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Article

Infrared-assisted dyeing of cotton fabric using waste *Camellia sinensis* leaf extract

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Highlights

- Tea waste used as natural dye for cotton, supporting circular economy.
- IR dyeing consumed less water than traditional dyeing methods.
- IR dyeing improved K/S relative to conventional dyeing.
- Mordants gave varied shades with better wash, rub, and light fastness.
- FTIR confirmed polyphenol-fiber bonding enabling stable coloration.

Abstract: The textile coloration industry often discharges dye-rich effluents that pose both environmental and health risks. To address these risks, research on the use of bio-based dyes is ongoing. This study reports on the sustainable extraction and dyeing of cotton fabric using an extract from Camellia sinensis (Tea) leaves waste. The dyeing process utilized infrared (IR) dyeing, which reduces water consumption in the dye solution and uses heat for dye fixation instead of electrolytes, thereby contributing to sustainable dyeing. The optimal dyeing process was carried out at 60 °C for 60 min, both with and without mordants. Tannic acid, aluminium potassium sulphate (alum) and ferrous sulphate were selected as affordable and less toxic mordant. The unmordanted sample exhibited the highest colour strength (K/S = 29.85), while while ferrous sulphate mordanted sample confers the best color fastness overall. Mechanical analysis indicated an increase in bursting strength of 27% in the unmordanted dyed fabric compared with the raw fabric, along with improved drapability, while air permeability decreased by 6.8%. The scanning electron microscopy (SEM) image confirms the dye particles within the cotton fabric, and Fourier Transform Infrared Spectroscopy (FTIR) analysis confirms the presence of polyphenolic and aromatic groups responsible for dye-fiber interaction.

Keywords: Natural dye; aqueous extraction; cotton fabric; IR dyeing; mordant; colour performance

1. Introduction

Bangladesh, the world's second-largest apparel exporter, relies heavily on its dyeing factories to support its thriving textile industry. However, dyeing factories are among the most polluting sectors within the textile industry [1], primarily due to the use of synthetic dyes that pose serious environmental and health hazards. Wastewater from such factories can exhibit BOD of 200–400 mg/L, COD of 800–2000 mg/L, pH 7–11, and TDS of 500–3000 mg/L [2,3], posing serious threats to aquatic ecosystems and human health if discharged untreated. This pollution has severe consequences for biodiversity [4]. Moreover, due to the rapid expansion of textile industries in Dhaka, Narayanganj, and Gazipur, six rivers in these districts have already been declared biologically dead [5]. Additionally, the presence of synthetic dyes in surface and subsurface water makes them visually unappealing and causes waterborne diseases such as dermatitis, mucous membrane infections, nasal septum perforation, and respiratory tract irritation [6]. To address this issue, adopting natural dyes as an alternative to hazardous synthetic dyes presents a sustainable and eco-friendly solution [7,8]. Sustainability refers to the use of less toxic or bio-based materials and the consumption of less energy or fewer environmental resources [9,10]. In this context, researchers have conducted experiments to extract natural colors from various sources, including waste onion peel [11], black rice [12], gardenia yellow [13], tulsi leaves [14], kinhshuk plants [15], dyer's bugloss roots [16], Coral Jasmine flower [17], and neem leaves [18]. Furthermore, sustainable dyeing of methyl blue has been investigated using green methods such as supercritical carbon dioxide and microwave-assisted processes [19]. Plant-based essential oils including eucalyptus, clove, mint, and neem have been applied as antimicrobial finishing agents for cellulosic fabrics [20]. Photocatalytic degradation of textile dyes [21], rare earth element-doped nanocomposites [22], has shown improved dye degradation, offering a sustainable approach for textile coloration.

Tea leaves, a source of natural dye, are widely available in Bangladesh, a leading tea producer and consumer. In 2020, Bangladesh's annual tea production was 86.39 million kilograms [23], with consumption reaching 84 million kilograms in 2021 [24]. This results in a large amount of tea waste, which contains valuable chemical compounds that could be harnessed for natural dyeing purposes. The composition of tea leaves consists of various components such as polyphenols (including catechins), caffeine, amino acids, carbohydrates, flavonoids, polysaccharides, and fluorine [25]. The chemical composition of tea can vary depending on factors such as weather, soil, and temperature differences in the growing region [26]. Flavonols, polyphenols, flavones, isoflavones and anthocyanins are thought to contribute to the colour and taste of a tea's infusion. During oxidation, flavanols are converted into theaflavins and thearubigins, shown in **Figure 1**, which are the compounds responsible for the dark color and robust flavors found in oxidized tea [27]. Flavanols contain hydroxyl groups that interact with mordants during the mordanting process [28]. making them easily mordantable dyes. Several studies have explored the tea leaf waste dye both with and without the mordanting method. One study focuses on extracting dye powder from green tea leaf waste and using it for batch dyeing without mordants, resulting in a dark brown color [29]. Another study investigates the use of tea leaves for natural dyeing of cotton, wool, and silk fabrics at low temperatures (40 °C) with metal mordants [30].

