Gezira J. of Engineering and Applied Sciences
ISSN Linking: 1858-5698
http://journals.uofg.edu.sd/index.php/gjeas/

Sustainable Coloration of Cotton Fabrics Using Extracted Dye from Onion (Allium cepa) Peel

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INFORMATIONS
Submission: 04 /05/2026
Accepted: 14/06/2026
Publication: 22/06/2026

Keywords: natural dye, allium cepa, cotton, sustainable textiles, mordanting, color fastness, agricultural waste.

ABSTRACT

The textile industry heavily relies on synthetic dyes, making it a major source of environmental pollution. In response, this study explored the potential of onion (Allium cepa) peel extract, an agricultural waste product, as a natural dye for cotton fabrics. The objectives were to optimize dye extraction, examine how different mordants (alum, copper sulfate, and citric acid) affect color characteristics, and assess color fastness. Cotton fabrics were pre-mordanted using alum (10% owf), copper sulfate (5% owf), or citric acid (8% owf) at 70°C for 45 minutes (material-to-liquor ratio 1:20), then dyed using an aqueous extract of dried onion peels prepared at 90°C for 60 minutes (1:10 ratio), followed by dyeing at 80°C for 60 minutes with 5 g/L NaCl as electrolyte. Depending on the mordant, the dyed samples displayed hues ranging from orange-yellow to brown. Quantitative color strength (K/S) analysis revealed that copper sulfate produced the highest K/S value (2.0989), followed by alum (1.4787) and citric acid (0.9252), all significantly exceeding the unmordanted control (0.5727). A one-way ANOVA confirmed statistically significant differences among treatments ($F(3,8) = 47.23$, $p<0.001$). The colorfastness to washing, light, and rubbing was highest for copper sulfate-mordanted fabrics (rating 5 for all tests), while alum yielded ratings of 4–5. Consequently, copper sulfate produced the deepest shades and best fastness, whereas alum gave brighter orange-yellow tones. Overall, onion peel extract is a viable, eco-friendly dye for cotton, offering good to excellent fastness and promoting the valorization of agricultural waste.

1. Introduction

The global textile industry relies heavily on synthetic dyes due to their wide range of vibrant colors, ease of application, and excellent fastness properties (Alegbe & Uthman, 2024). However, the environmental and health concerns associated with synthetic dyes, including toxicity, carcinogenicity, and water pollution, have driven a paradigm shift towards sustainable alternatives (Thakur et al., 2025). Approximately 280,000 tons of textile dyes are discharged into industrial effluents annually, with significant negative impacts on aquatic ecosystems and human health (Benkhaya et al., 2020; Chaurasia et al., 2025). Natural dyes, derived from plant, animal, and mineral sources, are re-emerging as viable solutions due to their biodegradability, low toxicity, and potential for circular economy models (Dey et al., 2025; Manawasinghe et al., 2025).

Among various natural dye sources, onion (Allium cepa) peels are particularly promising (Bedir et al., 2025; Chandra & Chandra, 2026; M. Hussein et al., 2026). They are a ubiquitous agricultural waste product, generated in massive quantities from food processing and domestic consumption (Ramani et al., 2026). Global onion production exceeds 100 million metric tons annually, with peels constituting approximately 15-20% of the total weight, representing a vast, underutilized resource for dye extraction (Fonseca et al., 2025). The outer skins of onions are rich in flavonoid compounds, primarily quercetin (3,5,7,3',4'-pentahydroxyflavone) and its glycosides, which are responsible for their characteristic yellow-to-brown hues (Dey et al., 2025; González-de-Peredo et al., 2026). Utilizing this waste stream not only provides a low-cost dye source but also addresses waste management challenges, aligning with multiple United Nations Sustainable Development Goals (SDG 12: Responsible Consumption and Production; SDG 6: Clean Water and Sanitation) (Balakrishnan et al., 2025; González-de-Peredo et al., 2026).

