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ENHANCING THE DYEING PERFORMANCE OF COTTON WITH CURCUMIN: A COMPARATIVE STUDY OF MORDANT TYPES AND APPLICATION METHODS

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ABSTRACT

Curcumin, a natural dye derived from turmeric, faces limitations in cotton dyeing due to its poor fibre affinity and inadequate fastness properties. This study systematically evaluates the enhancement of curcumin dyeing performance on cotton using three metallic mordants (alum, ferrous sulphate, and potassium dichromate) applied through pre-, meta- (simultaneous) and post-mordanting techniques. Dye exhaustion and fastness properties (wash, rubbing, and light) were assessed. Unmordanted cotton exhibited low dye exhaustion (45%) and poor fastness performance. Mordanting significantly improved dye uptake and fastness properties, with ferrous sulphate applied via pre-mordanting yielding the highest exhaustion (82%). Potassium dichromate and ferrous sulphate produced the most improved fastness results (wash fastness: 4–5; light fastness: 3–4). Among the mordanting techniques, pre-mordanting consistently demonstrated superior performance. The findings confirm that appropriate mordant selection and application strategy can substantially enhance curcumin dyeing, enabling its effective use as a high-performance and sustainable natural dye for cotton textiles, thus, offering a sustainable alternative to synthetic dyes.

Keywords: *Curcumin, Exhaustion, Mordanting, Curcuma longa, Cotton fabrics*

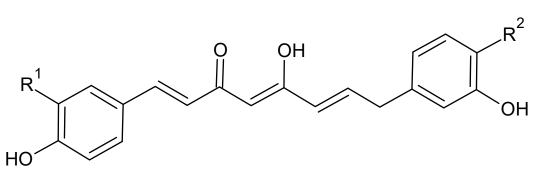
INTRODUCTION

The growing environmental consciousness and demand for reduction in the use of hazardous chemicals, particularly those identified as carcinogenic, mutagenic, or allergenic, necessitated the adoption of cleaner production by the textile finishing subsector (Gulza *et al.,* 2020; Kishor *et al.,* 2021). In recent years, increasing regulatory pressure related to human health risks and environmental impacts has intensified research efforts towards the development of non-toxic, sustainable, environmentally friendly, and cost-effective textile finishing processes (Islam and Mohammed, 2021; Sheriff *et al.,* 2020; Saxena *et al.,* 2016). As a result, hazardous substances are progressively being replaced with safer alternatives, leading to renewed interest in the use of natural dyes in textile finishing (Adeel *et al.,* 2019; Eid and Ibrahim, 2020).

Natural dyes are generally categorised into two groups: substantive dyes, which can bind directly to textile fibres without the use of mordants, and mordant (adjective) dyes, which require mordants to achieve fixation on fabrics (Ismail and Yıldırım, 2019). The majority of natural dyes fall into the latter category due to their inherently poor fastness characteristics, necessitating the use of auxiliary chemicals to enhance dye uptake and fixation within the textile matrix (Ding and Freeman, 2017). Furthermore, cotton exhibits limited affinity for natural dyes because the hydroxyl groups of cellulose ionise in aqueous media, generating negatively charged sites that repel similarly charged natural dye molecules (Janhom *et al.,* 2006). This electrostatic repulsion significantly restricts dye absorption by cotton fibres, thereby making the application of mordants essential to improve dye adsorption and retention.

A mordant is a chemical agent employed to facilitate the fixation of a dye within or onto a textile material by reacting with the dye to form an insoluble complex (Ismail and Yıldırım, 2019). Metallic mordants such as alum, tin, potassium permanganate, copper sulfate, ferrous sulfate etc., are widely employed to enhance the affinity between dyes and textile substrates, as they are capable of forming dye-metal coordination complexes, while the vacant orbitals of the metal ions can further interact with the cellulose chains of cotton fibres (Phan *et al.,* 2020). In addition to improving dye fixation, mordanting also enables the generation of diverse colour shades from a single dye source, depending on the type of mordant used.

Turmeric (*Curcuma longa*) is a perennial herbaceous plant belonging to the ginger family (Zingiberaceae). Its rhizome, an underground stem, is widely used as a spice, medicinal ingredient, and dye. It is native to South Asia, particularly India and Indonesia, and has been cultivated for thousands of years and used for centuries as a natural dye due to its vibrant golden-yellow colour, which can be an eco-friendly alternative to synthetic dyes, commonly used for fabrics, food, and even cosmetics. The demand for turmeric continues to rise across the food, pharmaceutical, and cosmetic sectors, driven by its well-documented anti-inflammatory, antimicrobial, antioxidant, anti-parasitic, anti-mutagenic, and anti-cancer properties (Praditya *et al.,* 2019). Recent reports estimate the global turmeric market at approximately 1.7 million metric tons, with projections indicating substantial growth by 2027 (Kotha and Luthria, 2019). The characteristic yellow colouration imparted on cotton fibres by turmeric is attributed to curcuminoids, a group of polyphenolic pigments present in the rhizome (Karabulut and Atav, 2020). Amongst these, curcumin is the major constituent, accounting for approximately 77%, while demethoxycurcumin and bisdemethoxycurcumin are present in lower amounts of about 17% and 6%, respectively (Kotha and Luthria, 2019). Figure 1 shows the structure of curcumin, which is the predominant colouring agent in turmeric.