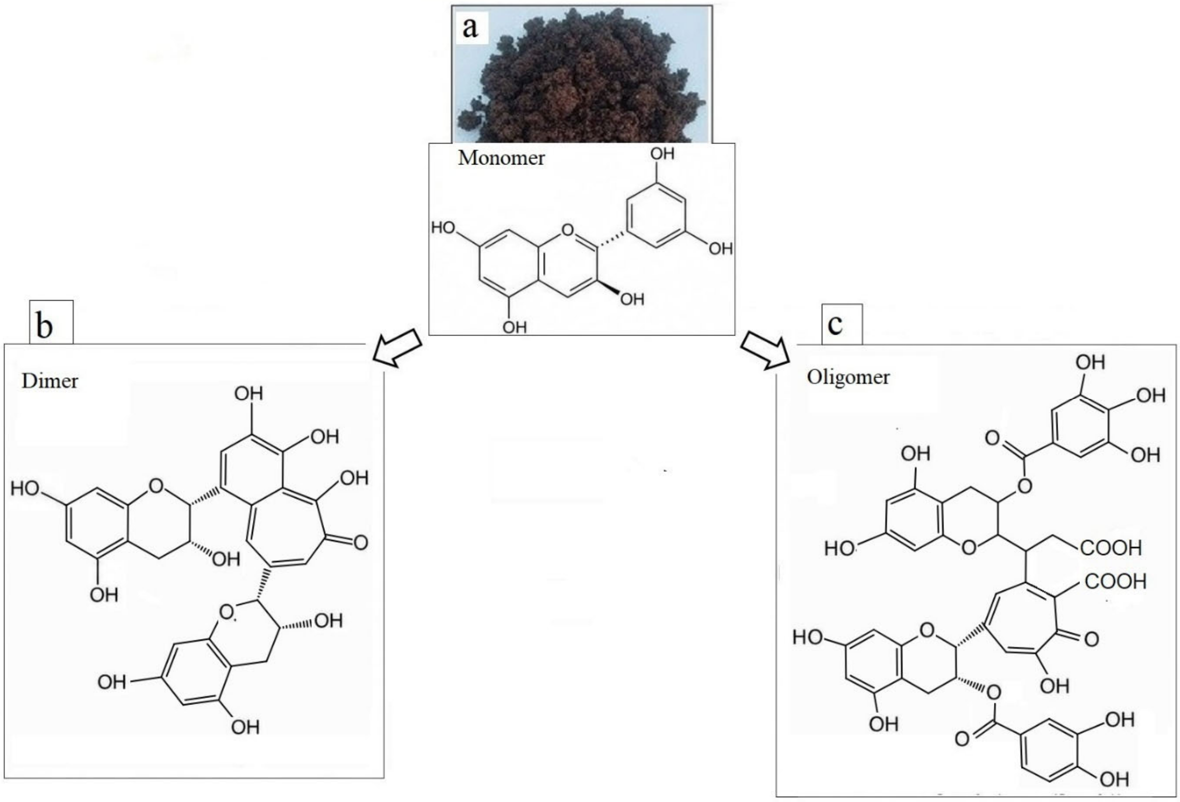

Figure 1. Color components in tea leaves, (**a**) flavanols, (**b**) theaflavins and (**c**) thearubigins.

Several other studies have explored tea waste as a natural colorant for textile dyeing and printing. The microwave-assisted extraction from powdered tea waste to dye bio-treated silk fabrics [31], methanol/water solvent-assisted extraction of tea leaves dye for dyeing mulberry silk fabrics using IR dyeing [32], aqueous extracts of tea waste to dye jute packaging fabrics using conventional methods [33], water or solvent-assisted extraction followed by exhaust dyeing on bamboo fabrics [34], methanol-assisted extraction of tea waste to dye wool and silk fibers via exhaust dyeing, noting a higher dye affinity for wool compared to silk [35], water-assisted extraction from waste tea bags, combined with fabric cationization using 3-chloro-2-hydroxypropyl trimethyl ammonium chloride, achieving 88.6% dye uptake and a 6.63 colour strength with good colour fastness properties [36], water-assisted extraction of black tea used with metal mordants in conventional dyeing achieved the highest depth of shade 2.71 for cotton, 3.9 for jute [37], water-assisted red tea extraction to dye chitosan pre-treated cotton fabric, which enhanced dye uptake and color performance [38], tea leaves with eco-friendly mordants for sustainable textile dyeing [39], black tea waste as a batik dye on cotton fabrics [40].

The abovementioned studies reveal that the dyeing of cotton fabric with tea leaf extract has primarily employed conventional dyeing techniques, which typically require a high material-to-liquor ratio of up to 1:50, resulting in significant water consumption and increased chemical usage. In contrast, IR dyeing technology operates at a lower material-to-liquor ratio of 1:10, reducing water consumption. The infrared radiation penetrates the fabric, generating uniform heating within the fiber matrix, which enhances dye molecule mobility and promotes deeper diffusion into cellulose fibers. This internal heating also accelerates the formation of stable bonds between the dye and hydroxyl groups of cellulose, improving fixation efficiency. Additionally, the process eliminates the need for electrolytes and reduces overall energy consumption due to rapid and targeted heat transfer [41,42].

Despite the potential benefits of IR dyeing, its application to cotton fabrics using tea leaf waste extract has not been reported in the literature. This study introduces a novel approach combining tea leaf waste-derived natural dye with infrared dyeing technology to develop a water- and energy-efficient dyeing process. The study primarily focuses on the optimization of dyeing time and temperature based on K/S values to achieve maximum dye uptake and fixation in IR dyeing. The color strength and color fastness properties of the dyed fabrics are then evaluated and a comparison with conventional dyeing methods is provided.

2. Experimental details

2.1. Materials and equipment

100% cotton single jersey knit fabric of 120 gm/m^2 (GSM) was collected from local textile mills in Dhaka, Bangladesh. Tea leaf waste was collected from a local tea stall in Dhaka, Bangladesh. The mordants, ferrous sulphate and alum were sourced from Merck (Darmstadt, Germany) and tannic acid was sourced from Luba Chemie (Mumbai, India). The dyeing experiments were conducted using an IR laboratory dyeing machine supplied by Labrotex (IR-12 SM), Taiwan.