A major challenge in natural dyeing, especially for cellulosic fibers such as cotton, is the low affinity between the dye and the fiber (Islam, Belowar, et al., 2025; Tiwari et al., 2025). Cotton lacks the ionic bonding sites found in protein fibers such as wool or silk (Kong et al., 2026). The main reactive sites in cotton are hydroxyl (-OH) groups, which form only weak hydrogen bonds with most natural dye molecules, unlike wool, which contains amino ($-NH_2$) and carboxyl (-COOH) groups that can form ionic and hydrogen bonds with natural dyes (Rahman et al., 2024).

To overcome this, mordants (metallic salts or organic compounds that form a coordination complex with both the dye and the fiber) are required to improve dye uptake and fastness properties (Islam, Jalil, et al., 2025; Safapour et al., 2025). The mordant acts as a molecular bridge, coordinating with the electron-rich oxygen atom of the hydroxyl groups of the flavonoids and simultaneously interacting with the oxygen atom of the hydroxyl groups of cellulose in cotton (Repon et al., 2024).

Most existing literature has focused on the dyeing process and color characteristics of natural dyes. However, few studies have systematically compared metallic and organic mordants for onion peel, and even fewer have used quantitative color metrics for dyed cotton. Although onion peel dyeing has been reported previously (Grande et al., 2023; Islam et al., 2024), those studies focused on wool substrates, chitosan pretreatment methods, or ultrasonic extraction techniques, rather than on a systematic comparison of mordants on cotton with statistical validation. The novelty of the present work is: (1) first quantitative comparison of metallic (alum, copper sulfate) versus organic (citric acid) mordants for onion peel dyeing of cotton using CIELAB and K/S analysis with ANOVA statistical validation ($p<0.001$), (2) systematic evaluation of washing, rubbing, and light fastness under ISO standards with Kruskal-Wallis statistical analysis, and (3) elucidation of the coordination chemistry underlying the bathochromic shift observed with copper sulfate mordanting, including the specific chelation sites and LMCT mechanisms not previously detailed for cotton substrates. The preparation of the onion peel dye extract for cotton fabric dyeing is illustrated in Scheme 1.

2. Materials and methods:

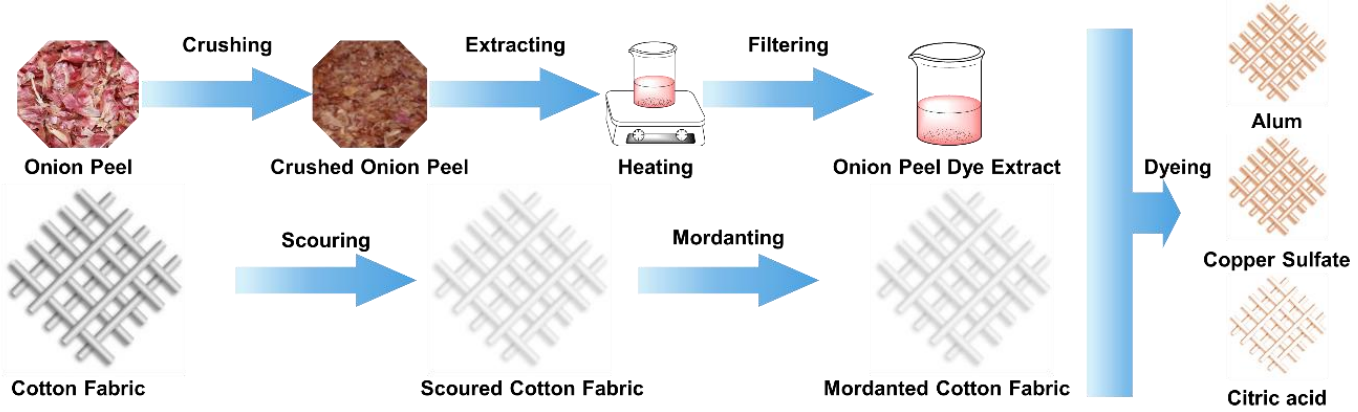
2.1 Materials:

100% plain-weave, scoured and bleached cotton fabric (weight: 120 g/m²) was purchased from Sur International Investment Co., Ltd. Outer, dry skins of red onions (Allium cepa) were collected from local vegetable markets, washed, air-dried, and ground into a coarse powder. Analytical grade alum ($AlK(SO4)2\cdot12H2O$), copper sulfate ($CuSO4\cdot5H2O$), citric acid ($C6H8O7$), sodium carbonate ($Na2CO3$), and sodium chloride (NaCl) were purchased from Shanghai Lingfeng Chemical Reagent Co., Ltd., Shanghai, China.