Where in, Curcumin (Cur): R^1 = $-OCH_3$, R^2 = $-OCH_3$
Demethoxycurcumin (DMC): R^1 = $-OCH_3$, R^2 = H
Bisdemethoxycurcurmin (BDMC): R^1 = H, R^2 = H

Fig. 1: Structure of curcumin dye

Although curcumin dye derived from turmeric rhizome offers an environmentally benign alternative to synthetic dyes, its application on cotton fabrics remains constrained by several challenges. The inherently low affinity between the curcumin dye molecules and cellulose fibres, arising from electrostatic repulsion in aqueous dyeing systems, results in poor dye uptake and weak fixation, ultimately leading to inadequate fastness properties, particularly against washing, light, and rubbing (Janhom *et al.,* 2006; Ding and Freeman, 2017; Karabulut and Atav, 2020). While the use of mordants has been shown to enhance dye–fibre interactions, the influence of mordant type and mordanting techniques on the dyeing performance of curcumin-dyed cotton fabric has not been systematically explored. The present study is aimed at addressing these gaps.

MATERIALS AND METHODS

Materials

Ethanol, n-Hexane, Potassium dichromate, Alum and Ferrous sulphate were bought from Merck, Germany. The chemicals were of analytical grade and were used without further purification. Bleached plain weave cotton fabric was purchased from African Textile Mill, Kano, Nigeria. UV-Visible Spectrophotometer (UV-2500PC Series), Fourier Transform Infrared Spectrophotometer (Agilent technology), Xenon Arch Light Fastness Tester, and Laboratory dyeing machine were used for the study. Other equipment used include; pulverizer (blender), Soxhlet apparatus, 500 ml round bottom flask, measuring cylinder, Cotton wool, Aluminium foil, stirring rod, Conical flask, Magnetic stirrer, Rotary evaporator, Thermometer etc.

Sample collection

Fresh turmeric rhizome was purchased from Zaria city market, Kaduna, Nigeria. They were peeled, cut into smaller sizes, dried at room temperature (27 °C) for eight (8) days till all the moisture was removed by evaporation, and this was later ground into powder form.

Methods

Extraction of Curcumin dye

The natural dye from turmeric was extracted by the Soxhlet extraction process using ethanol as solvent. Raw turmeric powder was placed in the thimble, followed by Soxhlet extraction assembly and was subjected to extraction for 8 h. The solvent was recovered using a rotary evaporator. The concentrated extract was washed several times with n-hexane to remove the waxy substances and other nonpolar impurities present. This was filtered to obtain pure turmeric dye extract, which was dried using a laboratory spray dryer to obtain powdered curcumin dye (Hafeena *et al.,* 2017).

Determination of Percentage Yield

The percentage yield of curcumin dye was calculated based on the mass of dried extract obtained relative to the initial mass of turmeric rhizome powder used for extraction. After completion of the extraction and solvent removal, the recovered dye extract was dried to constant weight and weighed using an analytical balance. The percentage yield was determined using the following equation.

$$\text{Percentage yield of dye (\%)} = \frac{\text{Weight of Curcumin extracted (g)}}{\text{Weight of turmeric powder used (g)}} \text{ X } 100 \text{ - - - - Eqn.1}$$

UV-visible spectroscopy

The pure dye was analysed for its absorbance using a UV-Vis spectrophotometer (Agilent 8453, USA). The spectrum was recorded over a wavelength range of 300–800 nm using a quartz cuvette with a path length of 1 cm.

FT-IR spectroscopy

The Infrared Spectrum was obtained using Agilent technology to find the functional groups present in the purified dye sample.

Solubility test

The solubility of curcumin dye was evaluated in six different solvents, comprising polar and non-polar solvents. 10 mg of curcumin dye was weighed and introduced into separate test tubes containing 10 mL of distilled water, ethanol, methanol, dimethylsulfoxide, acetone and n-hexane. The mixtures were stirred at room temperature (27 °C) for 15 min. The solubility was assessed based on visual observation of solution clarity and homogeneity, and the results are shown in Table 1.

Scouring of Cotton Fabric

The purchased cotton fabric was scoured following the method reported by Vankar *et al.* (2009) with slight modification. The fabric was boiled for 30 min. in a solution containing 2 g/l sodium carbonate and 2 g/l non-ionic detergent, keeping the material to liquor ratio at 1:40 o.w.f. The scoured cotton fabric was thoroughly washed with warm water, neutralised with 1 g/l acetic acid and rinsed again using distilled water.

Dyeing of Cotton Fabric with Curcumin Dye

1 % stock solution of curcumin dye was prepared and used to dye cotton fabric in accordance with the method reported by Islam *et al.,* (2021c), with slight modification. Pre-treated cotton fabric (1 g) was dyed using a material to liquor ratio 1:50. The dye bath pH was adjusted to 9 using a dilute sodium carbonate solution to enhance dye solubility and dyeing was carried out at a temperature of 90 °C for 60 min. in a standard laboratory dye master with constant agitation. After half of the dyeing time, 3 g/l sodium sulphate (Na_2SO_4) was added as an exhausting agent. At the end of dyeing, the dye bath was cooled to 40 °C and the fabric was removed, rinsed thoroughly with distilled water and dried at room temperature for further analysis.

Mordanting

Three mordanting techniques were adopted, which include: Chrome mordant process (Pre-mordanting), Meta-chrome process (Simultaneous mordanting) and After-chrome process (post-mordanting).