2.2. Methodology

2.2.1. Extraction of dye

After being consumed as a tea drink, the collected tea waste was dried under sunlight for 72 ± 2 h. 30 g of dried tea leaf waste was then combined with 600 mL of distilled water. The mixture was heated at 60 °C for 1 h covered with aluminium foil paper to prevent evaporation. The temperature of the gas burner was kept at 60 °C to prevent the degradation of dye molecules at higher temperatures [43]. The resulting extract was filtered using Whatman filter paper to separate the tiny tea leaf particles and stored at 4 °C to inhibit unwanted bacterial growth. **Figure 2** illustrates the sequential process of dye extraction from tea leaf waste.

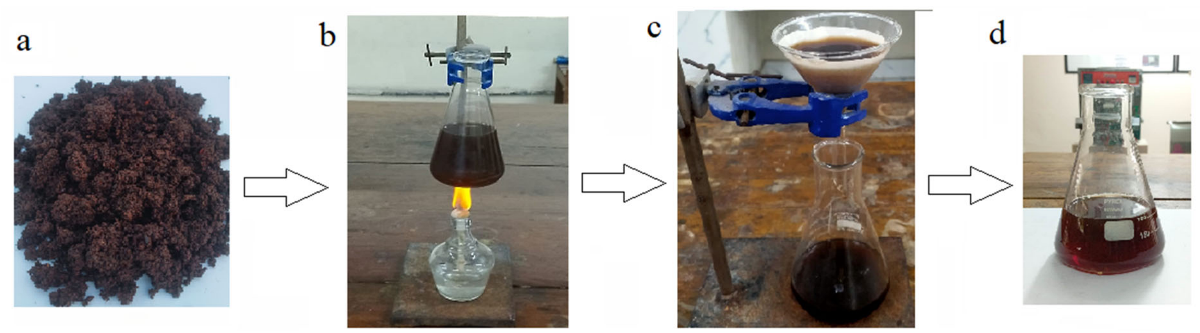

Figure 2. Dye extraction procedure: (**a**) tea leaves wastage, (**b**) heat-induced aqueous extraction, (**c**) filtering process, and (**d**) extracted dye solution.

2.2.2. Mordanting of cotton fabric

In this study, pre-mordanting was carried out. Three cotton fabric samples were immersed in separate beakers containing 2% ferrous Sulphate, 15% alum and 15% tannic acid with a 1:20 material-to-liquor ratio. The samples were left to soak for 48 h at 25 °C. One fabric sample was set aside without mordanting for comparison.

2.2.3. Dyeing of cotton fabric

The dyeing was initially carried out without mordants by varying the time (40, 50, 60, 70, 80 min) and temperature (50 °C, 60 °C, 70 °C, 80 °C, 90 °C) as illustrated in **Figure 3**. The dyeing at 60 °C for 60 min produced the highest color strength (K/S value). Based on these findings, subsequent dyeing of mordanted samples was conducted under the same optimal conditions of 60 °C for 60 min.

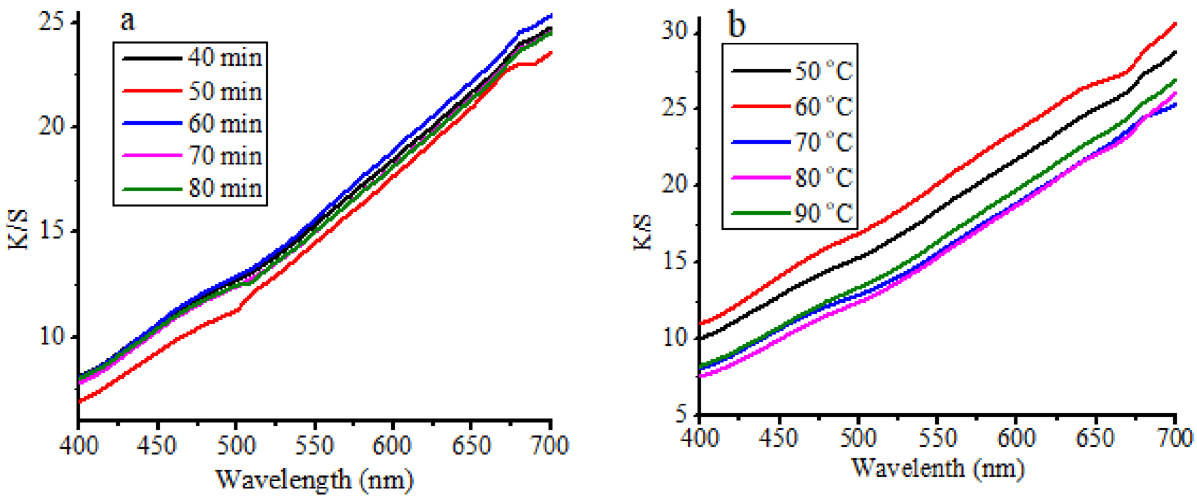

Figure 3. K/S graph as a function of (**a**) dyeing time and (**b**) dyeing temperature.

The material-to-liquor ratio was kept 1:10 and the dyeing was completed in a slightly acidic medium, keeping the pH at 5. **Figure 4** demonstrates the dyeing process schematically.

