GREEN AND SUSTAINABLE DEVELOPMENT OF FUNCTIONAL COTTON TEXTILES WITH AGRO-BASED BIO-COLORANT

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Green processing is globally demanded for its economic, social, and environmental benefits. Synthetic textile dyes and auxiliaries are not eco-friendly and negatively affect the wearer's skin and environment. In this work, cotton fabric samples were successfully dyed with a natural dye turmeric (*Curcuma longa*) and a green mordant, citric acid, was also used as a crosslinker. Turmeric colorant was extracted from *Curcuma longa* at a temperature of 90-100 °C. Three (pre-, meta- and post-) crosslinking techniques were examined by varying the parameters, such as the concentration of the natural dye and of the crosslinker. A high-temperature dyeing machine was used for carrying out the procedure at 80 °C for 40 minutes. It was found that results with the maximum K/S value were achieved with the meta-crosslinking method and it was also observed that natural dyes combined with green mordants produced excellent perspiration, crocking, and wash fastness properties, with no color fading. A satisfactory and moderate lightfastness was achieved. The results clearly show that turmeric and acetic acid are an excellent natural dye and auxiliary agent, respectively, for cotton textile coloration, allowing a green processing method.

Keywords: citric acid, turmeric, green crosslinking, eco-friendly dyeing, functional textile, sustainability

INTRODUCTION

In the textile industry, most of the chemicals used, especially synthetic dyes, are a major source of environmental pollution.[1] These dyes are synthesized from petrochemicals, which have a harmful impact on ecosystems and human beings.[2] Also, the chemical treatment of fabrics, involving wet-chemical processing steps, requires substantial amounts of water, chemicals, and various auxiliary agents.[3,4] These processes produce a substantial amount of wastewater, including dyes, pigments, and chemicals, which is discharged into natural water bodies.[5] The chemicals used in the pretreatment of fabrics thus cause pollution of water and soil, adversely affecting plants, animals, and the fertility of agricultural land.[6]

Based on their application method, synthetic dyes are classified as reactive, vat, direct, basic, acid, and dispersed dyes. Meanwhile, based on their chemical structure, they are categorized as azo, nitro, anthraquinone, indigo, sulfur, and phthalocyanine dyes.[7] Dyeing processes result in the production of effluent containing high concentrations of organic matter, colored substances, toxicants, surfactants, salts, and chlorinated compounds.[8] Such effluent is hazardous, possesses mutagenic and carcinogenic properties, and reduces light penetration and photosynthetic activity.[9,10,11] Textile wastewater also fluctuates in terms of the levels of biochemical oxygen demand (BOD) and chemical oxygen demand (COD) in water.[12] As synthetic dyes are non-biodegradable and originate from non-biodegradable sources, they persist in the environment for extended periods of time, posing significant hazards to living organisms.[13]

A significant drawback of synthetic reactive dyes is hydrolysis, leading to extensive washing as a substantial amount of dye fails to adhere to the fabric.[14] In the conventional reactive dyeing

process, elevated levels of salt and alkali are used, resulting in effluent that is harmful to human health, crops, and marine life.[15] Several studies have experimented with chemical modification techniques to cationize cotton fibers, aiming to reduce the amount of salt required in dyeing. These methods involve the use of compounds containing cationic groups to enhance dye absorption from dye baths.[16] However, these alteration techniques pose significant environmental concerns. As a consequence, the dyeing industry is actively exploring eco-friendly processes as substitutes for harmful chemicals and processes.