Chrome mordant process (Pre-mordanting): This was carried out by treating scoured cotton fabric in an aqueous mordant solution at a concentration of 5% o.w.f. The material-to-liquor ratio was maintained at 1:50. Mordanting was performed at 60 °C for 45 min with continuous agitation. After the treatment, the fabric was rinsed thoroughly with distilled water to remove excess mordant and then air-dried prior to dyeing.

Meta-chrome process (Simultaneous mordanting): In this method, the required amount of mordant (5% o.w.f.) was added directly to the dye bath containing the curcumin dye solution. The scoured cotton fabric was introduced into the bath, and both dyeing and mordanting were carried out simultaneously under the same dyeing conditions described earlier. Upon completion, the fabric was rinsed thoroughly with distilled water and dried at room temperature.

After-chrome process (Post-mordanting): After mordanting, the cotton fabric was first dyed with curcumin dye under the standard dyeing conditions mentioned above. The dyed fabric was then treated in a fresh aqueous mordant solution (5% o.w.f) at a material-to-liquor ratio of 1:50. Mordanting was carried out at 60 °C for 45 min with continuous agitation. After the treatment, the fabric was rinsed with distilled water to remove unfixed mordant and air-dried.

At the end of the dyeing process, the samples were rinsed with water, then soaped with a 2 g/L soap solution at 50 °C for 10 min, followed by rinsing and drying in the sun (Kumerasan *et al.,* 2011).

Dye Exhaustion

Before dyeing, an aliquot of the dye solution was taken from the dye bath and its optical density was measured using a UV–visible spectrophotometer; this value was recorded as OD_1. After completion of the dyeing process, the fabric was removed and the residual dye bath was allowed to cool to room temperature. A second aliquot was then collected, and its optical density was measured to obtain OD_2.

The percentage dye exhaustion was subsequently calculated using the following equation:

$$\text{Dye Exhaustion (\%)} = \frac{OD1-OD2}{OD1}\ X100 \text{ ------ Eqn. 2}$$

where OD1 = Optical density before dyeing
OD2 = Optical density after dyeing

Fastness testing
Wash fastness of the dyed samples was tested according to ISO 105-CO3 method. The samples were washed in standard soap solution at 60 °C for 30 min, keeping material to liquor ratio at 1:50. Dry and wet rubbing fastness of the dyeings were tested according to ISO 105-X12 method using a crock metre. Light fastness was tested according to ISO 105-BO2 method. The dyeings were exposed to xenon arc lamp for 24 h at standard testing conditions (Anon, 1990).

RESULTS AND DISCUSSION

Yield
The extraction of curcumin dye from turmeric rhizome powder yielded 0.8 g dye which corresponds to 4% of the starting material. This value is in agreement with the findings of Mandal *et al.,* 2007. The relatively low yield reflects a common limitation of natural dyes (Ukanah *et al.,* 2020) and is governed by factors such as plant growth conditions, extraction technique, and solvent efficiency. This yield is derived from a single experimental run and it represents an initial estimate of dye availability, thus, establishing a reference point for subsequent optimisation studies.

UV-Visible absorption spectrum
Figure 2 shows the UV-Visible spectrum of the extracted curcumin dye. The UV-Visible absorption was measured in ethanol using a quartz cuvette of 1 cm path length, 2 nm slit width, and dye concentration of 10 mg/L over the wavelength range of 300–800 nm. The absorbance maximum (λmax) was recorded at 424 nm, characteristic of curcuminoid compounds. This absorption band is attributed to ***π→π**** electronic transitions within the extended conjugated diketone structure of curcumin, which is responsible for its intense yellow colouration. The presence of this distinct λmax confirms the successful extraction of the principal chromophoric component of turmeric. This relatively high intensity and well-defined nature of the absorption band is indicative of effective solubilisation of curcumin in the solvent (ethanol) and minimal interference from non-chromophoric impurities. However, the observed minor band broadening may arise from the presence of closely related curcuminoids (demethoxycurcumin and bisdemethoxycurcumin), which commonly coexist in turmeric extracts and contribute to overlapping absorption features.

FT-IR Analysis of the Extracted Dye
Figure 3 shows the Fourier transform infrared (FT-IR) spectrum of the extracted dye. The spectrum was recorded in the range 4000 - 650 cm^{-1} at a resolution of 4 cm^{-1}. The FT-IR spectrum exhibited characteristic absorption bands that are consistent with the functional groups present in curcuminoid compounds, confirming the identity of the extracted curcumin dye.