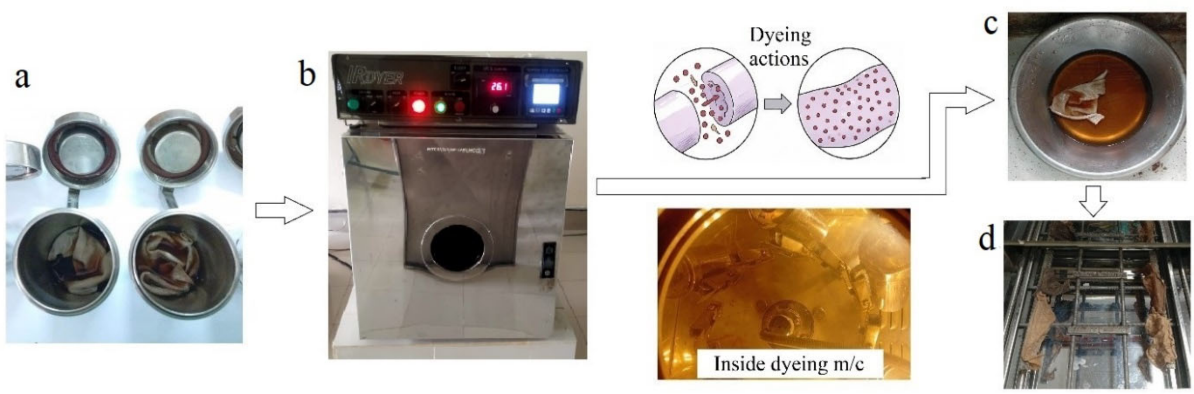

Figure 4. IR-assisted dyeing method, (**a**) Dye pot, (**b**) IR dyeing m/c, (**c**) washing after dyeing, and (**d**) curing.

According to the dyeing approach, the dyed samples with and without mordants were designated as DS1-DS4 based on their treatment conditions. Specifically, DS1 represents the fabric dyed with only tea-leaf extract, DS2 corresponds to tea-leaf extract with tannic acid as mordant, DS3 refers to tea-leaf extract with alum, and DS4 denotes tea-leaf extract with ferrous sulphate.

2.3. Measurement and characterization

2.3.1. Mechanical characterization

The strength, drape and breathability of the cotton single jersey fabrics were evaluated to determine the impact of the dyeing and mordanting processes on fabric performance. The bursting strength of the fabrics was measured according to ASTM D751-18 using a ball bursting system (Titan 10). The drape coefficient was determined following ISO 9073-9:1998 using a Cusick Drape Tester (SDL Atlas M227, Manchester, UK). The air permeability (breathability) of the fabrics was measured in accordance with ASTM D737 using a Shirley air permeability tester with a pressure difference of 200 pascal.

2.3.2. Colour strength and color difference

The colour strength and CIE Lab values of the dyed cotton knitted fabric samples were recorded using the Spectrophotometer 1050 (Datacolor, Lucerne, Switzerland) under illuminant D65 at a 10° observer angle. The colour strength refers to the K/S value, which was determined based on the Kubelka-Munk theory using the following **Equation (1)** [44], and the color difference was calculated using **Equation (2).** Where K is the absorption coefficient, R is the reflectance of the dyed sample, and S is the scattering coefficient [45].

$$\text{Color strength } \left(\frac{\text{K}}{\text{S}}\right) = \frac{(1-R)^2}{2R} \tag{1}$$

$$\text{Colour difference } (\Delta E^*_{ab}) = \sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2} \tag{2}$$

where, ΔE^* represents the total color difference on the CIE lab 2diagram, ΔL represents the difference in lightness/darkness value, Δa represents the difference on the red/green axis and Δb represents the difference on the yellow/blue axis.

2.3.3. Colour fastness performance

Color fastness refers to the resistance of the dyed samples to various external factors like wash, rubbing, perspiration, light, etc. that may cause fading. The color fastness to washing includes both color fading and color staining on adjacent fabrics, assessed using a greyscale according to ISO 105-C06 [46]. A fabric sample (14 cm × 12 cm) was sewn together with a multi-fiber fabric of the same dimensions on all four edges. The specimen was then washed in a gyro wash machine for 30 min at 60 °C using a 4 g/L detergent and 1 g/L soda ash, along with 10 steel balls, maintaining a 1:50 fabric-to-liquor ratio. The color fastness to rubbing was evaluated using a greyscale in accordance with ISO 105-X12:2002 [47]. Fabric samples (5 cm × 5 cm) were placed on the crockmeter's bed, while a white-bleached sample of the same size was positioned on the crockmeter's finger and pressed against the test fabric for 10 s over 10 cycles. The color fastness to light was assessed following ISO 105-B02:2014 [47]. Fabric specimens (3 cm × 3 cm) were positioned alongside a black reference thermometer in the same plane and orientation. The samples were exposed for 40 h at a standard black temperature of (47 ± 3) °C and a relative humidity of 40%. In accordance with ISO 105 E04: 201, colour fastness to perspiration was assessed in both alkaline and acidic conditions. The samples were divided into 15 × 4 cm pieces. To assess colour staining, multifiber fabric of the same size was stitched at each sample. The color fastness to washing, rubbing and perspiration was evaluated using a grey scale rating 1 (very poor) to 5 (excellent) while the color fastness to light was evaluated using a blue wool scale rating 1 (very poor) to 8 (excellent).

2.3.4. SEM analysis

SEM was used to analyse the surface morphology of both dyed and undyed samples. The SEM images were captured with the JSM-6610LV (JEOL, Japan Electron Optics Laboratory, Tokyo, Japan) at an accelerating voltage of 5.0 kV. SEM uses electrons with activated light emission energy to generate a range of signals from the surface of the samples [48].

2.3.5. FTIR

FTIR was used to find the existence of free functional groups in both dyed and undyed samples. PerkinElmer FTIR spectrometer (Waltham, MA, USA) was employed to measure the FTIR spectra and Spectrum software (version 10.7.2) was used to analyse the data. The operational parameters encompassed a wavelength range of 400–4000 cm^{-1}, 32 scans per sample, with a resolution of 4 cm^{-1} [49].

