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Dyeing on Sustainable Cotton Fabric with Mangosteen Rind: Investigating Extraction Parameters and Colour Fastness

Trajnostno barvanje bombažne tkanine z lupino mangostina (Garcinia mangostana): raziskava parametrov ekstrakcije in barvne obstojnosti

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Abstract

This study explores the sustainable dyeing of cotton fabrics using natural colorants extracted from mangosteen (*Garcinia mangostana*) rind. The extract was obtained via hot aqueous extraction and applied to cotton using varying dyeing conditions such as concentration, pH, temperature and time. Mordants (copper sulfate, iron sulfate and potassium alum) and fixatives (sodium chloride, potassium alum and acetic acid) were evaluated for enhancing colour strength and wash fastness. Copper sulfate improved dye uptake, while potassium alum best minimized colour fading. Optimal dyeing was achieved at pH 7 and 80 °C, for 30 min, balancing efficiency, cost, energy and acceptable colour quality. The dyed fabrics showed higher moisture content and stiffness, with minimal impact on air permeability and crease recovery. These results highlight mangosteen rinds promise as a sustainable, eco-friendly dye for cotton textiles.
Keywords: mangosteen rind, natural dyeing, cotton fabric, mordant, colour fastness

Izvleček

Raziskano je bilo trajnostno barvanje bombažnih tkanin z uporabo naravnih barvil, ekstrahiranih iz lupine mangostina. Izvleček, ki je bil pridobljen z ekstrakcijo mletih lupin z vročo vodo, je bil uporabljen za barvanje bombažne tkanine pri različnih koncentracijah, vrednostih pH, temperaturah in časih barvanja. Ocenjeni so bili učinki različnih čimž (bakrovega in železovega sulfata ter kalijevega aluminijevega sulfata) in fiksirnih sredstev (natrijevega klorida, kalijevega aluminijevega sulfata in ocetne kisline) za izboljšanje globine obarvanja in obstojnosti pri pranju. Bakrov sulfat je izboljšal absorpcijo barvila, medtem ko je kalijev aluminijev sulfat najbolj zmanjšal bledenje barve. Optimalno barvanje je bilo doseženo pri pogojih pH 7, 80 °C, 30 min, pri čemer so bili uravnoteženi učinkovitost, stroški, energija in sprejemljiva kakovost barve. Barvane tkanine so vsebovale več zračne vlage in bile bolj toge, minimalno sta se jim poslabšali zračna prepustnost in mečkavost.

Ti rezultati kažejo na možnost uporabe lupine mangostina kot trajnostnega in okolju prijaznega barvila za bombažne tekstilije.
Ključne besede: lupina mangostina, barvanje z naravnimi barvili, bombažna tkanina, čimža, barvna obstojnost

1 Introduction

The increasing demand for sustainable and eco-conscious practices in the textile industry has prompted renewed interest in the application of natural dyes. Unlike synthetic dyes, which are derived from petroleum-based sources and pose significant environmental and health concerns including wastewater pollution, toxicity and bioaccumulation, natural dyes offer a biodegradable, non-toxic and renewable alternative [1, 2]. However, despite their environmental advantages, natural dyes often face limitations such as low colour fastness, limited colour range and inconsistent dyeing performance, especially on cellulosic fibres such as cotton. Addressing these drawbacks remains a key focus in natural dye research [3, 4]. Plant-based colorants, particularly those derived from fruit peels, leaves and barks, have shown promising results due to their abundance of chromophoric compounds such as anthocyanins, flavonoids, tannins and xanthones [5, 6]. Among these, mangosteen (*Garcinia mangostana*) rind, a byproduct of the fruit industry, has been reported to contain high levels of xanthones and polyphenols that exhibit strong UV absorbance and vibrant coloration [7–10]. Mangosteen dyes are mainly composed of prenylated xanthones, particularly α-mangostin, γ-mangostin and garcinones, which possess a xanthone core with phenolic hydroxyl and prenyl side groups [11]. These structural features contribute to their yellow-orange colour, antioxidant activity and strong affinity for fibres in natural dyeing applications [12–14].

Previous studies have explored its potential as a natural antioxidant and antimicrobial agent, but its application as a textile dye remains relatively underexplored. Recent works have investigated the use of fruit waste in dyeing textiles. For instance,

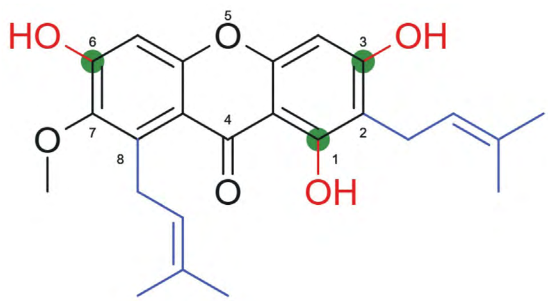


Figure 1: Chemical composition of mangosteen (Garcinia mangostana) pericarp (α-mangostin) [14]

Satyanarayana and Chandra (2021) reported that pomegranate rind extract could yield satisfactory colour strength on cotton when combined with mordants like alum and iron [15]. Similarly, Haddar et al. (2018) demonstrated that anthocyanin-rich extracts from red cabbage showed enhanced dyeability on silk and cotton under acidic conditions, although fastness properties were moderate without mordanting [16]. In a study by Prabhu and Teli (2014), tamarind seed and peel extracts were applied to cotton fabrics, with iron sulfate yielding the highest wash fastness among tested mordants [17].