There is an increase in the demand for natural dyestuffs globally as people are getting aware of the environmental and health risks of synthetic dyestuffs use in the textile industry.[17] Natural colorants are non-toxic, eco-friendly, and biodegradable, compared to synthetic dyes.[18] Most natural dyes are harmless, and some even have medicinal effects. For example, turmeric has antibacterial properties and is widely used to aid in wound healing.[19] Turmeric dyes contain various molecular components, including three gold-colored alkaloidal curcuminoids: bisdemethoxy curcumin, curcumin, and desmethoxy curcumin.[20] Curcumin possesses anti-inflammatory, antifungal, antibacterial, and antitumor properties.[21] However, natural dyes typically exhibit low substantivity towards fibers, necessitating the use of a mordant to enhance their affinity towards the fiber.[22]

To fix natural dyes onto textile fabrics, both synthetic and natural mordants are employed.[23,24] Citric acid (CA), a polycarboxylic acid used as a green crosslinking agent for cotton, is both cost-effective and environmentally friendly.[25] Citric acid can be produced from various agricultural by-products and waste materials.[26] Citric acid facilitates the bonding of natural dyes with natural fibers by promoting crosslinking between them. Citric acid, being non-volatile, plays a significant role in regulating the pH levels necessary throughout the dyeing process and subsequent dyeing cycles.[27]

Three different mordanting methods can be utilized: pre-mordanting, meta-mordanting, and post-mordanting. The durability characteristics of the dyed material may vary based on the mordanting method employed. With pre-mordanting, the fabric undergoes mordant treatment before dyeing. Meta-mordanting, also called simultaneous mordanting, involves adding both mordant and dye to the dye bath simultaneously. Post-mordanting, on the other hand, applies the mordant to the fabric after it has been dyed.[28]

Numerous studies have explored turmeric dye, focusing on dyeing conditions and the characteristics of dyed cotton fabrics, predominantly employing synthetic mordants.[29,30,31,32] Unlike them, this study utilizes citric acid as a mordant with natural turmeric dye powder at varying concentrations and treatment levels (pre-mordanting, meta-mordanting, and post-mordanting) to assess the true impact of the mordant on cotton fabrics. The basic aim of this research has been to attain an eco-friendly or green cellulosic dyeing process by using natural dye and citric acid, without using any other salt and auxiliary.

In this study, we developed a method for extracting a natural colorant, without using organic solvents. Citric acid served as a green mordant/crosslinker to enhance the color strength of the natural colorant. In order to understand the impact of different amounts of mordant (citric acid) combined with various turmeric concentrations at different stages (pre-, meta-, and post-), the dyed fabric samples were studied for their color strength (K/S), colorfastness to dry and wet rubbing, wash fastness, light fastness, and visual uniformity of the final dyed samples. Additionally, the antibacterial activity of turmeric-dyed cotton was evaluated. Our main objective was to establish a technology for developing sustainable and eco-friendly functional cotton textiles from natural bio-based colorants and a crosslinker.

EXPERIMENTAL

Materials

Turmeric (*Curcuma longa*) was used as a natural colorant, which was extracted in the lab. Citric acid (Sigma Aldrich) was used as a crosslinker to fix the dye on cotton fabric. 100% pre-treated, but not mercerized cotton fabric was used in this research. To perform this experiment, a high-temperature dyeing machine (GT-D22 China) was used.

Methodology

Extraction of natural dye

The process flow of the experiment is illustrated in Figure 1. The fresh rhizome of turmeric was collected, after washing with distilled water and then drying at room temperature for about a week, the dried rhizomes were ground into powder with an electronic mill. At first, natural dye powder with a quantity of 40 g was

dissolved in 2 beakers containing 400 mL of distilled water. The extraction of turmeric dye was performed at 100 °C in the water bath for 1 hour, under continuous stirring to achieve better extraction of the dye. Afterwards, the colorant was filtered and dried in the oven, then it was ground to obtain a fine powder.