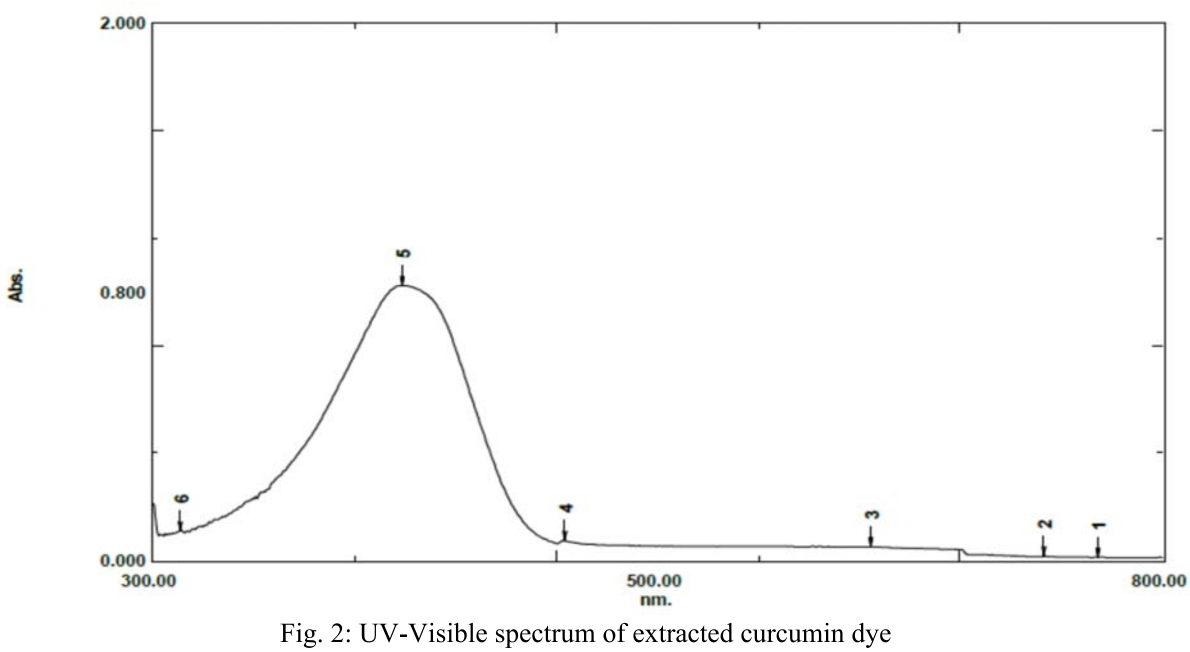


Fig. 2: UV-Visible spectrum of extracted curcumin dye

The spectrum was analysed to identify the functional groups responsible for metal coordination and their role in enhancing dyeing performance on cotton. A broad band observed in the region of 3362.1-3218.6 cm⁻¹ is attributed to O–H stretching vibrations of phenolic hydroxyl groups, which are involved in intramolecular hydrogen bonding and play a role in metal coordination reactions. These hydroxyl groups provide active binding sites for metal ions during mordanting, facilitating the formation of metal–dye complexes (Kotha and Luthria, 2019).

The absorptions near 2916.6–2842.1 cm⁻¹ correspond to aliphatic C–H stretching vibration originating from the methoxy substituents present in curcumin derivatives. The absorption band around 1625.1–1584.1 cm⁻¹ corresponds to the C=O stretching vibration of the β-diketone moiety in the enol form, overlapped with C=C stretching of the conjugated aromatic system. This band is a defining feature of curcumin and reflects its highly conjugated structure. This C=O group undergoes keto–enol tautomerism and acts as a strong chelation site for transition metal ions such as Fe^{2+}/Fe^{3+} and Cr^{3+} (Kolev *et al.,* 2005; Barik *et al.,* 2007). Coordination through the β-diketone structure is widely recognised as a key mechanism responsible for the enhanced fixation of curcumin on cellulosic fibres in the presence of metallic mordants (Samanta and Agarwal, 2009).

Peaks observed near 1509.6–1459.3 cm⁻¹ are associated with aromatic C=C stretching, further supporting the presence of phenyl rings. Absorption bands in the region of 1258.0–1241.2 cm⁻¹ are assigned to C–O stretching vibrations of phenolic and enolic groups, while absorptions around 1028.7 cm⁻¹ are attributed to C–O–C stretching of ether linkages. The absorption peaks below 800 cm⁻¹ are associated with out-of-plane C–H bending vibrations of substituted aromatic rings.

Although the FTIR analysis of the dyed cotton fabrics was not conducted due to instrumental limitations, the identification of phenolic –OH and β-diketone C=O groups in curcumin provides strong mechanistic support for metal–dye complexation during mordanting. The formation of these complexes is known to reduce dye solubility and mobility, and promote stronger dye fixation within the fibre structure, resulting in increased dye exhaustion and improved fastness properties, as seen in the enhancement of dye uptake and fastness performance of mordanted cotton fabrics, particularly when ferrous sulphate and potassium dichromate were employed. This is in agreement with the findings of Bechtold and Mussak (2009).

Solubility of Curcumin Dye

Table 1 shows the results of the solubility of the extracted curcumin dye in solvents of different polarity. The dye contains a polar hydroxyl group capable of entering hydrogen bonding to enhance solubility in aqueous media, but its extensive conjugation system renders it hydrophobic, thus resulting in poor solubility in aqueous media (Priyadarsini, 2014) as seen in Table 1.

This low solubility in water can be as a result of the inability of water molecules to solvate the hydrophobic backbone of the curcumin despite having the potential of entering hydrogen bonding with the phenolic groups (Anand *et al.,* 2007).