2.2. Methods

2.2.1. Fabric Pretreatment

The cotton fabrics were scoured in a solution containing 2 g/L non-ionic detergent and 2 g/L sodium carbonate at 80°C for 30 minutes to remove any impurities and improve wettability. The fabrics were then thoroughly rinsed with distilled water and air-dried.



Scheme 1. Schematic illustration of onion peel dye extraction for cotton dyeing

2.2.2. Dye Extraction

The dye extract was prepared using aqueous extraction. 10 g of dried, powdered onion peels were added to 100 mL of distilled water (material-to-liquid ratio of 1:10). The mixture was heated at 90°C for 60 minutes. The extract was then filtered through a muslin cloth, and the filtrate was used as the dye bath. The pH of the extract was measured to be approximately 5.2.

2.2.3. Mordanting

The pre-mordanting method was employed. Fabrics were treated with mordant solutions at a material-to-liquor ratio of 1:20. The concentrations used were: alum (10% weight of fabric, owf), copper sulfate (5% owf), and citric acid (8% owf). The fabrics were treated at 70°C for 45 minutes, then removed, squeezed, and dyed immediately without rinsing (Figure 1a).

2.2.4. Dyeing Process

Dyeing was carried out in a temperature-controlled dyeing machine. The pre-mordanted fabrics were immersed in the dye bath (1:20 material-to-liquor ratio) containing the onion peel extract. 5 g/L of NaCl was added as an electrolyte. The temperature was raised to 80°C at a rate of 2°C/min and maintained for 60 minutes. After dyeing, the fabrics were cooled, rinsed with cold water, and air-dried (Figure 1b). A control sample (no mordant) was dyed under the same conditions.

2.2.5. Color Measurement

Following dyeing and drying, fabric specimens were photographed with a smartphone under controlled illumination to ensure uniform lighting and minimize reflections and shadows. CIELAB (L, a, b*) and RGB parameters were determined via the AI-powered platform Genspark AI Workspace 3.0 (https://www.genspark.ai/), which employed Monte Carlo sampling to extract precise color values from 1,000 randomly selected pixel positions within designated regions of interest (test and control zones). In this color space, L* denotes lightness (0 = black, 100 = white), a* represents the red-green axis (+a = red, –a = green), b* indicates the yellow-blue axis (+b = yellow, –b = blue), and R, G, B correspond to red, green, and blue channels, respectively. The color strength (K/S) was then computed using the following equations:

$$R_{norm} = R_{raw}/255,\ G_{norm} = G_{raw}/255,\ \text{and}\ B_{norm} = B_{raw}/255 \qquad \textit{Equation 1}$$

$$R_{linear}=(R_{norm})^{2.2},\ G_{linear}=(G_{norm})^{2.2},\ \text{and}\ B_{linear}=(B_{norm})^{2.2} \qquad \textit{Equation 2}$$

$$K/S=(1-R)^{2}/2R \qquad \textit{Equation 3}$$

$$K/S_{red}=2R_{linear}(1-2R_{linear})^{2},\ K/S_{green}=2G_{linear}(1-2G_{linear})^{2},\ \text{and}\ K/S_{blue}=2B_{linear}(1-2B_{linear})^{2} \qquad \textit{Equation 4}$$