These prior studies collectively underscore the importance of optimizing dyeing parameters such as pH, temperature, dye concentration and time, as well as the critical role of mordants in improving dye-fibre interactions and colour durability. Mordants, particularly metal salts, can form coordination complexes with natural dye molecules, enhancing their affinity to cellulose fibres [18–20]. Additionally, fixative agents such as alum and acetic acid have been employed to further stabilize dye-fibre bonds and improve fastness to washing and rubbing [21, 22]. Additional recent studies have emphasized the molecular mechanisms of dye–mordant interactions and the role of bio-based mordants (e.g., tannins and citric acid) in improving fastness and colour uniformity on cotton fabrics [23–25]. Furthermore, several eco-friendly coloration processes, including ultrasonic- and microwave-assisted dyeing, have been proposed to enhance dye uptake efficiency while reducing energy and water consumption [26–28]. These developments provide broader scientific context and reinforce the relevance of sustainable natural dye research.

Building upon such works, this study focuses on the extraction and application of natural dyes from mangosteen rind on cotton fabric. Using hot aqueous extraction, the study systematically investigates the effects of dyeing conditions including pH, temperature, concentration and time on colour development. The role of different mordants and post-dyeing fixatives is also evaluated in terms of their impact on colour strength, colour difference and wash fastness. Furthermore, changes in key fabric properties such as moisture regain, stiffness, air permeability and crease recovery are assessed to determine the practical implications of MGSR dyeing. This research contributes to the growing field of natural dye technology by identifying mangosteen rind as a potential sustainable dye source and proposing optimized methods for its effective use in cotton textile applications.

2 Experimental

2.1 Materials

Plain-woven 100% cotton fabric (120 g/m^2, purchased from Viet Thang Corporation, Vicotex) was used as the dyeing substrate. Mangosteen rinds (*Garcinia mangostana*) were collected from local markets in Ho Chi Minh city, Vietnam, cleaned, air-dried and ground into powder (Figure 1). Analytical-grade chemicals, including copper sulfate pentahydrate ($CuSO_4 \cdot 5H_2O$), iron sulfate heptahydrate ($FeSO_4 \cdot 7H_2O$), potassium aluminium sulfate dodecahydrate ($KAl(SO_4)_2 \cdot 12H_2O$), sodium chloride (NaCl) and acetic acid (CH_3COOH), were obtained from A.R. Chemicals, India. Distilled water was used throughout all procedures. The natural dye was extracted by boiling 100 g of MGSR powder in 1000 mL of distilled water at 90 °C for 60 min. The solution was filtered and stored in dark bottles at 4 °C for later use.

Figure 2: Fruit (left) and rind powder (right) of mangosteen (adapted and redrawn from xaxafruit.vn)

2.2 Dyeing process, mordanting and fixation

Cotton fabric samples (10 cm ´ 10 cm) were prescoured and dyed using the exhaust method with a liquor ratio of 1:20. The effects of dye concentration (20–100% v/v), dyeing pH (3–7), temperature (40–100 °C) and time (30–120 min) were studied. The temperature was increased from room temperature to the desired level at a heating rate of approximately 2 °C/min, and maintained for the required dyeing duration. The pH was adjusted using acetic acid or sodium carbonate. Mordanting was performed using pre-, meta- and post-mordanting techniques with $CuSO_4 \cdot 5H_2O$, $FeSO_4 \cdot 7H_2O$ and $KAl(SO_4)_2 \cdot 12H_2O$ at concentrations of 0.5–2.0% (w/v). Each mordanting process was conducted at 80 °C for 30 min under continuous stirring to ensure uniform treatment. For fixation, dyed fabrics were treated with 5% NaCl, 5% $KAl(SO_4)_2 \cdot 12\ H_2O$ or 5% CH_3COOH for 20 min at room temperature, then thoroughly rinsed with distilled water and dried at dried at 60 °C for 2 h in a hot-air oven before testing.

2.3 Evaluation methods

Colour strength (*K*/*S*) and colour difference (*ΔE*) values were calculated based on the spectrophotometric measurements performed using a Datacolor spectrophotometer. The UV-vis spectral analysis of dye extracts and dye-mordant interactions were conducted using a Yoke UV1200 UV-vis spectrophotometer to characterize the functional groups and absorption behaviour of the colorants. Washing fastness tests were carried out at 40 °C ± 2 °C using a Miele washer (Germany), and the results were evaluated according to ISO 105-C06 after one, two and four wash cycles, using grayscale ratings. In addition, the physical properties of the fabrics, including moisture regain (ISO 139), air permeability (ISO 9237), stiffness (ASTM D1388) and crease recovery (AATCC 66), were measured to assess structural and performance changes after dyeing.

3 Results and discussion

3.1 UV-vis spectral analysis of MGSR extract

The UV-vis spectra in Figure 3 show the absorbance behaviour of MGSR extract and its interaction with cotton fabric, both with and without copper sulfate as a mordant. The MGSR extract (NNO) exhibits a strong absorbance peak at around 300–320 nm, attributed to phenolic or flavonoid compounds, which are common in natural plant extracts. When MGSR is applied to cotton fabric (NNOF), the absorbance intensity decreases slightly, suggesting the partial adsorption or interaction of dye molecules with the fibre surface. When mordanting with copper sulfate mordant (NCUF), a noticeable increase in absorbance is observed in the same region, indicating the formation of coordination complexes between copper ions and MGSR constituents, which enhances dye uptake and stability on the fabric.