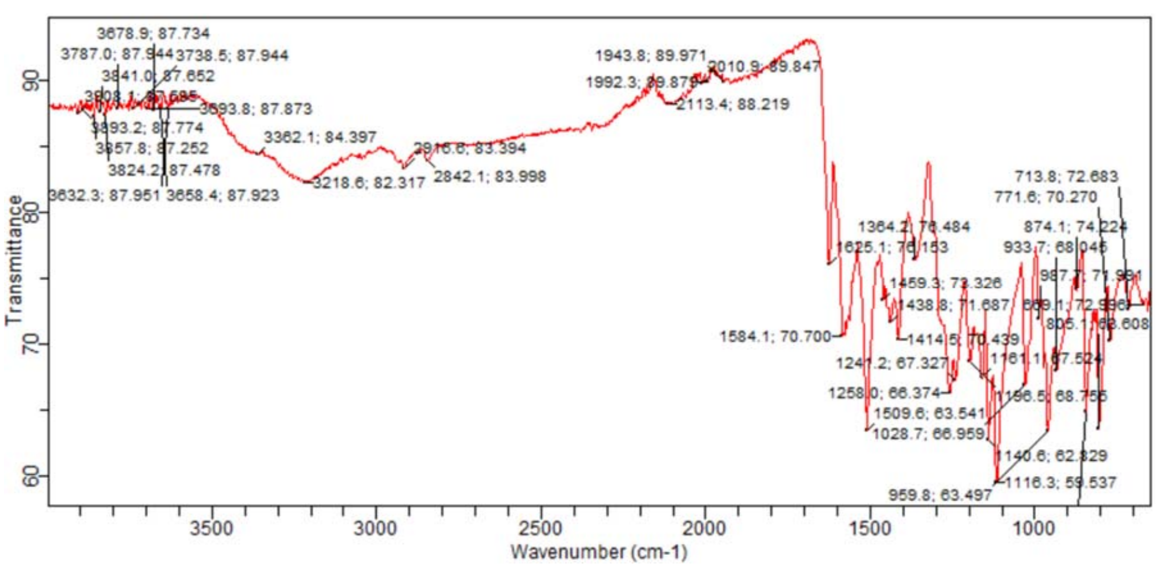


Fig. 3: FTIR spectrum of extracted curcumin dye

Table 1: Solubility of curcumin dye in different solvents

Solvent	Polarity	Solubility	Visual Observation
Distilled water	Polar	Sparingly soluble	Turbid suspension, yellow colouration
Acetone	Polar aprotic	Moderately soluble	Yellow solution
Ethanol	Polar protic	Soluble	Clear, yellow solution
Methanol	Polar protic	Soluble	Clear, yellow solution
Dimethyl sulfoxide	Polar aprotic	Very soluble	Clear, yellow solution
nHexane	Non polar	Non soluble	No dissolution

In contrast, the dye dissolved well in organic solvents like ethanol, methanol, acetone and DMSO, and this may be attributed to favourable solvent-solute interactions. DMSO show the highest solubility and this may be due to its aprotic nature and high polarity, which allows for effective interaction with both polar and non-polar regions of the curcumin molecule (Wang *et al.,* 2015). In a non-polar solvent, the dye was completely insoluble, as seen in the case of nhexane showing no interaction between the solute and the solvent.

Dye Exhaustion of mordanted and unmordanted cotton fabric

The dye exhaustion of curcumin on cotton fabric is strongly influenced by the presence of mordants, which enhance dye–fibre interactions through coordination mechanisms. In the absence of mordant, curcumin-dyed cotton exhibited moderate exhaustion of 45%, indicating limited transfer of dye from the dye bath to the fibre (Samanta and Agarwal, 2009; Yusuf *et al.,* 2017).

Cotton fibres are composed mainly of cellulose, which contains hydroxyl (–OH) groups capable of forming hydrogen bonds with the phenolic and enolic groups of curcumin. However, these interactions are relatively weak and predominantly physical in nature, resulting in incomplete dye uptake and retention. Consequently, a significant proportion of curcumin remains in the dye bath after dyeing, leading to the observed moderate exhaustion values (Vankar, 2014).

The introduction of mordants significantly increases dye exhaustion by facilitating the formation of metal–dye–fibre coordination complexes, which improves dye affinity toward cellulose and reduces dye solubility in the dye bath (Gulrajani, 2001). Three different mordants, including alum, potassium dichromate and ferrous sulphate, were used in this study.

Alum mordanted cotton gave a percentage exhaustion of 65%, reflecting the formation of aluminum–curcumin complexes, which have a limited coordination stability (Bechtold *et al.,* 2003; Yusuf *et al.,* 2017).

Potassium dichromate mordanted cotton fabric exhibited a high exhaustion percentage of 77% when compared with the alum mordanted fabric, and this can be attributed to the formation of highly stable octahedral chromium–curcumin complexes that strongly anchor the dye within the fibre matrix (Gulrajani, 2001; Uddin, 2014). These strong coordination interactions reduce dye mobility and promote deeper fibre penetration, resulting in higher exhaustion.

The highest exhaustion was observed for cotton mordanted with ferrous sulphate, with a percentage exhaustion of 82%**.** Iron ions form strong chelation complexes with the diketone and phenolic groups of curcumin, leading to rapid dye uptake and minimal dye residue in the dye bath (Samanta and Agarwal, 2009; Vankar, 2014). The high exhaustion achieved with ferrous sulphate correlates well with the darker shades and superior washing and rubbing fastness commonly observed in iron-mordanted natural dye systems (Uddin, 2014).

In addition, it was established that mordanting significantly influenced the hue of the dyed cotton fabrics. While iron mordanting resulted in duller, brownish-yellow shades, consistent with the tendency of iron to darken and muffle natural dye colours through strong metal–dye complexation (Vankar, 2014; Gulrajani, 2001), potassium dichromate produced deeper and more intense yellow hues which aligns with the findings of Samanta and Konar, (2011), that chromium can increase chromatic depth via coordination with natural dye chromophores. The Alum mordanted cotton fabrics showed a lighter yellow hue, and this is likely due to its relatively weaker complexation effects.