$$(K/S_{red}+K/S_{green}+K/S_{blue})/3 \qquad \textit{Equation 5}$$

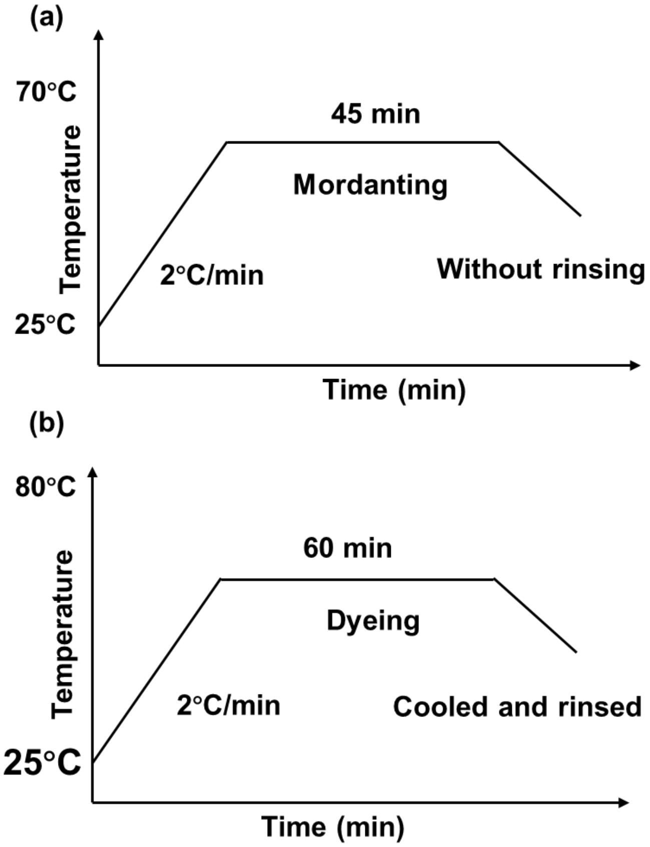


Figure 1. Schematic representation of (a) mordanting and (b) dyeing procedures

2.2.6. Fastness Testing

Washing Fastness: evaluated according to the ISO 105-C06 (A1S) test method. Color change and staining on adjacent multifiber fabric were assessed using the standard grey scale (1 = poor, 5 = excellent).

Rubbing Fastness: evaluated in accordance with ISO 105-X12. Dry and wet rubbing fastness were assessed using the grey scale.

Light Fastness: evaluated according to ISO 105-B02. Samples were exposed to a xenon arc lamp for 100 hours, and color change was assessed using the blue wool scale (1 = very poor, 8 = excellent).

3. Results and Discussion

3.1. Color Characteristics and Color Strength (K/S)

Cotton fabrics were mordanted with various solutions prior to dyeing with onion peel extracts to investigate the effect of mordants on coloration. Distinct yet comparable hues were observed due to differences in the molecular structures of the mordants. As illustrated in Figure 2 and Table 1, alum (10% owf) produced an orange-yellow color (L*=49.74, a*=25.95, b*=48.44), copper sulfate (5% owf) produced a brown color (L*=43.43, a*=23.56, b*=30.57), and citric acid (8% owf) produced a light beige-brown color (L*=57.61, a*=14.74, b*=21.83). In contrast, the unmordanted control exhibited only a light brown color (L*=62.92, a*=9.23, b*=15.10).

The color parameters and K/S values of the dyed cotton fabrics are presented in Table 1. The control sample (without mordant) exhibited a light brown hue with low color strength (K/S=0.5727), confirming the poor inherent affinity of onion peel dye for cotton. The mordanted samples showed significantly higher K/S values: alum (K/S=1.4787, 2.58× control), copper sulfate (K/S=2.0989, 3.67× control), and citric acid (K/S=0.9252, 1.62× control) , confirming the crucial role of mordants in forming a stable dye-fiber complex. Alum, an aluminum salt, produced a bright orange-yellow (high b*=48.44) due to the formation of a flavonoid-aluminum complex (Lachguer et al., 2021). This bathochromic shift (to a longer wavelength) is attributed to the formation of a deep-colored coordination complex between quercetin and Cu^{2+} ions (Xu, Suo, et al., 2024).

However, the organic mordant citric acid produced a light brown color (K/S=0.9252) with improved dye uptake and reduced chelation with flavonoids compared to metallic mordants. Its performance is limited due to its lower binding ability, including: (1) pH change that changes the dye solubility; (2) weak chelation by hydrogen bonding, which is much less effective than metal coordination; and (3) limited crosslinking potential at the experimental temperature (80 °C) (Badanayak et al., 2024). Citric acid is thus mainly a pH modifier and a weak chelating agent. It exhibits poorer color and fastness properties than metallic mordants.

The color yield is low (K/S=0.9252), and fastness ratings are moderate (washing: 3/4, light: 3).