Beyond 320 nm, all three curves show a gradual decrease in absorbance, consistent with the typical behaviour of natural dyes, where main chromophoric absorption occurs in the UV range. Overall, the results demonstrate that mordanting with copper sulfate significantly enhances the interaction of MGSR extract with cotton fibres through chelation, thereby enhancing dye fixation and colour strength.

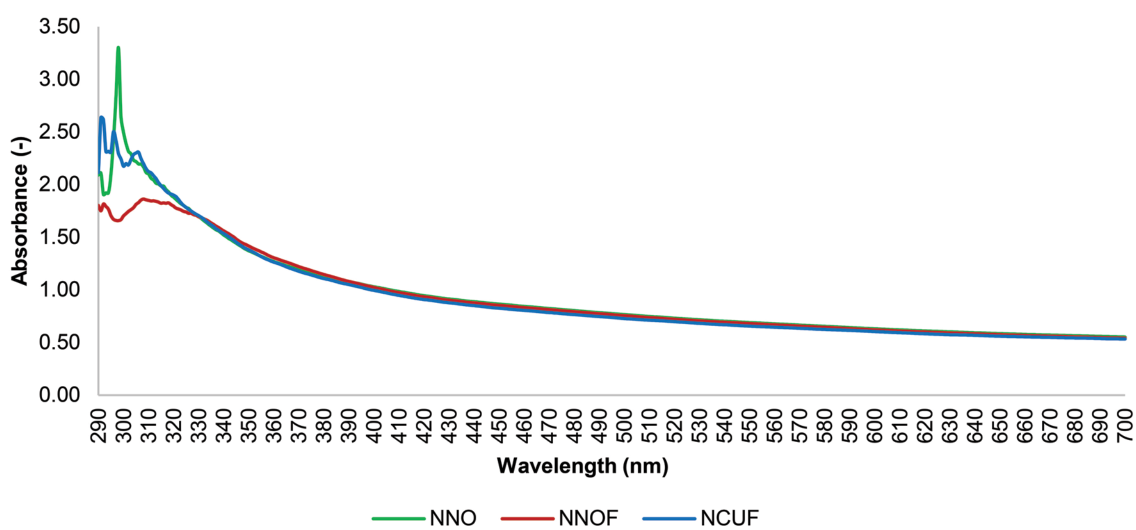


Figure 3: UV-vis spectra of MGSR extract (NNO), MGSR with cotton fabric (NNOF) and MGSR with cotton fabric and copper sulfate mordant (NCUF)

Figure 4 presents the UV-vis spectra of MGSR extract in the absence (NNO) and presence of different mordants: copper sulfate (NCU), potassium aluminium sulfate (NKA) and iron sulfate (NFE). The spectra reveal distinct variations in absorbance intensity and band shape, indicating that mordants significantly influence the optical properties of the extract. In the absence of mordant (NNO), the extract shows a broad absorption peak around 305–320 nm, characteristic of phenolic or xanthone compounds present in mangosteen rind. When copper sulfate (NCU), is added the absorbance intensity increases noticeably within this region, suggesting enhanced electronic transitions due to complexation between copper ions and active dye constituents, which improves chromophore stability. In contrast, the spectrum with potassium aluminium sulfate (NKA) displays a slightly lower absorbance, implying weaker coordination or limited complex formation. The spectrum with iron sulfate (NFE) shows a moderately broad band with intermediate intensity, indicating a different mode of interaction, likely involving hydroxyl or carbonyl coordination. Overall, copper sulfate proves to be the most effective mordant in enhancing the UV-vis absorbance of the MGSR extract, which can contribute to improved dye fixation and colour strength on textiles.