3. Results and discussions

3.1. FTIR analysis

The FTIR spectra of the tea leaves extract and dyed samples are presented in **Figure 5**. The FTIR spectrum of the tea leaves extract reveals key functional groups present in its composition. A distinct peak at 1035 cm^{-1} is attributed to C-O stretching in amino acids [50], while the presence of an alkane is suggested by the C-H stretching vibration observed at 2919 cm^{-1} [51]. A strong peak at 1624 cm^{-1} suggests the presence of C=C stretching in aromatic rings and C=O stretching in polyphenols [51]. Additionally, a broad band at 3291 cm^{-1} corresponds to O-H stretching modes, characteristic of polyphenols. This suggests the components of tea leaves in the extract [52].

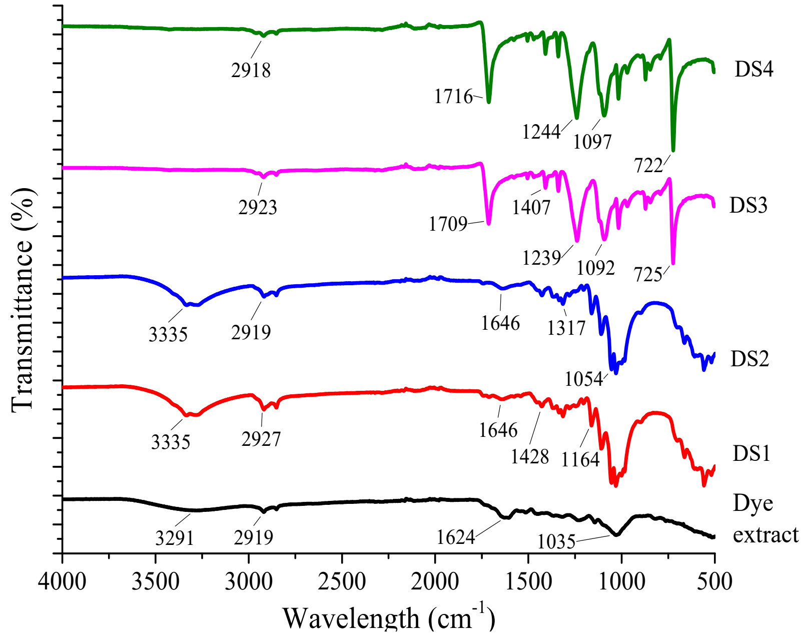

Figure 5. FTIR spectra of dyed samples: (**a**) DS1, (**b**) DS2, (**c**) DS3, and (**d**) DS4.

The FTIR spectra among dyed samples represent notable differences due to mordanting. The fabrics DS1 and DS2 show a broad cellulosic O-H stretching band at 3335 cm^{-1} with a minor shift, along with C-H stretching at 2927 cm^{-1} and 2919 cm^{-1}, and C=C stretching in aromatic rings at 1646 cm^{-1}. The peak at 1164 cm^{-1} represents the possibility of C-O stretching in esters, and 1428 cm^{-1} represents the possibility of C-H bending in the methyl group [53]. For fabric DS3 and DS4, shifts and intensity variations are observed, particularly in the 1600–1700 cm^{-1} and 1000–1300 cm^{-1} regions, indicating interactions between metal ions and polyphenolic compounds. The peaks at 1092 cm^{-1} and 1097 cm^{-1} represent C–O stretching in amino acids. The C-H stretch in alkane and O-H stretch in carboxylic acid appear at 2923 and 2918 cm^{-1}, respectively [50,51]. A band at 1709 cm^{-1} and 1616 cm^{-1} indicates the possibility of a carboxylic acid group. These spectral changes suggest the possible interactions between mordants and tea leaves extract, which correlates with the observed dyeing and mechanical performance. Stronger intermolecular interactions, particularly in DS3, suggest improved dye fixation and enhanced bursting strength, whereas variations in DS2 and DS4 indicate the mordant-induced chemical effects that may contribute to reduced mechanical performance.

3.2. SEM analysis

The morphological changes in cotton knit fabrics due to the tea waste liquor dyeing technique were analysed in **Figure 6**. Compared to the dyed samples, the raw cotton fabrics (a and b) exhibited a noticeably smoother and more refined surface. In contrast, the dyed organic cotton fabrics (c and d) displayed irregular surface morphology at the microscale, likely resulting from the interaction between dye molecules and fibers during the dyeing process [54]. The observed roughness suggests surface modification after dyeing. The absence of noticeable dye agglomeration suggests a relatively uniform distribution of dye on the fabric surface. This interpretation, supported by increased fabric weight after dyeing and reduced air permeability due to partial filling of inter-fiber spaces, aligns with FTIR characteristic peaks associated with interactions between dye molecules and cellulose chains.