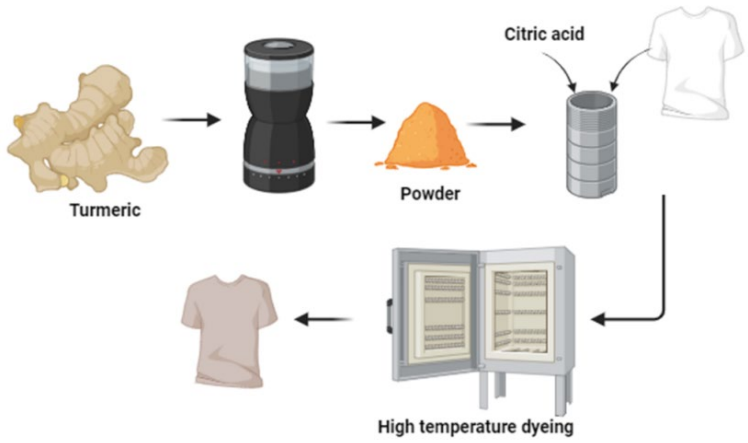

Figure 1: Process flow of the experiment from extraction to application

Dyeing

The cotton fabric samples were dyed by the exhaust method. The crosslinker (citric acid) was added in different concentrations. Pre-treated and crosslinked cotton fabric was put in an HT dyeing machine containing various (1%, 2%, 4%, 8%) concentrations of turmeric extract at a material to liquor ratio of 40:1 at 80 °C for 40 minutes. Three different crosslinking techniques, *i.e.* pre-crosslinking, meta-crosslinking, and post-crosslinking were employed in this research.

In the pre-crosslinking method, cotton fabric (5 g) was treated with citric acid at 80 °C, followed by dyeing with turmeric, maintaining a liquor ratio of 40:1. The crosslinker and natural dye form a complex inside the fibers. At the end of the chosen period of dyeing, washing at 70 °C for 15 minutes was carried out. A washing agent, Felosan RGN, was added.

The meta-crosslinking treatment was done by treating the fabric with the dye and the crosslinker simultaneously at 80 °C for 40 minutes in an HT dyeing machine. The fabric after dyeing was washed at 70 °C for 15 minutes by adding a washing agent.

In the post-crosslinking method, the fabric was initially dyed with turmeric at 80 °C for 40 minutes in the HT machine. Then, the dyed fabric was treated with citric acid at 70 °C for 40 minutes. Finally, the citric acid-treated fabric was washed at 70 °C for 15 minutes.

Characterization techniques

FTIR spectroscopic analysis

Fourier transform infrared spectroscopy (FTIR) is an analytical technique that identifies functional groups in a molecule by recording the IR absorption spectrum. An FT-IR Spectrometer (Bruker ALPH, Germany) was used to identify the functional groups of the samples, after collecting all high-resolution spectral data simultaneously over a wide spectral range (4000 to 400cm^{-1}).

Analysis of color strength

The K/S (absorption coefficient (K) and scattering coefficient (S)) determines the depth of color of a dyed fabric. In textile applications, K/S values are used to regulate color process factors in dyeing and finishing textiles. Color strength (K/S) is an important variable to check the quality of a sample in terms of the depth of the color-dyed fabric. The color yield of the dyed fabric samples was determined by using a spectrophotometer. The K/S values of the dyed samples were calculated by using the Kubelka Munk equation (1):

$$K/S = (1-R_\infty)^2/2R_\infty \quad (1)$$

where R = reflectance of incident light from the dyed material, K = absorption, and S= scattering coefficient factor of the dyed fabric.

Analysis of color fastness to washing

Dyed cotton fabric was washed at 60 °C for 30 minutes in a laundrometer to assess its washing fastness. Color degradation is compared to non-washed samples, and staining is checked with multi-fabric. Color change was measured using the greyscale, which ranges from 1 (poor) to 5 (excellent). Fastness to washing was evaluated according to ISO 105-C01 standards.

Analysis of color fastness to light

UV and visible light from the sun may damage any substance, including our skin, metal, and even dyed fabric. Light fastness refers to how well and how long a dye resists fading when exposed to continuous light. Light fastness was evaluated by using a light fastness tester according to ISO 105-

BO2 standard, and the rating was taken with a blue scale (rating from 1 to 8).