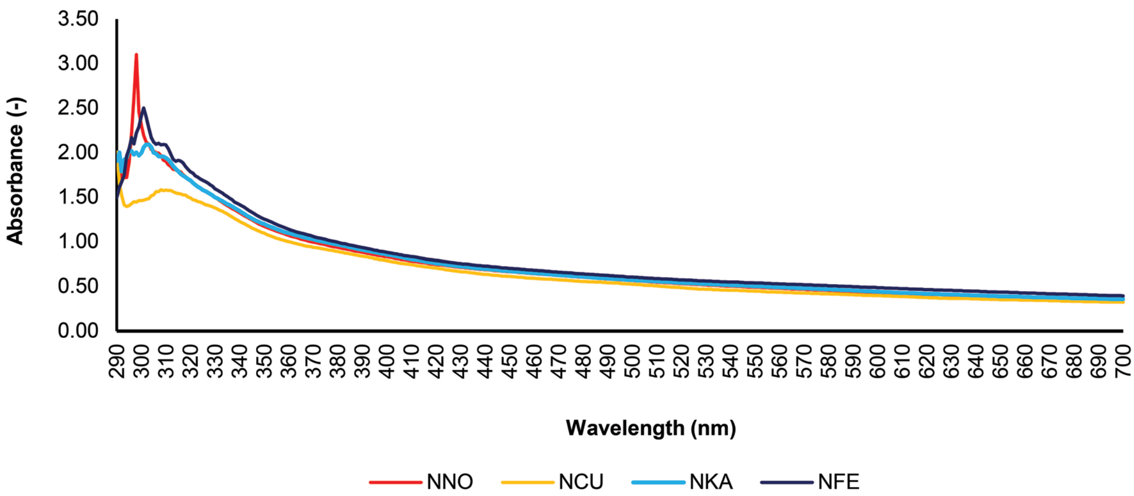


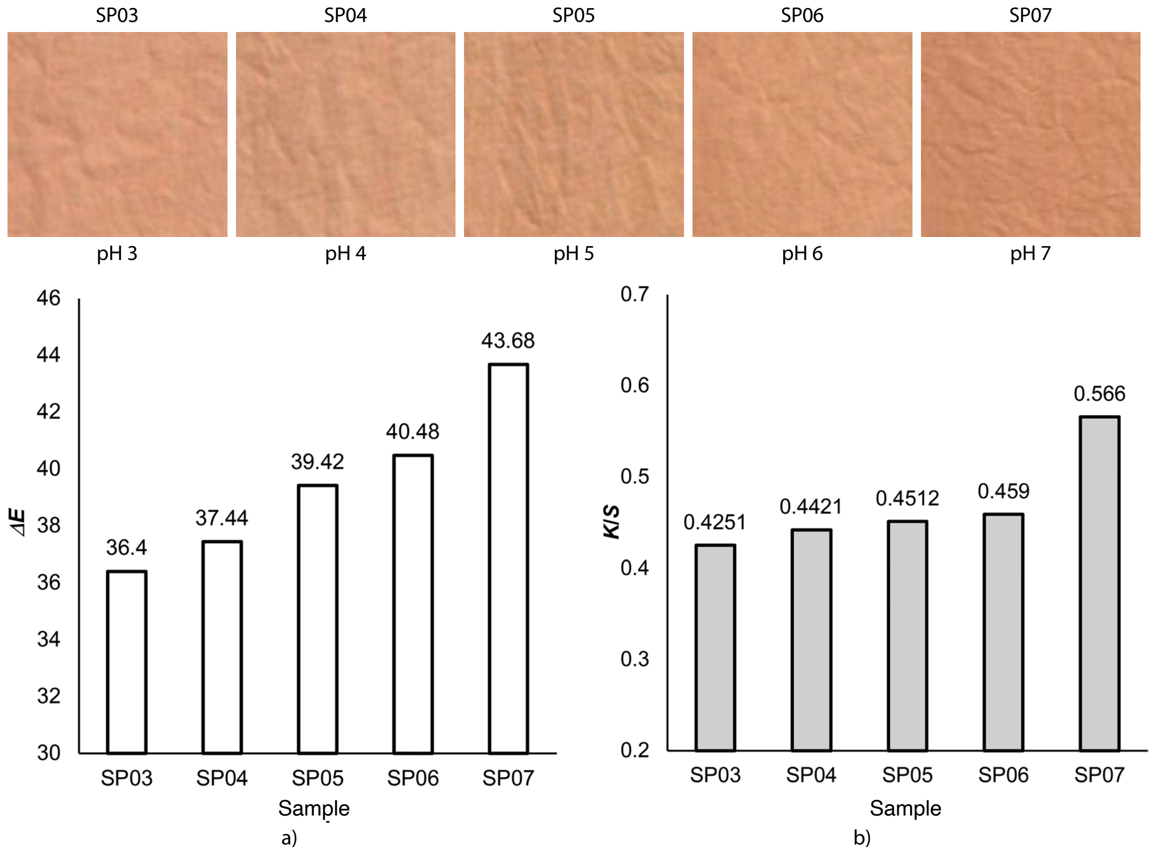
Figure 4: UV-vis spectra of MGSR extract in the absence of mordant (NNO), and in the presence of copper sulfate (NCU), potassium aluminium sulfate (NKA) and iron sulfate (NFE)

3.2 Effect of pH on dye uptake

Figure 5 illustrates the *K*/*S*, *ΔE* values and colorimetric parameters (*L**, *C**, and *h**) of cotton fabrics dyed with MGSR extract at varying pH levels from 3 to 7. The fabric images visually confirm that the colour becomes progressively darker and redder as the pH increases. The *K*/*S* values, which indicate dye uptake and colour strength, gradually rise from 0.4251 at pH 3 to 0.5660 at pH 7, showing enhanced absorption under near-neutral conditions. Similarly, the *C** values increase from 23.93 to 30.67 and the hue angle (*h**) shifts from 64.22° to 62.82°, suggesting higher colour saturation and a slightly deeper reddish tone at higher pH. The pH-sensitive behaviour of MGSR extract is likely related to the ionization and stability of phenolic or anthocyanin compounds, which are more reactive in less acidic environments. Adjusting the dye bath to near-neutral pH (6–7) can thus optimize the colour strength and stability of MGSR as a natural dye for cotton textiles.