Although potassium dichromate demonstrated improved dye exhaustion and fastness properties, its use raises significant environmental and health concerns due to the presence of hexavalent chromium (Cr(VI)), which is highly toxic and carcinogenic. However, it is expected that under the employed dyeing conditions, Cr(VI) is reduced to the more stable and less toxic Cr(III) species, which is responsible for coordination with curcumin. Nevertheless, because chromium-based mordants are subject to strict regulatory control, potassium dichromate mordant is used primarily as a benchmark mordant to elucidate metal–dye interaction mechanisms rather than as a preferred option for eco-friendly dyeing.

Effect of mordanting techniques on dye exhaustion of curcumin-dyed cotton fabric

The dye exhaustion of curcumin on cotton fabric was also influenced by the type of mordant and mordanting techniques employed, as seen in Table 2. The three mordanting techniques, such as chrome mordant process or pre-mordanting, meta-chrome process or simultaneous mordanting and after-chrome process or post-mordanting, were adopted for this study, and each method alters the availability and distribution of metal ions on the fibre, thereby influencing the extent of dye–fibre coordination and overall dye uptake.

In this case, pre-mordanting resulted in the highest dye exhaustion with percentage exhaustion as seen in Table 2, and this may be because metal ions are first fixed onto the cotton fibre, thereby creating active coordination sites before dyeing. During dyeing, curcumin molecules readily form stable metal–dye complexes directly on the fibre, leading to enhanced dye affinity and reduced dye solubility in the dye bath (Gulrajani, 2001). This high exhaustion observed in pre-mordanted samples indicates efficient dye transfer from the dye bath to the fibre and deeper dye penetration. This method is therefore considered the most effective for improving exhaustion in curcumin dyeing of cotton, and it correlates well with increased colour depth and improved wash and rubbing fastness (Samanta and Agarwal, 2009).

As for the meta-mordanting, where mordant and dye were applied simultaneously unto the fabric, the percentage exhaustion was found to be moderate and this could be because of the competition between dye molecules and cellulose hydroxyl groups for metal ions thereby limiting the efficiency of complex formation (Bechtold *et al.,* 2003) while post mordanting gave the lowest dye exhaustion as compared to the pre-mordanting and the simultaneous mordanting. In the post-mordanting, dyeing had already taken place, followed by mordant application and since curcumin was initially weakly adsorbed onto the fibre, partial dye desorption may occur before effective metal-dye complexation takes place (Vankar, 2014), thus, leading to low percentage exhaustion.

Table 2: Percentage dye exhaustion of curcumin-dyed cotton fabric

Mordant Type	Pre-mordanting (%)	Meta-mordanting (%)	Post-mordanting (%)
Unmordanted	45	—	—
Alum	65	60	54
Potassium dichromate	77	68	58
Ferrous sulphate	82	70	62

Fastness properties of dyed cotton fabric

Table 3 shows the fastness properties of curcumin-dyed cotton fabrics. The fastness properties were significantly influenced by the application of mordants. A clear improvement in wash, rubbing, and light fastness was observed in mordanted samples compared to unmordanted ones, thus confirming the critical role of mordanting in enhancing dye fixation.

Wash Fastness

Unmordanted cotton fabric exhibited poor to moderate wash fastness of 2-3, as seen in Table 3. This appreciable loss of colour is attributed to the weak physical adsorption of curcumin onto cellulose through hydrogen bonding, which is insufficient to resist dye removal during laundering (Samanta and Agarwal, 2009). In contrast, mordanted cotton fabrics showed improved wash fastness, having a rating of 3–4. The formation of metal–dye–fibre coordination complexes significantly increased dye fixation within the fibre matrix, thereby reducing dye solubilisation and migration during washing (Gulrajani, 2001). Iron and chromium mordants were particularly effective due to their strong chelating ability with the β-diketone and phenolic groups of curcumin (Vankar, 2014).

Table 3: Colour fastness of dyed cotton fabric

Fastness Property	Unmordanted	Alum mordant	Potassium dichromate mordant	Ferrous sulphate mordant
Wash fastness	2–3	3–4	4	4–5
Dry rubbing fastness	3	4	4	4–5
Wet rubbing fastness	2–3	3	3–4	4
Light fastness	2	3	4	3–4

Rubbing Fastness

The rubbing fastness of unmordanted samples showed a moderate rating of 3 in dry rubbing and a poor to moderate rating of 2-3 in wet rubbing, as seen in Table 3. The differences in rating between the dry rubbing and wet rubbing fastness could be a result of the presence of moisture on the fabric during wet rubbing, which facilitated dye transfer in wet rubbing, thus leading to colour loss. The mordanted samples demonstrated better dry rubbing fastness with a rating of 4 and improved wet rubbing fastness with a rating of 3–4. This improvement is associated with enhanced dye penetration and stronger anchoring of the dye within the fibre structure through metal coordination, which limits surface dye removal under mechanical action (Bechtold *et al.,* 2003).