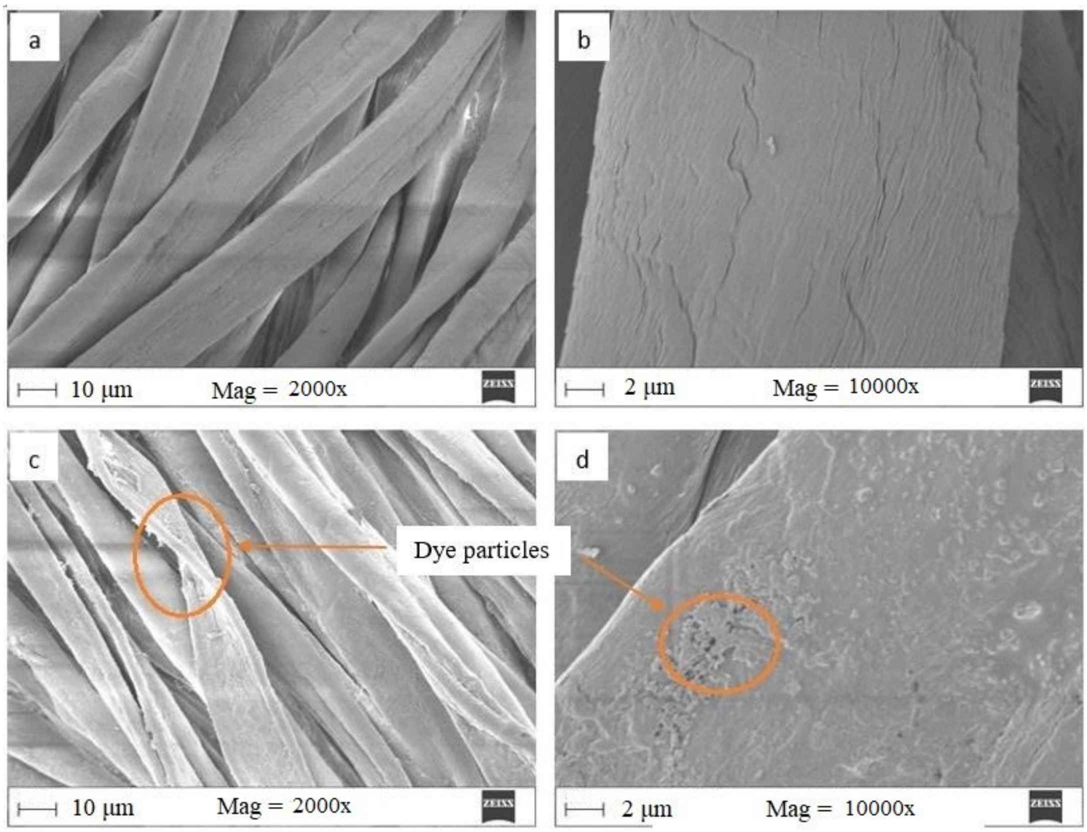

Figure 6. SEM images of (**a**,**b**) raw fabrics at magnification of (**a**) 2000× and (**b**) 10000×, and (**c**,**d**) dyed fabrics at (**c**) 2000× and (**d**) 10000×.

3.3. Mechanical performance

The strength, drapability and breathability performance of the fabrics dyed with and without mordants are presented in **Table 1**, in comparison with the undyed fabric, to evaluate the performance changes resulting from IR irradiation.

Table 1. Mechanical performance of the fabrics before and after dyeing.

Description	Raw fabric	DS1	DS2	DS3	DS4
Bursting strength (N) (SD)	181.51 (3.23)	231.03 (2.64)	39.13 (3.86)	219.48 (3.31)	178.11 (3.97)
Drape co-efficient (SD)	0.281 (0.022)	0.246 (0.019)	0.238 (0.025)	0.232 (0.028)	0.221 (0.031)
Air permeability ($cm^3/cm^2/s$) (SD)	220 (4.05)	205 (2.24)	192 (2.89)	198 (3.09)	185 (2.93)
Pre-dyeing weight (gm) (SD)	-	2.542 (1.05)	2.529 (0.83)	2.468 (0.95)	2.510 (0.98)
Post-dyeing weight (gm) (SD)	-	2.515 (0.99)	1.638 (0.96)	2.241 (0.88)	2.117 (1.46)

SD—Standard deviation.

The bursting strength of the raw fabric varied notably after dyeing, with DS1 and DS3 showing improved strength, likely due to enhanced hydrogen bonding between cellulose fibers and tea polyphenols, with additional reinforcement in DS3 from metal-tannate complexes formed between alum (Al^{3+}) and tea tannins. DS2 showed slightly lower strength, possibly due to partial hydrolysis of cellulose caused by the acidic tannic acid mordant, while DS4 exhibited lower strength, likely from oxidative degradation of cellulose induced by Fe^{2+} ions. The weight of the samples before and after dyeing was also examined to further support the observed changes in strength. Sample DS1 showed a weight gain due to dye absorption, whereas DS2, DS3, and DS4 exhibited weight loss, likely due to the detrimental effects of the mordants. Despite this, DS3 still demonstrated improved strength, which may be attributed to the formation of strong metal complexes among the fiber, tea polyphenols, and the mordant [55].

The drape coefficient gradually decreased from the raw fabric to DS4, indicating improved flexibility and softness after dyeing. This behaviour may result from fiber swelling and the presence of tea extract constituents that act as surface lubricants, reducing inter-fiber friction. Meanwhile, air permeability slightly decreased in all dyed samples, suggesting a minor densification of the fabric structure caused by fiber swelling and deposition of dye-mordant complexes within the inter-fiber spaces. Despite this reduction, the air permeability values remained within a comfortable range for apparel applications.

3.4. Shading effect after dyeing

The samples of the cotton fabrics dyed both with and without mordants are presented in **Figure 7**. It highlights the shading effects resulting from the use of mordants in combination with tea leaf extracts. The fabric DS1 and DS3 exhibited a light brown shade, while the fabric DS2 produced a dark brown shade. The fabric DS4 developed a dark grey shade. The variation in shades is attributed to the mordanting effect on the fabric.