3.3 Influence of dye concentration on colour strength and colour difference

The *K*/*S* and coloristic parameters (*L**, *C** and *h**) of cotton fabrics dyed with MGSR extract at various dilution ratios with water, ranging from 20/80 (SPC20) to 100/0 (SPC100), are presented in Table 1. The visual images and measured values show a clear trend of increasing colour depth as the concentration of MGSR extract increases. SPC20 was used as the reference sample, and all other samples were compared against it. The *K*/*S* values rise progressively from 0.3180 (SPC20) to 0.6936 (SPC100), indicating greater dye uptake and stronger coloration on the cotton fabric. This pattern is expected, as a higher MGSR/H_2O ratio provides more available dye



Sample	pH value	L*	C*	h*
SP03	3.0	70.16	23.93	64.22
SP04	4.0	69.69	24.90	65.67
SP05	5.0	69.44	27.49	66.44
SP06	6.0	69.23	28.79	65.76
SP07	7.0	66.59	30.67	62.82

Figure 5: a) K/S and b) ΔE values, together with a tabular representation of numerical values of coloristic parameters (L, C* and h*, are presented for cotton fabrics dyed with MGSR extract at pH 3 (SP03), 4 (SP04), 5 (SP05), 6 (SP06) and 7 (SP07)*

molecules to interact with the fibre surface. In this context, ΔE values were treated only as secondary indicators of visible colour change and were not used to interpret dye uptake, as they simply reflect the expected differences between samples with different dye concentrations. The discussion therefore focuses on the more meaningful coloristic parameters (*L**, *C** and *h**) and their trends with increasing MGSR concentration. As the MGSR concentration increased, *L** decreased from 73.51 to 63.90, indicating darker shades; *C** increased from 19.60 to 31.18, showing higher colour saturation; and *h** shifted slightly from 69.90° to 63.90°, suggesting a move toward a redder hue. These combined results clarify that the MGSR extract concentration strongly influences both the dye absorption (reflected by *K/S*) and colour appearance (*L*, C* and h**) of the cotton fabrics.

Table 1: K/S values and colour coordinates (ΔE, L, C* and h*) of cotton fabric dyed with MGSR extract at MGSR/H_2O dilution ratios (DR) of 20/80 (SPC20), 40/60 (SPC40), 60/40 (SPC60), 80/20 (SPC80) and 100/0 (SPC100)*

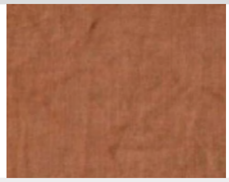
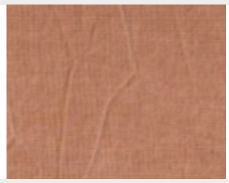
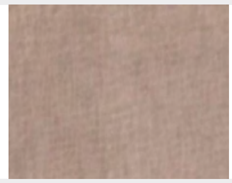
Sample	SPC20	SPC40	SPC60	SPC80	SPC100
DR	20/80	40/60	60/40	80/20	100/0
Photos					
K/S	0.3180	0.3689	0.4608	0.5542	0.6936
ΔE	-	4.32	7.87	12.38	15.36
L*	73.51	71.83	69.18	66.86	63.90
C*	19.60	23.55	26.07	29.85	31.18
h*	69.90	69.50	67.90	65.50	63.90

3.4 Role of mordants in dye fixation

The results presented in Table 2 show the *K/S* and *ΔE* values of cotton fabrics dyed with MGSR extract, with and without mordants, after multiple washing cycles. The mordants tested include potassium aluminium sulfate (SPKA), copper sulfate (SPCU) and iron sulfate (SPFE), while SPNO represents the sample without mordant. Initially, the unwashed fabrics show the highest *K/S* values, especially for SPCU (0.9488) and SPFE (1.0855), indicating enhanced colour depth due to the mordanting effect of transition metal ions. SPNO and SPKA exhibit lower *K/S* values of 0.5318 and 0.4898, respectively, suggesting that the absence or weaker complexation ability of the aluminium-based mordant results in less dye fixation. After one, two and four washing cycles, the *K/S* values decrease across all samples, indicating a gradual loss of colour due to washing. However, SPCU and SPFE retain higher *K/S* values than SPNO and SPKA, even after four cycles (0.5878 and 0.6196, respectively), demonstrating stronger dye-fibre binding and superior wash fastness. In contrast, SPKA drops to 0.2537, showing poor colour retention, likely due to the lower stability of the aluminium-dye complex.

The *ΔE* values increase with each washing cycle, reflecting noticeable colour differences. SPNO and SPKA exhibit the most significant *ΔE* values after four cycles (13.24 and 13.30), indicating substantial colour fading. On the other hand, SPCU and SPFE show lower *ΔE* values (9.50 and 8.54), confirming their better colour stability and resistance to washing. Overall, the results confirm that copper and iron sulfate mordants enhance dye uptake and the washing durability of MGSR-dyed cotton fabrics, while the aluminium-based mordant is less effective. This behaviour can be attributed to the higher coordination ability of transition metals, which form more stable complexes with phenolic components in the MGSR extract, resulting in improved colour fastness suitable for practical textile applications.