Light Fastness

Light fastness was poor for unmordanted cotton fabric, having a rating of 2 due to the inherent photosensitivity of curcumin, whose conjugated chromophoric system undergoes photo degradation upon exposure to UV and visible light (Vankar, 2014). Mordanting resulted in a noticeable enhancement in light fastness, with the rating increasing to 3–4 and 4, particularly for iron and chromium mordanted samples. This improvement is attributed to the stabilisation of the curcumin chromophore through metal complexation, which reduces photochemical degradation and slows down colour fading (Samanta and Agarwal, 2009; Bechtold *et al.,* 2003).

However, the light fastness of iron mordanted samples 3–4 was seen to be slightly lower than that observed for chromium mordanted cotton and this behaviour is attributed to the ability of iron ions to catalyse oxidative and photo-oxidative reactions, which may accelerate partial degradation of the curcumin chromophore under light exposure (Vankar, 2014; Priyadarsini, 2014).

Limitation of study

The present study was conducted under laboratory-scale conditions, and no economic feasibility assessment was performed. Consequently, the large-scale applicability of curcumin dyeing, such as costs of production, energy requirements and competitiveness with conventional synthetic dyes, remains to be fully evaluated. Future work should focus on pilot-scale feasibility investigations, detailed cost analyses and sustainability assessment to determine the industrial viability of curcumin-based dyeing processes.

CONCLUSION

This study systematically demonstrated that both mordant type and mordanting technique significantly influence the dyeing performance of curcumin on cotton fabrics. Unmordanted cotton exhibited low dye exhaustion (45%) and poor fastness properties, confirming the inherently weak affinity of curcumin for cellulose. In contrast, mordanting significantly enhanced performance. Among the evaluated systems, pre-mordanting with ferrous sulphate produced the highest dye exhaustion (82%), along with good to very good fastness properties (wash fastness: 4-5; rubbing fastness: 4–5; light fastness: 3–4). Potassium dichromate also yielded excellent fastness performance (wash fastness: 4; rubbing fastness: 4; light fastness: 4) and deep colour shades, particularly when applied by pre-mordanting, but did not surpass ferrous sulphate. While potassium dichromate enhanced the dyeing performance of curcumin on cotton, the toxicity and environmental risks associated with hexavalent chromium limit its suitability for sustainable textile applications. In contrast, ferrous sulphate provides a favourable balance of high performance and lower environmental risk. Accordingly, pre-mordanting with ferrous sulphate is recommended for an optimal balance of performance and environmental safety. Future work should explore environmentally benign mordants such as tannins, chitosan, neem extract, aloe vera extract, citric acid, etc., as sustainable alternatives, and investigate the colourimetric data like CIELAB coordinates, hue angle, and chroma of the resulting shade.

REFERENCES

Adeel, S., Rehman, F. U., Rafi, S., Zia, K. M. and Zuber M. (2019). Environmental friendly plant-based natural dyes: extraction methodology and applications. *Phytochemistry and Molecular Aspects,* (2) 383-415. http:// dx.doi.org/10.1007/978-3-030-03344-6_17.

Anand, P., Kunnumakkara, A. B., Newman, R. A., and Aggarwal, B. B. (2007). Bioavailability of curcumin: Problems and promises. *Molecular Pharmaceutics*, 4(6), 807–818.

Anon, J. (1990). Methods of test for colour fastness of textiles and leather. *The Society of Dyers and Colourists*, Bradford, UK.

Barik, A., Mishra, B., Kunwar, A. and Priyadarsini, K. I. (2007). Interaction of curcumin with metal ions: Spectroscopic and antioxidant studies. *Journal of Molecular Structure*, 826, 58–64.

Bechtold, T., and Mussak, R. (2009). Handbook of Natural Colorants. Wiley.

Bechtold, T., Turcanu, A., Ganglberger, E., and Geissler, S. (2003). *Natural dyes in modern textile dyehouses. Journal of Cleaner Production,* 11(5), 499–509. https://doi.org/10.1016/ S0959-6526(02)00077-X.

Ding, Y. and Freeman, H.S. (2017). Mordant dye application on cotton: Optimisation and combination with natural dyes. *Coloration Technology*, Vol. 133 No. 5, pp. 369-375.

Eid, B.M. and Ibrahim, N.A. (2020). Recent developments in sustainable finishing of cellulosic textiles employing biotechnology. *J. Clean. Prod.* 284, 124701.

Gulrajani, M. L. (2001). Present status of natural dyes. *Indian Journal of Fibre and Textile Research*, 26, 191–201.

Gulzar, T., Farooq, T., Kiran, S., Ahmad, I. and Hameed, A. (2020). Green Chemistry in the Wet Processing of Textiles, in the Impact and Prospects of Green Chemistry for Textile Technology. *Elsevier*: Amsterdam, Netherlands, pp. 1–20.

Haneefa, M.M. (2017), Green synthesis characterization and antimicrobial activity evaluation of manganese oxide nanoparticles and comparative studies with salicylal chitosan functionalized nano form. *Asian Journal of Pharmaceutics*, 11(01).

Islam, M.T., Liman, M.L.R., Roy, M.N., Hossain, M.M., Repon, M.R. and Mamun, M.A.A., (2021c). Cotton dyeing performance enhancing mechanism of mangiferin enriched bio-waste by transition metals chelation. J. Text. Inst. https://doi.org/10.1080/ 00405000.2021.1892337.

Islam, S.U. and Mohammad, F. (2014). Emerging Green Technologies and Environment Friendly Products for Sustainable Textiles; *Springer*: pp. 63–82.