Analysis of color fastness to rubbing

Rubbing fastness assesses a dyed fabric's ability to retain its color when rubbed. Dry rubbing color fastness measures resistance to fading and discoloration when rubbed with a regular white cloth. Wet rubbing color fastness evaluates fading or staining when rubbed with a wet white cloth. Staining is assessed by comparing the white fabric to staining sample cards, with values ranging from 1 to 5 indicating poor to excellent fastness. Auto crock equipment from Advance System Logic Company was used to determine wet and dry rubbing fastness values, following ISO 105-X12 standard procedures.

Analysis of color fastness to perspiration

Perspiration fastness measures a fabric's resistance to staining and fading due to sweat, which contains salt among other components. The AATCC-15 standard was used to test perspiration fastness. To measure the perspiration fastness, the samples attached with a multifiber swatch were dipped in a solution of 10 g/L NaCl, 1 g/L disodium hydrogen phosphate, and 0.25 g/L histidine with a maintained pH of 4.3. The soaked specimens were positioned between plates in a perspiration tester, with a 10 lb weight applied to compress them. The tester was then placed in an oven at around 38 °C for 6 hours, simulating body temperature. After removal, both the multifiber swatch and the textile specimen were inspected in a lightbox under D65 artificial daylight.

Analysis of antibacterial activity

The agar diffusion test was conducted to observe the effect of turmeric dyed samples against the growth of bacteria. The bacteria were spread on an agar plate, incubated and then observed. Agar diffusion tests were used to determine the antimicrobial potential of the samples.

RESULTS AND DISCUSSION

Fourier transform infrared spectroscopy (FTIR)

FTIR spectroscopy was employed to analyze the functional groups present in the cotton fabric. The spectra of untreated, pre-crosslinked, meta-crosslinked, and post-crosslinked samples are presented in Figure 2. FTIR analysis was performed on the fabric sample that showed the highest K/S value, treated with 60 g/L citric acid and dyed using 8% dye concentration. The stacked FTIR spectra illustrate the chemical structure and functional group changes in cotton fabrics treated with turmeric dye and different concentrations of citric acid as a crosslinking agent. The untreated cotton fabric (Fig. 2a) shows characteristic cellulose peaks, including a broad O–H stretching vibration around 3300 cm^{-1}, C–H stretching near 2900 cm^{-1}, and strong C–O–C and C–O stretching vibrations in the range of 1000-1200 cm^{-1}. A rare and notable ester carbonyl (C=O) stretching peak appears around 1700-1730 cm^{-1} in Figure 2b, indicating successful esterification between citric acid and the hydroxyl groups of cellulose. This confirms the formation of crosslinks between the fabric and the citric acid. The spectra of the pre-treated, meta-treated, and post-treated samples with citric acid show very similar patterns due to the subtle nature of chemical changes involved in the esterification and dye-fixation processes, which often do not significantly alter the major functional group peaks. Additionaly, due to overlapping peaks and the semi-quantitative nature of FTIR, particularly in complex biological matrices like dyed cotton, the spectral changes may appear as minimal.

Visual uniformity analysis

From Figure 3 (a, b, c), it is evident that the developed samples exhibit good uniformity. This is attributed to the presence of citric acid and the low acidic condition (around pH 4), where turmeric displays a uniform yellow color, at low dye concentrations, and reddish at high dye concentrations. Additionally, pre-crosslinked cotton fabric samples show dark shades, compared to meta and post-crosslinked dyed fabrics. This is because pre-crosslinking involves treating the cotton fabric with citric acid first, forming better crosslinks between the citric acid and the fabric.