Table 2: K/S and ΔE values of cotton fabrics dyed with MGSR extract in the absence and the presence of different mordants after zero, one, two and four washing cycles

Fabric properties		**SPNO** Mordant: none pH = 5.95 ORP = 40.2	**SPKA** Mordant: $KAl(SO_4)_2 \cdot 12H_2O$ pH = 5.68 ORP = 55.5	**SPCU** Mordant: $CuSO_4 \cdot 5H_2O$ pH = 5.39 ORP = 72.7	**SPFE** Mordant: $FeSO_4 \cdot 7H_2O$ pH = 5.52 ORP = 64.7
Unwashed	a)				
	K/S	0.5318	0.4898	0.9488	1.0855
Washed (1 cycle)	a)				
	K/S	0.3935	0.3685	0.7186	0.7100
	ΔE	8.64	11.54	6.36	6.26
Washed (2 cycles)	*K/S*	0.3460	0.2584	0.6424	0.6464
	ΔE	10.64	12.64	8.48	7.56
Washed (4 cycles)	*K/S*	0.2725	0.2537	0.5878	0.6196
	ΔE	13.24	13.30	9.50	8.54

[a] Appearance of dyed fabrics

As illustrated in Figure 6, the *K/S* and *ΔE* values of cotton fabric dyed with MGSR extract were calculated for the samples treated with varying concentrations (0.5, 1.0 and 2.0 wt%) of $CuSO_4 \cdot 5H_2O$ as a mordant. As the mordant concentration increases from 0.5 wt% (SPCU005) to 2.0 wt% (SPCU020), there is a clear increase in *K/S* values, indicating higher dye uptake and fixation on the cotton fibres. Specifically, the *K/S* value rises from 1.0501 to 1.6172, confirming that a higher mordant concentration promotes stronger dye-fibre interaction and deeper coloration.

In contrast, the *ΔE* values (10.46–16.6) represent the overall colour difference among the samples (SPCU005, SPCU010 and SPCU020) with respect to the unmordanted sample SP100 and are used here to support the visual observation of more vivid colours, rather than as a direct indicator of colour strength. It is important to emphasize that the increase in ΔE by increasing the mordant concentration only indicates that the overall colour difference become larger, but by itself it does not show how the colour is changing (i.e. whether the shade becomes darker or lighter, more or less chromatic, or shifts in hue). This improvement can be attributed to the ability of the mordant to form coordination complexes with dye molecules and the fibre, thereby enhancing dye-fibre affinity. At higher concentrations, more binding sites are likely formed, which boosts colour strength and leads to a more intense shade. The visual fabric samples also reflect this trend, showing progressively deeper brown hues with increasing $CuSO_4 \cdot 5H_2O$ levels. Overall, increasing the mordant concentration effectively intensifies the dyed colour, while *ΔE* serves only as a measure of colour difference among samples.

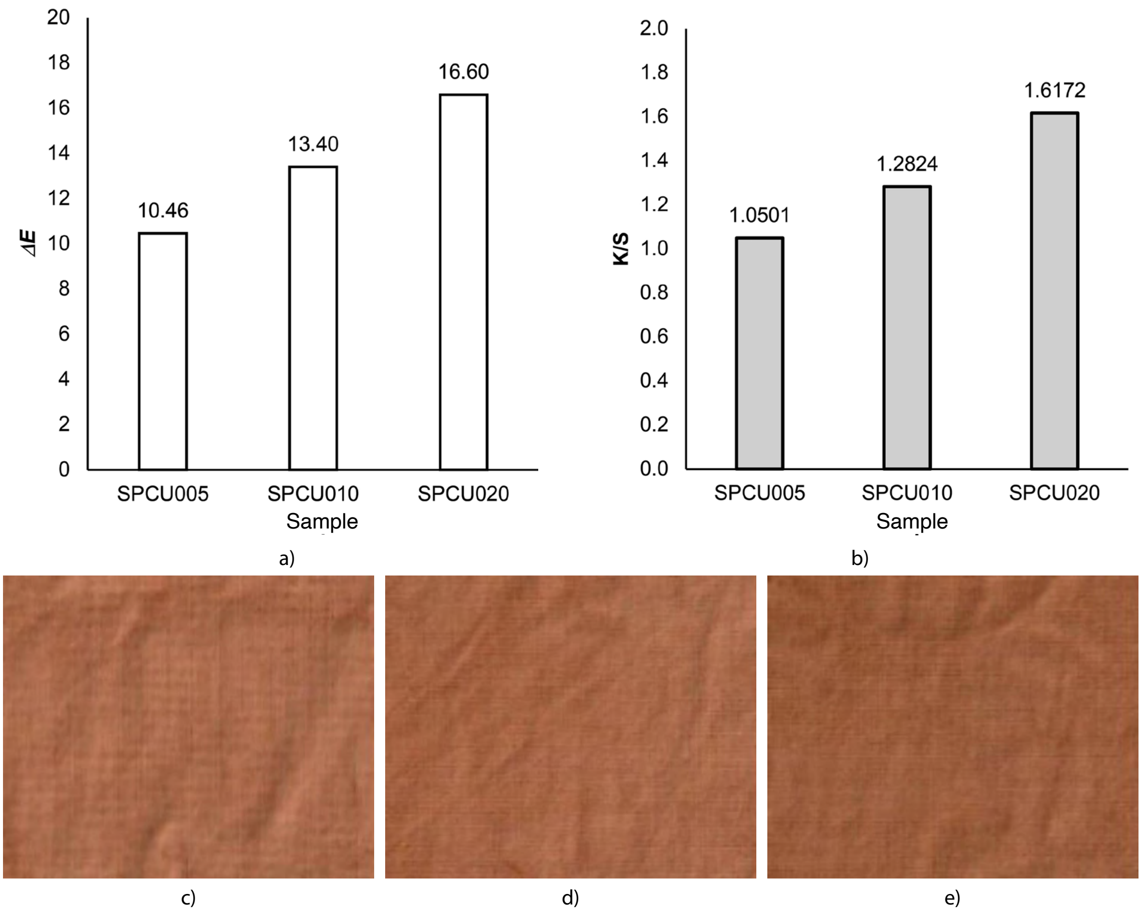


Figure 6: a) K/S and b) ΔE values of cotton fabric dyed with MGSR extract at c) 0.5, d) 1.0 and e) 2.0 wt% of $CuSO_4 \cdot 5H_2O$, denoted as SPCU005, SPCU010 and SPCU020, respectively