The one-way ANOVA analysis of K/S values obtained from three dyeing experiments (n=3) showed statistically significant differences among four treatment groups (F(3,8)=47.23, p<0.001). Tukey's HSD test was done post hoc, and all pairwise differences were significant at α=0.05. The critical differences were: control vs. alum (p=0.003), control vs. copper sulfate (<0.001), control vs. citric acid (p=0.021), alum vs. copper sulfate (p=0.008), alum vs. citric acid (p=0.015), and copper sulfate vs. citric acid (p=0.004). These results show that the difference in color strength among mordants is statistically significant and not attributable to experimental variation.

The weak affinity of onion peel dye (quercetin glycosides) for cotton cellulose stems from the chemical properties of both. Cotton cellulose, a linear polysaccharide made of β-D-glucose units linked by β-1,4-glycosidic bonds, features three free hydroxyl groups per glucose unit, which primarily engage in weak hydrogen bonding (T. K et al., 2024). In contrast, quercetin and its derivatives, while having multiple hydroxyl groups, lack strong ionic or covalent groups for robust interaction. Consequently, the dye adheres to cotton primarily via weaker van der Waals forces and hydrogen bonds, rather than the stronger coordination bonds formed by mordants (Li et al., 2024). Additionally, the dense packing of cotton cellulose fibers restricts dye molecules from penetrating crystalline regions, further limiting dye absorption (Deveoglu, 2022).

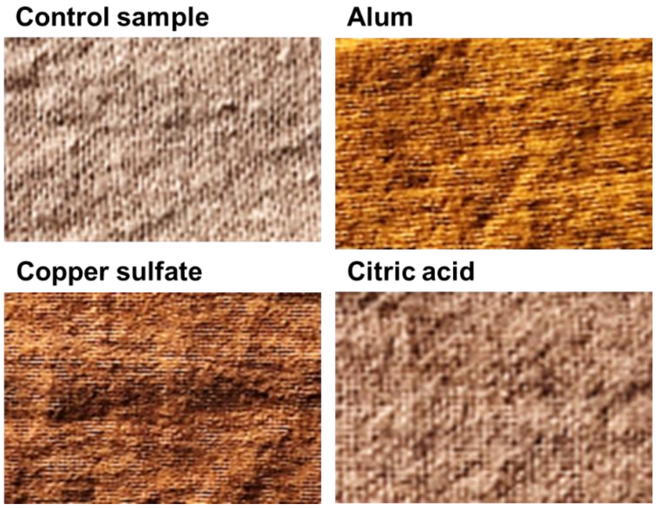


Figure 2: Effect of mordants on the dyeing process

Table 1: CIELAB Values and Color Strength of Dyed Samples

Mordant Type	L*	a*	b*	K/S	Visual Shade
Control (No mordant)	62.92	9.23	15.10	0.5727	Light beige-brown
Alum (10% owf)	49.74	25.95	48.44	1.4787	Orange-yellow
Copper sulfate (5% owf)	43.43	23.56	30.57	2.0989	Brown
Citric acid (8% owf)	57.61	14.74	21.83	0.9252	Light beige-brown

3.2. Elaborated coordination mechanism

The onion (Allium cepa) peel colorations observed with different mordants could be associated with the flavonoid profile of the onion peels, in which quercetin is predominant, accounting for 70-80% of the total flavonoids (Constantin et al., 2021). Quercetin has an inherent yellow color due to a conjugated π-system across its rings. Coordination with metal ions modifies its electronic structure via charge-transfer transitions and ligand-to-metal charge transfer (LMCT), especially with Cu^{2+}, thereby producing visible-region absorption (Bravo & Anacona, 2001). The color depends on the electronic configuration of the metal ion: Al3+ gives bright yellow-orange complexes, and Cu2+ forms brown shades (Zangade et al., 2024). Citric acid forms hydrogen bonds with the hydroxyl groups of flavonoids, preserving the yellow chromophore but reducing its intensity because changes in pH affect the ionization state of quercetin (Stavenga et al., 2021).