Color strength

Table 1 shows the color strength values of pre-, meta- and post-crosslinked dyed samples. It has been noticed that pre-crosslinked cotton fabric exhibited a deeper shade, compared to the meta- and post-crosslinked samples. A few deep shades have been found in meta-crosslinked colored fabric. In the pre-crosslinked cotton fabric, the sample was first treated with citric acid, allowing for crosslinking between citric acid and the fabric to take place, and then, the fabric was treated with the dye. As the shade depth increased, the K/S value also increased, as may be noted in Table 1. Hence, the fabric dyed by the turmeric pre-crosslinking technique shows a good K/S value (3.650).

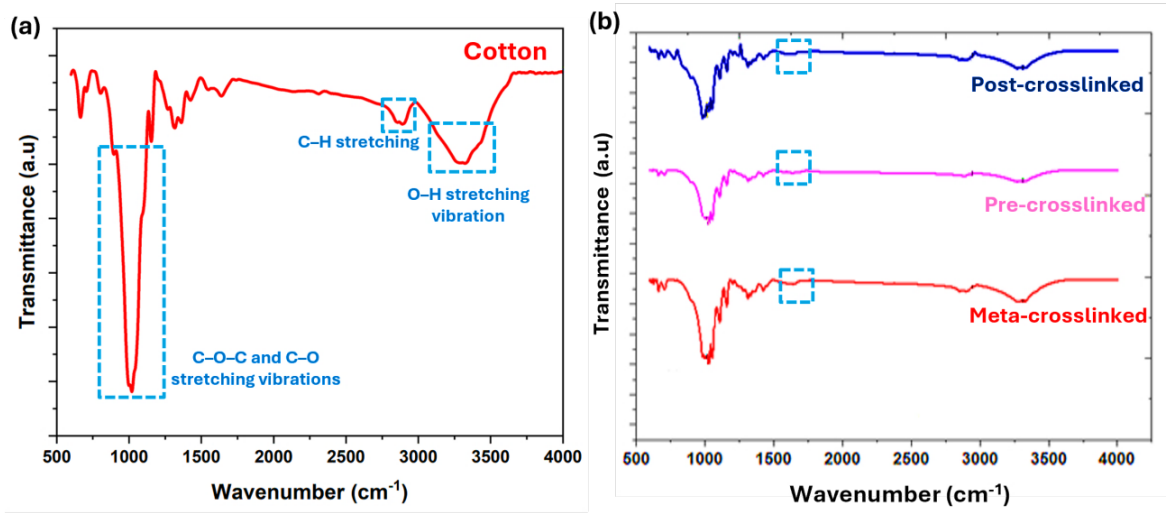

Figure 2: FTIR spectra of (a) untreated cotton, and (b) pre-, meta- and post-crosslinked fabrics