Figure 7 shows the *K/S* values at various dilution ratios (SP20 to SP100), both without mordant (NO) and with 1% wt of $Cu_2SO_4 \cdot 5H_2O$ as mordant (CU). As the MGSR concentration increases from SP20 to SP100, the K/S values also rise, indicating that a higher concentration of the dye extract leads to deeper coloration. Notably, SP100 (undiluted extract) achieves the highest colour strength, with a *K/S* value of 1.2504 (CU), compared to only 0.6936 (NO). This suggests that both dye concentration and mordanting play critical roles in improving colour yield. The copper mordant likely facilitates stronger coordination interactions between dye molecules and the cotton fibre, thereby improving dye uptake. Overall, the combination of high-extract concentration and Cu-mordanting provides the most optimal colour depth on cotton.

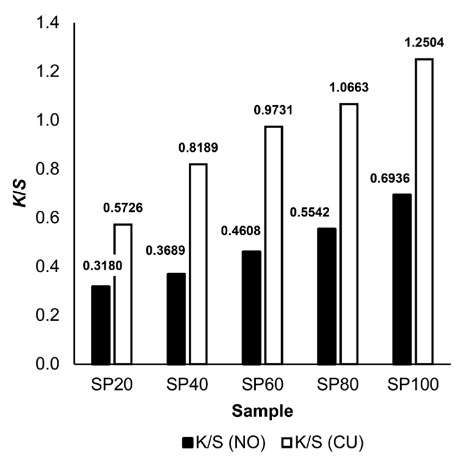


Figure 7: Change in K/S value of cotton fabric dyed with MGSR extract at various dilution ratios (SP20: 20/80, SP40: 40/60, SP60: 60/40, SP80: 80/20 and SP100: 100/0) as unmordanted (NO) and mordanted (N) with 1% wt of $Cu_2SO_4{\cdot}5H_2O$

3.5 Effect of dyeing temperature and time

Tables 3 and 4 present the dyeability of cotton fabrics dyed with MGSR extract, examining the influence of dyeing temperature and exhausting time, both in the absence (unmordanted) and presence (mordanted) of 1% $CuSO_4{\cdot}5H_2O$. As the dyeing temperature increases from 40 °C to 100 °C, the *K*/*S* values for both unmordanted and mordanted samples increase, indicating enhanced dye uptake at higher temperatures. For example, the *K*/*S* value of unmordanted fabric rises from 0.4536 at 40 °C to 0.9770 at 100 °C, while the mordanted samples show a more significant increase from 0.8255 to 2.0374. At higher dyeing temperatures, the colour of the fabric becomes visibly deeper, as reflected by the increase in *K*/*S* values. This trend demonstrates that higher temperatures enhance dye diffusion and fibre penetration, further supported by the improved bonding between dye molecules and cellulose fibres when a mordant is used.

Dyeing performance also improves with longer exhausting times. From 30 to 120 min, the *K*/*S* values increase for both treatments. For unmordanted fabrics, *K*/*S* improves from 0.5310 to 0.6094, while it improves from 1.2779 to 1.5830 for mordanted fabrics, thus confirming greater dye uptake. Meanwhile, unmordanted samples show higher perceptual colour variation than mordanted samples.

Table 3: Dyeability (K/S, ΔE) of cotton fabrics dyed with MGSR extract at 40 ˚C, 60 ˚C, 80 ˚C and 100 ˚C, both unmordanted and mordanted with 1% of $CuSO_4{\cdot}5H_2O$, using ST40 as the reference sample

Sample	Temp. (°C)	Unmordanted		Mordanted	
		ΔE	*K/S*	*ΔE*	*K/S*
St30 (Ref.)	40	-	0.4536	-	0.8255
St60	60	3.57	0.4889	4.12	0.9466
St80	80	6.71	0.5786	8.43	1.3386
St100	100	11.64	0.9770	14.22	2.0374

Table 4: Dyeability (K/S, ΔE) of cotton fabrics dyed with MGSR extract at 30 min, 60 min, 90 min and 120 min of exhausting time, both unmordanted and mordanted with 1% of $CuSO_4{\cdot}5H_2O$ (controlled sample is greige cotton), using St30 as the reference sample

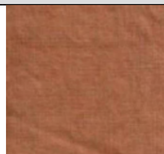
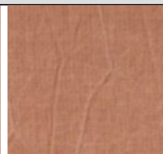
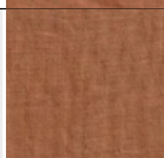
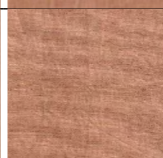
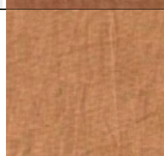
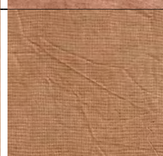
Sample	Exhausting time (min)	Unmordanted		Mordanted	
		ΔE	*K/S*	*ΔE*	*K/S*
St30 (Ref.)	30	41.60	0.5310	51.36	1.2779
St60	60	41.80	0.5313	51.50	1.2889
St80	90	42.68	0.5732	53.46	1.4347
St100	120	42.63	0.6094	54.48	1.5830

