a pronounced change to a dark blue/greyish-blue color, indicating a strong interaction between the iron mordant and the RC pigments, consistent with prior UV-vis observations. The wash fastness results are where the mordants demonstrate their crucial role. After just 1 washing cycle, all samples experience a substantial drop in  $\Delta E$ . SMNo, without a mordant, shows a drastic reduction to 14.90, becoming visibly pale. While SMCu (21.74) and SMKa (18.36) offer some improvement in color retention compared to SMNo, they still fade considerably. Crucially, SMFe demonstrates superior wash fastness, retaining a  $\Delta E$  of 33.28, remaining significantly darker and maintaining its blue hue much better than the other samples. This trend continues after 5 washing cycles.

Table 4

K/S and  $\Delta E$  values of cotton samples dyed with RC extracts in 30, 60, 90, 120 dyeing minutes (denoted as St30, St60, St90, and St120, respectively)

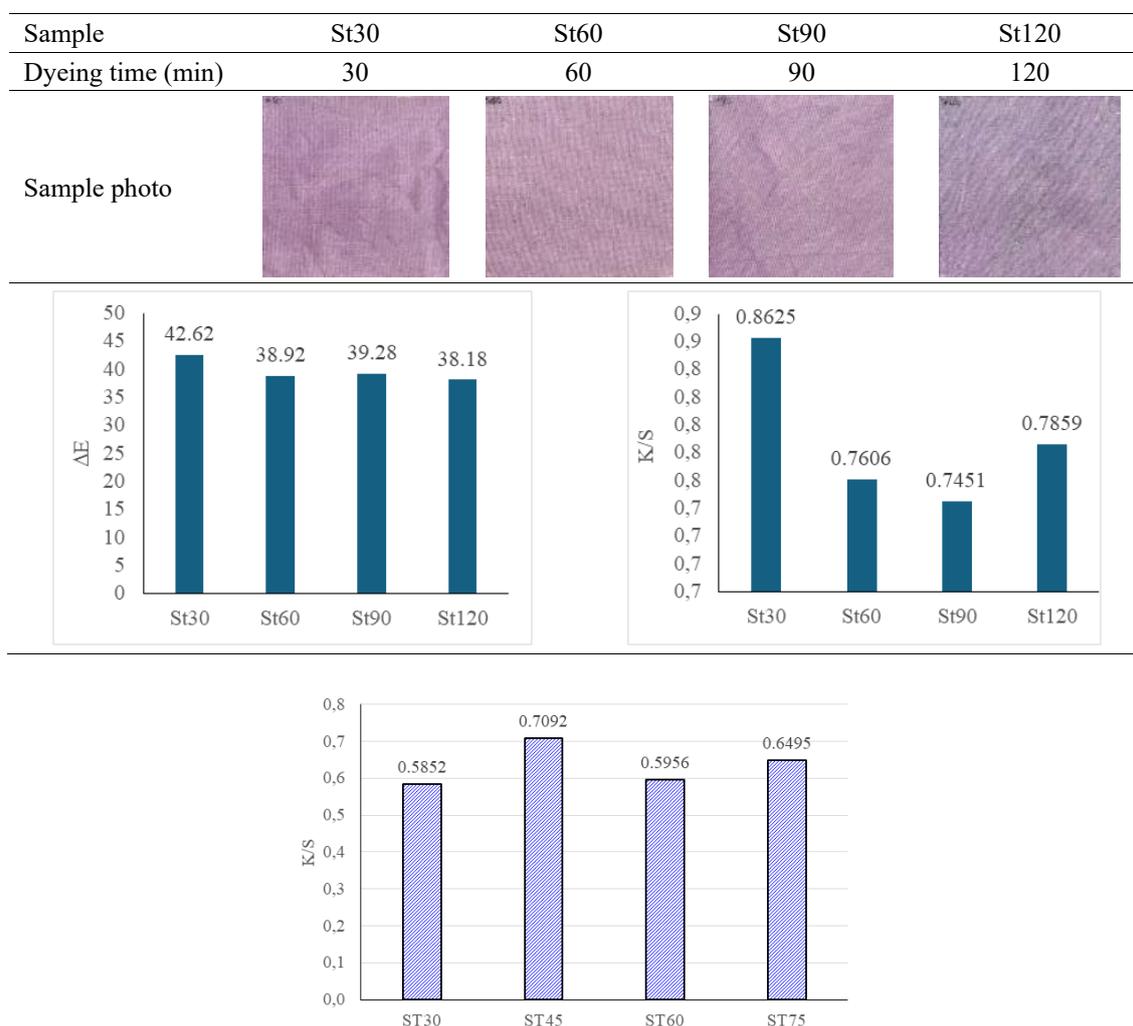


Figure 7: K/S values of cotton fabric dyed with RC extracts at 30, 45, 60 and 75 °C