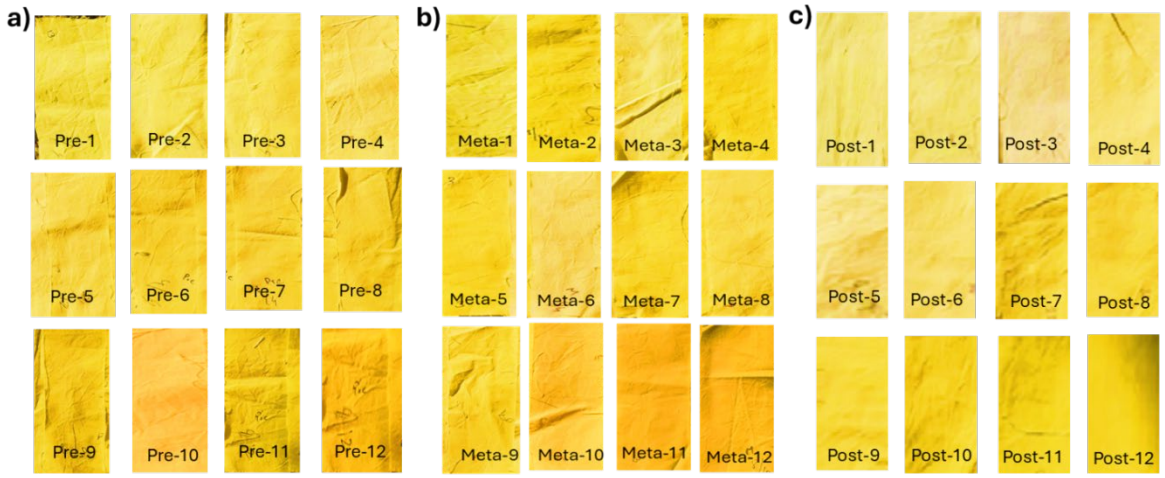

Figure 3: Visual uniformity of a) pre-crosslinked, b) meta-crosslinked, and c) post-crosslinked turmeric dyed fabrics

The K/S values of meta-crosslinked dyed fabric are relatively moderate compared to those of the pre-crosslinked dyed fabric; this is because both turmeric and citric acid are used in the meta-crosslinking process at the same time, so that the simultaneous crosslinking of the citric acid with the dye molecule and the cellulose initiates the process. Thus, the moderate reactivity of citric acid opposes the movement of dye molecules through the cellulose fabric. Similarly, the K/S value of the meta-crosslinked dyed cotton fabric was lower than that of the pre-crosslinked dyed cotton fabric. In this case, however, K/S increased with the percentage of the crosslinker. In addition, many meta-crosslinked fabrics have good color fastness (K/S value 3.81).

On the other hand, poor K/S values were observed for post-crosslinked dyed cotton fabric (2.404). This is because after crosslinking, cotton fabric is pretreated mainly with turmeric dye, which has the highest affinity and the lowest functional affinity with cellulose-containing functional group (-OH), followed by citric acid. Due to this fact, the pre- and meta-crosslinked dyed fabrics gave satisfactory K/S values compared to the post-crosslinked dyed cotton fabric.

Table 1
K/S values of pre-, meta- and post-mordanted cotton fabric

Sample	Dye conc. (%)	Crosslinking method	Crosslinker conc. (g/L)	Colour strength (K/S) values
pre-1	1	pre	20	1.283
pre-2	1	pre	40	1.080
pre-3	1	pre	60	1.069
pre-4	2	pre	20	1.692
pre-5	2	pre	40	1.170
pre-6	2	pre	60	1.928
pre-7	4	pre	20	2.399
pre-8	4	pre	40	2.585
pre-9	4	pre	60	2.393
pre-10	8	pre	20	3.650
pre-11	8	pre	40	2.704
pre-12	8	pre	60	2.693
meta-1	1	meta	20	0.485
meta-2	1	meta	40	0.600
meta-3	1	meta	60	1.097
meta-4	2	meta	20	0.367
meta-5	2	meta	40	1.431
meta-6	2	meta	60	0.516
meta-7	4	meta	20	2.257
meta-8	4	meta	40	1.865
meta-9	4	meta	60	2.619
meta-10	8	meta	20	3.296
meta-11	8	meta	40	3.814
meta-12	8	meta	60	3.414
post-1	1	post	20	0.336
post-2	1	post	40	0.379
post-3	1	post	60	0.148
post-4	2	post	20	0.782
post-5	2	post	40	0.416
post-6	2	post	60	0.644
post-7	4	post	20	1.788
post-8	4	post	40	1.470
post-9	4	post	60	1.662
post-10	8	post	20	2.404
post-11	8	post	40	1.991
post-12	8	post	60	1.586

Washing fastness

Table 2 shows the color fastness to washing of dyed cotton with different shade depths of 1%, 2%, 4%, and 8% with different concentrations of 20 g/L, 40 g/L and 60 g/L of citric acid with pre-, meta- and post-crosslinking techniques. The color fastness to washing of the samples dyed with turmeric using a natural citric acid crosslinker shows excellent results, with rating 5 for the pre-crosslinking technique. However, as the dye concentration increases, the rating for staining declines to 4/5 on the grey scale. The results show that meta- and post-crosslinked dyed cotton fabric follows almost the same trend in washing fastness as the pre-crosslinked fabric.