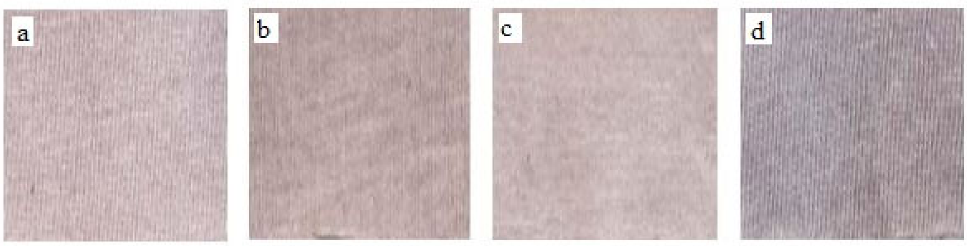

Figure 7. Shades of dyed samples—(**a**) DS1, (**b**) DS2, (**c**) DS3 and (**d**) DS4.

3.5. Color coordinates, color strength and color difference

The colour co-ordinates according to the colour spaces under the illuminant D65 for lightness/darkness (L*), red/green axis (a*), yellow/blue axis (b*), chroma (C*) and hue (h^*) and the colour difference for the dyed sample with and without mordants are presented in **Tables 2** and **3**.

Table 2. Color coordinates of dyed samples with and without mordants.

Sample ID	CIE lab values				
	L*	**a***	**b***	**C***	**h***
DS1	65.60	5.60	16.59	17.51	71.35
DS2	64.36	4.38	12.59	13.33	70.81
DS3	75.39	3.07	12.85	13.21	76.57
DS4	56.73	2.79	11.12	11.47	75.89

The L* values indicate that DS3 is the brightest sample, while DS4 is the darkest. The b* values are highest for DS1, showing a stronger yellow component, whereas DS4 has the lowest, indicating a more muted yellow presence. DS1 is the most vivid, while DS4 is the least. Finally, the hue angle is fairly similar across all samples, suggesting they all fall within a similar color range with minor variations.

The colour strength curves of the dyed samples with and without mordants are presented in **Figure 8**. The colour strength values of DS1, DS2, DS3, and DS4 were found to be 29.85, 27.88, 28.64, and 22.68, respectively, in the visible region. A reduction in colour strength was observed compared to the unmordanted sample, which could be attributed to the formation of dye-metal complexes leading to precipitation. Among the mordants, ferrous sulphate, being a strong metal complex-forming agent, exhibited the lowest K/S value. The greater color strength represents better depth of shade [56]; hence, the fabric DS1 represents the greatest depth of dyed shade.

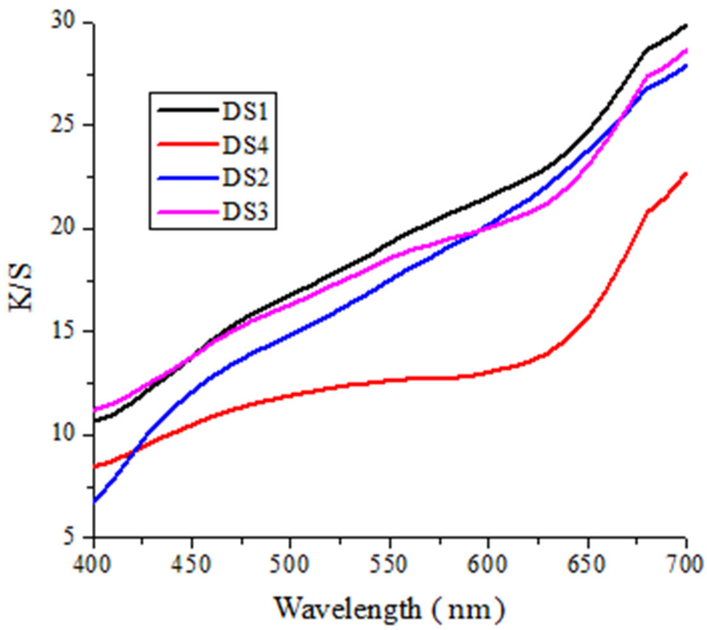

Figure 8. Colour strength value of dyed samples with and without mordants.

Table 3. Color difference of dyed samples with and without mordants.

ID	Illuminants/ observation angle	Colour difference						Metamerism index
		DL*	Da*	Db*	DC*	DH*	CMC DE	
DS1	Reference Sample							
DS2	D65/10° F02/10° A/10°	9.78 9.49 9.30	−2.53 −1.68 −2.87	−3.74 −4.26 −4.50	−4.30 −4.47 −5.29	1.38 0.98 0.66	5.16 4.82 4.95	1.29 1.22
DS3	D65/10° F02/10° A/10°	−1.24 −1.49 −1.61	−1.22 −0.77 −1.78	−3.99 −4.57 −4.38	−4.17 −4.64 −4.71	−0.14 −0.10 −0.41	2.75 2.93 2.94	0.75 0.69
DS4	D65/10° F02/10° A/10°	−8.87 −9.24 −9.52	−2.80 −1.80 −3.66	−5.47 −6.27 −6.36	−6.04 −6.48 −7.32	1.12 0.74 0.55	5.50 5.51 5.83	1.14 1.02

The sample DS2 represents lighter with moderate color shifts, while DS3 darkens slightly with a noticeable shift toward blue (Δb^* negative) but smaller perceived differences. DS4 experiences the most significant darkening and color shifts, with the highest CMC DE and MI values.

3.6. Colour fastness

The color fastness performance of the dyed samples with and without mordants is presented in **Table 4**. In terms of color change for color fastness to washing, all four samples perform with fair resistance to washing, with sample DS4 slightly better than the others. The improved resistance of DS4 can be attributed to the ability of ferrous ions to form strong metal-polyphenol complexes with the polyphenolic compounds in the tea leaf extract, which stabilizes the dye on the cellulose fibers. On the contrary, the color staining of multifiber fabric (wool, acrylic, polyester, nylon, cotton, and acetate) samples DS2, DS3, and DS4 performed significantly better with good to excellent fastness, suggesting minimal staining compared to DS1. Because the absence of mordants limits the formation of covalent or coordination bonds, leaving more free dye molecules capable of migrating during washing.