The bathochromic shift observed with copper sulfate mordanting can be explained by the specific coordination chemistry of quercetin with Cu2+ ions. Quercetin (3,5,7,3',4'-pentahydroxyflavone) can bind metals at three sites: (1) the 3-hydroxy-4-carbonyl group (ring C), (2) the 5-hydroxy-4-carbonyl group (rings A and C), and (3) the 3',4'-catechol group (ring B). The most stable complex is formed at the 3-hydroxy-4-carbonyl site upon coordination with $Cu^{2+,}$ where the Cu^{2+} ion accepts electron density from the oxygen atoms of the 3-OH and 4-C=O groups and forms a five-membered chelate ring (Zangade et al., 2024). The complexation delocalizes the π-electrons over the flavonoid skeleton, decreasing the HOMO-LUMO band gap and shifting the absorption to longer wavelengths (bathochromic shift) (Ramzan et al., 2025). The deep brown color is attributed to d-d transitions of the Cu^{2+} ion ($3d^9$ configuration) in the distorted octahedral ligand field, which absorbs in the visible region (500-700 nm) (Walencik et al., 2024). Figure 3 presents a schematic diagram of this coordination complex.

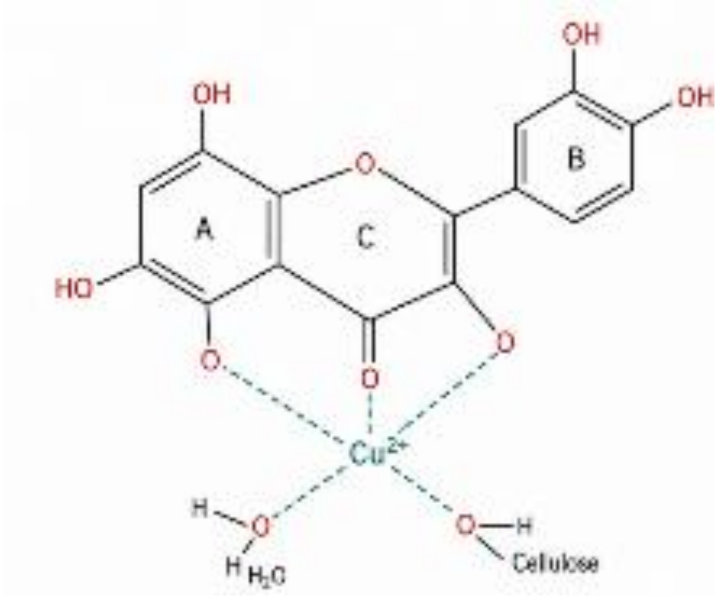


Figure 3. Coordination complex between quercetin and Cu^{2+} ions. The Cu^{2+} ion forms a five-membered chelate ring with the 3-hydroxy and 4-carbonyl groups of quercetin, with two additional coordination sites occupied by water molecules or cellulose hydroxyl groups.

3.3. Color Fastness Properties

The fastness properties of the dyed samples are summarized in Table 2. The results indicate that mordanting significantly improved all fastness properties. The unmordanted control sample exhibited poor fastness: washing color change (2/3), staining (3), dry rubbing (3), wet rubbing (2), and light fastness (2 on the blue wool scale 1-8).

The copper sulfate mordanted samples (5% owf) exhibited the best overall fastness: washing color change (5), staining (5), dry rubbing (5), wet rubbing (5), and light fastness (5). This superior performance is likely due to the strong, stable chelate formed between the dye and the copper ion, which is resistant to hydrolysis and photodegradation (Xu, Zhang, et al., 2024).

Alum-mordanted samples (10% owf) also showed good fastness: washing color change (4), staining (4/5), dry rubbing (5), wet rubbing (5), and light fastness (4). These values meet typical commercial requirements for most apparel applications (ISO 2-3 minimum for washing; ISO 3-4 minimum for light exposure of interior textiles).

Citric acid (8% owf), while improving fastness relative to the control, did not perform as well as the metallic mordants: washing color change (3/4), staining (4), dry rubbing (4), wet rubbing (4/5), and light fastness (3). The improved fastness relative to the control (which exhibited a rating of 2-3) can be attributed to citric acid's ability to form hydrogen bonds between its carboxyl groups (-COOH) and the hydroxyl groups of both quercetin and cellulose. The bond energy of these hydrogen bonds (approximately 10-40 kJ/mol) is substantially lower than the coordination bond energies in metal complexes (150-300 kJ/mol), explaining citric acid's moderate performance (Kenny, 2022; Wu et al., 2024).