Light fastness

Table 3 shows the light fastness of dyed cotton fabric at various dye and crosslinker concentrations, using different crosslinking methods. Pre-crosslinked fabric exhibits fair light fastness, with a rating of 2 on the blue scale. Meta-crosslinked fabric has poor light fastness, rated 1, while post-crosslinked fabric shows poor to fair light fastness, with a rating of 1-2. Turmeric shows poor fastness to light due to its inner structure. It contains -OH groups, which intensify the depth of shade according to their increased number in one dye molecule.

Table 2
Washing fastness of pre-, meta- and post-crosslinked dyed cotton fabric

Sample	Acetate	Cotton	Nylon	PES	Acrylic	Wool	Shade change
pre-1	4/5	4/5	4	4/5	4/5	4/5	5
pre-2	4/5	4/5	4	4/5	4/5	4/5	5
pre-3	4/5	4/5	4	4/5	4/5	4/5	5
pre-4	4/5	4/5	4/5	4/5	4/5	4/5	5
pre-5	4/5	4/5	4	4/5	4/5	4/5	5
pre-6	4/5	4/5	4	4/5	4/5	4/5	4/5
pre-7	4/5	4/5	4	4/5	4/5	4/5	4/5
pre-8	4/5	4/5	3	4/5	4/5	4/5	5
pre-9	4/5	4/5	3	4/5	4/5	4/5	4/5
pre-10	4/5	4/5	3	4/5	4/5	4/5	5
pre-11	4/5	4/5	4	4/5	4/5	4/5	4/5
pre-12	4/5	4/5	2/3	4/5	4/5	4/5	5
meta-1	4/5	4/5	4/5	4/5	4/5	4/5	5
meta-2	4/5	4/5	4/5	4/5	4/5	4/5	5
meta-3	4/5	4/5	4	4/5	4/5	4/5	5
meta-4	4/5	4/5	4/5	4/5	4/5	4/5	5
meta-5	4/5	4/5	3/4	4/5	4/5	4/5	4/5
meta-6	4/5	4/5	4	4/5	4/5	4/5	5
meta-7	4/5	4/5	4	4/5	4/5	4/5	4/5
meta-8	4/5	4/5	3	4/5	4/5	4/5	5
meta-9	4/5	4/5	4	4/5	4/5	4/5	4/5
meta-10	4/5	4/5	3	4/5	4/5	4/5	4/5
meta-11	4/5	4/5	2/3	4/5	4/5	4/5	4/5
meta-12	4/5	4/5	3	4/5	4/5	4/5	5
post-1	4/5	4/5	4/5	4/5	4/5	4/5	5
post-2	4/5	4/5	4/5	4/5	4/5	4/5	5
post-3	4/5	4/5	4/5	4/5	4/5	4/5	5
post-4	4/5	4/5	4	4/5	4/5	4/5	5
post-5	4/5	4/5	4	4/5	4/5	4/5	5
post-6	4/5	4/5	4/5	4/5	4/5	4/5	5
post-7	4/5	4/5	3	4/5	4/5	4/5	4/5
post-8	4/5	4/5	3	4/5	4/5	4/5	4
post-9	4/5	4/5	3/4	4/5	4/5	4/5	4/5
post-10	4/5	4/5	3	4/5	4/5	4/5	4
post-11	4/5	4/5	3	4/5	4/5	4/5	4/5
post-12	4/5	4/5	3/4	4/5	4/5	4/5	5