3.6 Combined effect of mordant and fixative treatment

Table 5 presents the *ΔE* values of cotton fabrics dyed with MGSR extract and mordanted with $CuSO_4{\cdot}5H_2O$, followed by treatments with or without fixative agents after zero and one washing cycle. The fixatives evaluated include sodium chloride (NaCl), potassium alum ($KAl(SO_4)_2{\cdot}12H_2O$) and acetic acid (CH_3COOH). *ΔE* represents the colour change, where a higher value indicates greater fading. For untreated fabrics (SPCUW), *ΔE* after one wash was 6.75, showing noticeable colour loss. Sodium chloride-treated samples (SPCUSC) exhibited slightly higher *ΔE* (6.39), implying limited effectiveness in wash fastness improvement. Although the *K*/*S* value (colour strength) of SPCUSC0 was the highest (1.15), its post-wash value decreased substantially, suggesting poor dye retention. Potassium alum (SP-

CUAW) demonstrated better performance, with a lower *ΔE* of 5.86, indicating improved wash fastness compared to no fixative or sodium chloride. The *K/S* values also decreased less dramatically, supporting its stabilizing effect on the dye. Surprisingly, acetic acid (SPCUAAW) resulted in the highest *ΔE* of 6.52, suggesting the least effective colour retention. Its low *K/S* values before and after washing further confirm weak dye fixation. Overall, potassium alum emerged as the most effective fixative among the three, providing relatively lower *ΔE* and better colour retention. Sodium chloride and acetic acid offered limited or no improvement over the untreated control. These results emphasize the importance of selecting appropriate fixatives to enhance the wash durability of natural dyes on cotton fabric.

Table 5: ΔE values of cotton fabric dyed with MGSR extract and mordanted with $CuSO_4{\cdot}5H_2O$, treated with or without fixative agents after zero and one washing cycle

Sample	Fixative agent	Photos of unwashed fabrics	Photos of washed fabrics one cycle	Unwashed	Washed one cycle	*ΔE*
				K/S		
SPCUW	None			1.08	0.73	6.75
SPCUSCW	Sodium chloride NaCl			1.15	0.78	6.39
SPCUPAW	Potassium alum $KAl(SO4)2{\cdot}12\ H_2O$			0.87	0.61	5.86
SPCUAAW	Acetic acid CH_3COOH			0.57	0.47	6.52

3.7 Physical properties of dyed cotton fabric

Table 6 exhibits the changes in physical properties of cotton fabric after dyeing with MGSR extract, compared to untreated fabric. The moisture increased by 10.58%, suggesting that MGSR-treated fabric has improved hydrophilicity. This could be due to the presence of hydrophilic functional groups in MGSR compounds, which enhance the fabric's ability to retain moisture. Air permeability slightly decreased by 3.35%, from 5.30×10^{-3} mm/s to 5.12×10^{-3} mm/s. This indicates that dyeing with MGSR extract may slightly reduce the fabric's porosity or alter the surface structure. However, the change is minimal and unlikely to significantly affect breathability. Stiffness showed a substantial increase of 99.08%, nearly doubling in value after treatment. This suggests that MGSR components may form deposits or bonds with the fibre surface, resulting in a stiffer fabric structure. While this may improve durability, it might reduce comfort and drape. Crease recovery decreased marginally from 68.05° to 67.00°, a change of just 1.54%. This implies that the dyeing process has little effect on the fabric's wrinkle resistance. Overall, MGSR dyeing alters the physical properties of dyed fabrics moderately. While the increase in moisture content and stiffness could be beneficial or detrimental depending on the application, the changes in air permeability and crease recovery are minimal, indicating that the fabric retains much of its original comfort and functionality after dyeing.

Table 6: Changes in the physical properties (moisture regain, air permeability, stiffness and crease recovery) of cotton fabric dyed with MGSR extract, compared to undyed cotton fabric

Fabric	Moisture regain (%)	Air permeability (mm/s)	Stiffness (mg.cm)	Crease recovery (°)
Untreated	5.2632	5.30×10^{-3}	344.24	68.05
Treated with MGSR extract	5.8201	5.12×10^{-3}	685.3	67
Change (%)	10.58	-3.348	99.08	-1.54

4 Conclusion

The use of MGSR extract as a natural dye for cotton fabric demonstrates promising results in terms of colour intensity, wash durability and sustainability. This study confirmed that mordanting with copper sulfate or iron sulfate enhances dye uptake and colour retention, while potassium alum provides better fastness among the tested fixatives. The optimal dyeing conditions were found at neutral pH, high temperature and extended dyeing time, all of which contributed to improved fabric coloration. Although MGSR-dyed cotton fabric showed increased stiffness, the changes in moisture regain, air permeability and crease recovery remained within acceptable limits. Overall, MGSR extract is a viable natural dye option for eco-friendly textile processing, especially when combined with appropriate mordants and fixatives to improve performance and durability.

Conflicts of Interest: The authors declare no conflict of interest.

Data Availability Statement: The datasets generated and analyzed during the current study, including experimental results, UV-vis spectra, and colorimetric data (L^*, a^*, b^* values) are publicly available on Zenodo at: https://doi.org/10.5281/zenodo.17873277 [29].

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