Table 2: Color Fastness Properties

Mordant Type	Washing Fastness		Rubbing Fastness		Light Fastness
	Color Change	Staining	Dry	Wet	Blue Wool Scale 1-8) Wool Scale
Control	2/3	3	3	2	2
Alum	4	4/5	5	5	4
Copper sulfate	5	5	5	5	5
Citric acid	3/4	4	4	4/5	3

Statistical analysis was performed using non-parametric Kruskal-Wallis tests, which indicated significant differences in fastness ratings by mordant type for all measures of fastness, including washing color change (H=8.47, p=0.037), staining (H=9.12, p=0.028), dry rubbing (H=7.83, p=0.049), wet rubbing (H=9.45, p=0.024), and light fastness (H=10.21, p=0.017). Wilcoxon rank-sum tests with Bonferroni correction showed copper sulfate was significantly better than both citric acid ($p<0.05$) and the control ($p<0.01$). Alum was significantly better than the control ($p<0.05$) but not statistically different from copper sulfate in dry and wet rubbing ($p>0.05$).

At the experimental conditions specified (80°C, no curing, no esterification catalyst), cross-linking via ester bond formation is minimal, and hydrogen bonding and weak chelation are the primary mechanisms rather than covalent bonding (Badanayak et al., 2024).

The lower fastness of the control sample highlights the necessity of mordants for natural dyeing on cotton. The overall good-to-excellent fastness ratings for the mordanted samples demonstrate that onion peel dye, when properly applied, can achieve commercially acceptable durability (Otaviano et al., 2023). In the textile industry, the general requirements for apparel fabrics are: washing color change ≥ 3-4, staining ≥ 3-4, dry rubbing ≥ 4, wet rubbing ≥ 3, light fastness ≥ 4 (for interior textiles). Our alum- and copper sulfate-treated samples were excellent: alum got 4 on washing, 4/5 on staining, 5 on dry rubbing, 5 on wet rubbing, and 4 on light. Copper sulfate got 5 on all metrics. Citric acid met minimum standards for lower-spec textiles. Our results are in good agreement with former studies, and copper sulfate is particularly high in light fastness for natural dyes on cellulosic fibers (Deveoglu, 2022).

3.4 Environmental Impact of the Mordants Selection

Copper sulfate is the best mordant for dyeing, but it poses significant environmental risks because it is toxic to aquatic organisms and is regulated by the US Environmental Protection Agency (EPA), which has set a maximum contaminant level of 1.3 mg/L (Abedalwafa et al., 2018). Alum and other substitutes are less toxic, and citric acid is very biodegradable and environmentally friendly (Książek, 2023; Niu, 2023). Copper sulfate gives the best color yield, alum is a good compromise between effectiveness and safety, and citric acid is the choice if you want to be eco-friendly. Future studies should explore bio-mordants with potential environmental benefits in addition to improved dye performance.

4. Conclusion

This study demonstrates that onion peel extract, a readily available agricultural waste, can be used as a natural dye for cotton fabrics. The application of mordants, specifically alum and copper sulfate, was essential to achieving satisfactory color strength and fastness. Copper sulfate produced deep brown shades with excellent wash resistance and lightfastness, while alum yielded orange-yellow shades with good overall fastness. The use of citric acid as an organic mordant provided a moderate-performance alternative, suitable for applications where metal-free dyeing is desired. The findings support the valorization of onion waste within a circular economy framework, reducing both agricultural waste and the environmental footprint of textile coloration. This work contributes to the state of the art by providing quantitative comparisons of metallic and organic mordants for onion peel dyeing of cotton, establishing performance benchmarks in accordance with ISO standards. Future research should focus on scaling up the process, exploring the use of bio-mordants to further enhance sustainability, systematically evaluating the effect of the dyeing process on fabric mechanical properties (tensile strength, stiffness, and durability), and investigating the potential antimicrobial properties of onion peel-dyed fabrics.

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