Table 4. Color fastness performance of dyed samples with and without mordants.

Performance description			DS1	DS2	DS3	DS4
Fastness to washing		Colour change	2	3	3	3/4
		Colour staining	2/3	4/5	4/5	4/5
Fastness to rubbing		Dry	4	4	4	4/5
		Wet	1/2	2	2	2/5
Fastness to perspiration	Acidic	Colour change	4/5	3/4	4	4/5
		Colour staining	4/5	4	4	4/5
	Alkaline	Colour change	4	3/4	4	4
		Colour staining	4	4	4/5	4
Fastness to light			3	3/4	4	4

Regarding rubbing fastness, all samples showed similar performance under dry conditions, indicating adequate dye adhesion to the fiber surface. However, wet rubbing fastness was lower, particularly for DS1, reflecting the weakest performance. This limitation is typical for cotton dyed with natural polyphenolic dyes [57]. In wet conditions, water molecules and mechanical rubbing weaken hydrogen bonds by competing with dye-fiber interactions. Among the samples, DS4 showed better wet rubbing fastness, which may be attributed to the formation of more stable metal-polyphenol complexes with Fe^{2+} ions. Color fastness to light varied considerably among samples. DS1 showed the lowest performance, indicating moderate susceptibility to fading. DS2 demonstrated a slight improvement, while DS3 and DS4 achieved the highest ratings, suggesting superior stability under light exposure. This enhancement is attributed to the ability of mordants, particularly alum and ferrous sulfate, to stabilize the chromophoric groups in tea polyphenols, preventing photodegradation. In terms of perspiration fastness, all samples exhibited good resistance under both acidic and alkaline conditions, with minimal variation between the two environments. Interestingly, sample DS1 performed slightly better than some of the mordanted samples. This counterintuitive result could be attributed to the nature of the tea polyphenols in the extract, which can interact directly with cellulose fibers through hydrogen bonding, providing moderate fixation even without mordants. In mordanted samples, although metal ions enhance dye fixation overall, some mordant-dye complexes may be partially sensitive to pH changes in perspiration solutions, slightly reducing color change resistance under acidic or alkaline conditions. Despite this, DS2-DS4 generally show superior fastness in washing, rubbing, and light exposure tests, indicating that mordants still play a key role in overall color stability. The color staining data confirm that mordanted samples exhibit minimal dye migration, whereas DS1 shows a slightly higher tendency for staining under other conditions, reflecting the balance between direct polyphenol-cellulose interaction and mordant-assisted stabilization.

It should be noted that the colorimetric and color fastness properties were obtained as single measurements under controlled and consistent experimental conditions. The results are presented as indicative trends, and future work will incorporate replicate testing with full statistical analysis.

3.7. Comparison with traditional dyeing

A comparison of the performance of this study with traditional exhaust and low-temperature dyeing methods is presented in **Table 5.** The results reveal that IR-assisted dyeing produced the highest color strength compared to traditional and low-temperature methods, owing to efficient infrared heat transfer that enhanced dye fixation. Fastness to washing and perspiration was comparable across all methods, while wet rubbing resistance was slightly lower for the IR-treated fabric. Light fastness was moderate for the IR process and higher for conventional methods. Notably, the IR-assisted technique required a shorter dyeing time and a lower liquor ratio (1:10), thereby reducing both water and energy consumption.

Table 5. Comparison of tea leaf–dyed cotton fabrics under different dyeing methods.

Criterion	IR-assisted dyeing (this study)	Traditional exhaust dyeing [36]	Low temperature dyeing [30]
Substrate	Cotton fabric(120 GSM)	Cotton fabric (157 GSM)	Cotton fabric (105 GSM)
Process time/temperature	Dyeing at 60 °C for 60 min	Dyeing at 90 °C for 60 min	Dyeing at 40 °C for 180 min
Water usage	Reduced liquor ratio (1:10)	Moderate (1:20–1:30)	Water intensive (1:50)
K/S	22.68	6.63	12
Wash fastness	3/4 (color fading), 4/5 (color staining)	3/4 (color fading), 4/5 (color staining)	4 (color fading and staining)
Rubbing fastness	4/5 (dry), 1/2 (wet)	4/5 (dry), 3/4 (wet)	4 (dry), 4 (wet)
Perspiration fastness	4/5 (acidic), 4 (alkaline)	3/4 (acidic), 4 (alkaline)	4 (acidic), 4 (alkaline)
Light fastness	4	5	5

4. Conclusion

This study demonstrated that tea leaf waste can serve as an effective and eco-friendly dye for cotton fabrics. The dyed samples exhibited light to deep brown shades, which were confirmed by spectrophotometric measurements. Optimal IR-assisted dyeing conditions (60 °C, 60 min) produced fabrics with the highest color strength while maintaining acceptable air permeability and improved flexibility. The use of mordants, particularly ferrous sulphate, significantly improved color fastness to washing, rubbing, perspiration, and light compared with non-mordanted samples. In addition, the IR dyeing process reduced the material-to-liquor ratio from conventional levels (up to 1:50) to 1:10, indicating substantial reductions in water consumption and energy use.

However, this study was limited to laboratory-scale dyeing conditions. Further research is required to evaluate the scalability of the IR dyeing process, the long-term storage stability of dyed fabrics and to conduct quantitative evaluations to support sustainable development in the textile industry.

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