SMNo further fades to 12.60, appearing almost white. SMCu and SMKa also show further deterioration to 15.38 and 15.10, respectively, becoming very light. In stark contrast, SMFe still retains a robust  $\Delta E$  of 25.40, visibly preserving its color much more effectively than all other treatments.

These findings underscore that mordants are indispensable for enhancing the wash fastness of natural dyes on cotton. Iron sulfate, in particular, proves to be the most effective mordant for red cabbage extract, not only yielding a strong initial color, but also forming highly stable complexes with the dye molecules that resist extensive washing, significantly outperforming copper, aluminum, and the absence of mordant.

### Physical properties of cotton fabrics dyed with RC extracts

Table 6 presents a comparison of selected physical properties of cotton fabrics dyed with RC extracts versus untreated greige fabrics. Firstly, the crease angle decreased from 78.14° for the greige fabric to 72.03° for the dyed fabric, representing a change of -7.81%. This reduction suggests that the RC extract may slightly improve wrinkle resistance, making the fabric less prone to creasing. Secondly, air permeability showed a slight decrease from  $3.72 \times 10^{-4}$  m/s to  $3.69 \times 10^{-4}$  m/s, a change of -0.80%.

Table 5  
Color difference ( $\Delta E$ ) of cotton samples dyed with RC extracts in the absence (SMNo) and presence of mordants ( $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ : SMCu,  $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ : SMFe,  $\text{KAl}(\text{SO}_4)_2 \cdot 12\text{H}_2\text{O}$ : SMKa) after 0, 1, and 5 washing cycles

Washing cycles	SMNo		SMCu		SMFe		SMKa	
	$\Delta E$		$\Delta E$		$\Delta E$		$\Delta E$	
0	39.65		39.76		44.04		38.38	
1	14.90		21.74		33.28		18.36	
5	12.60		15.38		25.40		15.10	

Table 6  
Some physical properties of cotton fabrics dyed with RC extracts as compared to greige fabrics

Physical properties	Value		Change (%)
	Greige fabric	Dyed fabric	
Crease angle ( $^\circ$ )	78.14	72.03	-7.81
Air permeability (m/s)	$3.72 \times 10^{-4}$	$3.69 \times 10^{-4}$	-0.80
Moisture (%)	5.5	5.8	+5.45
Stiffness (mg/cm)	0.0454	0.0559	+23.05

This minimal reduction indicates that the dyeing process does not significantly affect the fabric's breathability, a desirable property for wearing comfort. Thirdly, moisture content increased from 5.5% to 5.8%, corresponding to a positive change of 5.45%. This suggests that the dyed fabric may have a slightly higher moisture affinity, potentially enhancing comfort in applications where perspiration absorption is beneficial. Finally, stiffness exhibited the most notable change, increasing from 0.0454 mg/cm to 0.0559 mg/cm, equivalent to a significant increase of +23.05%.

This suggests that the red cabbage dyeing process results in noticeably stiffer fabric, which could affect drape and hand feel factors that should be considered depending on the intended application.

## CONCLUSION

This study comprehensively investigated the use of red cabbage extract as a natural dye for cotton fabric, meticulously analyzing the impact of various dyeing parameters and mordanting techniques on dye uptake and color fastness. The findings confirm that the dyeing process with red cabbage extract is highly sensitive to external conditions. Optimal dyeing conditions were identified at mildly acidic pH (5–6), 45  $^\circ\text{C}$ , and 30 minutes, which yielded the highest K/S and  $\Delta E$  values. The role of metallic mordants was found to be indispensable, significantly enhancing both the color depth and the critical wash and rubbing fastness properties of the dyed fabric. Among the mordants tested,  $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$  proved to be exceptionally effective, yielding the highest color retention even after multiple washing cycles. This

comprehensive analysis underscores the potential of red cabbage extract as a viable and environmentally friendly alternative to synthetic dyes for cotton textiles. These results provide valuable insights for sustainable textile production and support the continued advancement of natural dye applications within the framework of eco-textile development and the circular fashion economy.

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