Isma'il, Ö.E. and Yıldırım, L. (2019). Metal mordants and biomordants, in the Impact and Prospects of Green Chemistry for Textile Technology, *Elsevier*, pp. 57-82, doi:10.1016/B978-0-08-102491- 1.00003-4.

Janhom, S., Watanesk, R., Watanesk, S., Griffiths, P., Arquero, O. and Naksata, W. (2006). Comparative study of Lac dye adsorption on cotton fibre surface modified by synthetic and natural polymers. *Dyes and Pigments*, Vol. 71 No. 3, pp. 188-193.

Karabulut, K. and Atav, R. (2020). Dyeing of cotton fabric with natural dyes without mordant usage Part I: determining the most suitable dye plants for dyeing and UV protective functionalization. *Fibres Polym.* 21 (8), 1773–1782. https://doi.org/10.1007/ s12221-020-9365-2.

Kishor, R., Purchase, D., Saratale, G.D., Saratale, R.G., Ferreira, L.F.R., Bilal, M., Chandra, R., and Bharagava, R.N. (2021). Ecotoxicological and health concerns of persistent colouring pollutants of textile industry wastewater and treatment approaches for environmental safety. *J. Environ. Chem. Eng.* 9, 105012.

Kolev, T. M., Velcheva, E. A., Stamboliyska, B. A. and Spiteller, M. (2005). DFT and vibrational spectroscopic study of curcumin. *International Journal of Quantum Chemistry*, 102, 1069–1079.

Kotha, R.R. and Luthria, D.L. (2019). Curcumin: biological, pharmaceutical, nutraceutical, and analytical aspects. *Molecules* 24, 293. https://doi.org/10.3390/ molecules24162930.

Kumerasan, M. Palnisamy, P. N. and Kumar, P. E. (2011). Application of Eco-friendly natural dye obtained from flower of *spathodescampanulata* on silk. *European Journal of Scientific Research* 52(3): 306–312.

Mandal, V., Mohan, Y. and Hemalatha, S. (2007). Optimization of curcumin extraction by microwave assisted *in-vitro* plant bursting by orthogonal array designed extraction process and HPTLC analysis. *Pharmacognosy Magazine* 3(11):132–138.

Phan, K., Van Den Broeck E., Van Speybroeck V. (2020). The potential of anthocyanins from blueberries as a natural dye for cotton: a combined experimental and theoretical study. *Dyes Pigm* 176:108180. https:// doi. org/ 10. 1016/j. dyepig. 108180.

Praditya, D., Kirchhoff, L., Brüning, J., Rachmawati, H., Steinmann, J. and Steinmann, E., (2019). Anti-infective properties of the golden spice curcumin. Front. *Microbiol.* 10, 912. https://doi.org/10.3389/fmicb.2019.00912.

Priyadarsini, K. I. (2014). The chemistry of curcumin: From extraction to therapeutic agent. *Molecules*, 19(12), 20091–20112.

Samanta, A. K. and Agarwal, P. (2009): Application of Natural Dyes on Textiles: A review. *Indian Journal of fibre and Textile Research,* 34:384-399.

Samanta, A. K. and Konar, A. (2011). Dyeing of textiles with natural dyes. InTech, Fontana, CA.
http://www.intechopen.com/books/natural-dyes/dyeing-of-textiles-with-natural-dyes

Saxena, S., Raja, A.S.M. and Arputharaj, A. (2016). Challenges in Sustainable Wet Processing of Textiles; *Springer*: Singapore, pp. 43–79.

Sheriff, I., Debela, S.A., Kabia, O.A., Ntoutoume, C.E. and Turay, M.J. (2020). The phase out of and restrictions on per-and polyfluoroalkyl substances: Time for a rethink. *Chemosphere*, 251, 126313.

Uddin, M.G. (2014). Extraction of eco-friendly natural dyes from mango leaves and their application on silk fabric *Journal of Textiles and Clothing Sustainability*, doi:10.1186/s40689-015-0007-9.

Ukanah, P.S., Gadimoh, S., Salisu, Z.M., Suleiman, M.A., Sulaiman, I.A., Chibuzo-Anakor, N.C., Umar, I.S., Lawal, O.M. and Oddy-Obi, I.C. (2020). Influence of Selected Mordants and Mordanting Techniques on Eco-Friendly Dyeing of Cellulosic Fabric using Natural Flavonoid Dye Extracted from Onion Outer Scale. *Nigerian Journal of Textiles (NJT),* vol. 6.

Vankar, P. S. (2014). Chemistry of natural dyes. Woodhead Publishing.

Vankar, P.S. and Shanker, R. (2009). Eco-friendly pre-treatment of silk fabric for dyeing with *Delonix regia* extract. *Color Technol* 125(3):155–160. https:// doi. org/ 10. 1111/j. 1478- 4408. 2009. 00189.x

Wang, Y. J., Pan, M. H., Cheng, A. L., Lin, L. I., Ho, Y. S., Hsieh, C. Y., & Lin, J. K. (2015). Stability of curcumin in buffer solutions and characterization of its degradation products. *Journal of Pharmaceutical and Biomedical Analysis*, 15(12), 1867–1876.

Yusuf, M., Shabbir, M. and Mohammad, F. (2017). Natural Colorants: Historical, Processing and Sustainable Prospects. *Nat. Prod. Bioprospect*, 7(1): 123–145.