Table 3
Light fastness of pre-, meta- and post-crosslinked dyed fabric samples

Sample	Dye conc. (%)	Crosslinker conc. (g/L)	Crosslinking method	Light fastness values
pre-1	1%	20	pre	2
pre-2	1%	40	pre	2
pre-3	1%	60	pre	1
pre-4	2%	20	pre	2
pre-5	2%	40	pre	1
pre-6	2%	60	pre	2
pre-7	4%	20	pre	2
pre-8	4%	40	pre	2
pre-9	4%	60	pre	2
pre-10	8%	20	pre	2
pre-11	8%	40	pre	2
pre-12	8%	60	pre	2
meta-1	1%	20	meta	1

meta-2	1%	40	meta	1
meta-3	1%	60	meta	1
meta-4	2%	20	meta	1
meta-5	2%	40	meta	1
meta-6	2%	60	meta	1
meta-7	4%	20	meta	1
meta-8	4%	40	meta	1
meta-9	4%	60	meta	1
meta-10	8%	20	meta	2
meta-11	8%	40	meta	1
meta-12	8%	60	meta	1
post-1	1%	20	post	1
post-2	1%	40	post	1
post-3	1%	60	post	1
post-4	2%	20	post	1
post-5	2%	40	post	1
post-6	2%	60	post	1
post-7	4%	20	post	2
post-8	4%	40	post	2
post-9	4%	60	post	1
post-10	8%	20	post	1
post-11	8%	40	post	1
post-12	8%	60	post	2

These groups are common pathways to UV rays or sunlight and therefore, color fades quickly due to a photochemical reaction. In order to overcome this, it is necessary to block the exposure of the –OH groups of the dye.

Table 4
Rubbing fastness of pre-, meta- and post-crosslinked dyed cotton fabric

Sample	Dye conc. (%)	Crosslinking method	Crosslinker conc. (g/L)	Dry rubbing fastness	Wet rubbing fastness
pre-1	1%	pre	20	5	5
pre-2	1%	pre	40	5	5
pre-3	1%	pre	60	5	5
pre-4	2%	pre	20	5	5
pre-5	2%	pre	40	5	5
pre-6	2%	pre	60	5	4/5
pre-7	4%	pre	20	5	4/5
pre-8	4%	pre	40	5	4/5
pre-9	4%	pre	60	5	4/5
pre-10	8%	pre	20	5	4/5
pre-11	8%	pre	40	5	4/5
pre-12	8%	pre	60	5	4/5
meta-1	1%	meta	20	5	5
meta-2	1%	meta	40	5	4/5
meta-3	1%	meta	60	5	5
meta-4	2%	meta	20	5	5
meta-5	2%	meta	40	5	4/5
meta-6	2%	meta	60	5	5
meta-7	4%	meta	20	5	4/5
meta-8	4%	meta	40	5	4/5
meta-9	4%	meta	60	5	4/5
meta-10	8%	meta	20	5	4/5
meta-11	8%	meta	40	5	4/5
meta-12	8%	meta	60	5	4/5

post-1	1%	post	20	5	4/5
post-2	1%	post	40	5	5
post-3	1%	post	60	5	5
post-4	2%	post	20	5	5
post-5	2%	post	40	5	5
post-6	2%	post	60	5	5
post-7	4%	post	20	5	4/5
post-8	4%	post	40	5	4/5
post-9	4%	post	60	5	4/5
post-10	8%	post	20	4/5	4
post-11	8%	post	40	5	4/5
post-12	8%	post	60	5	4

Table 5
Perspiration fastness of pre-crosslinked dyed cotton fabric

Sample	Shades depth (%)	Crosslinker conc. (g/L)	Acetate	Cotton	Nylon	PES	Acrylic	Wool	Shade change
pre-1	1	20	4	4	4	4/5	4/5	4	4/5
pre-2	1	40	4	4	4	4/5	4/5	4/5	4/5
pre-3	1	60	4	4	4	4/5	4/5	4/5	4/5
pre-4	2	20	4	4	4	4/5	4/5	4	4/5
pre-5	2	40	4/5	4/5	4/5	4/5	4/5	4/5	4
pre-6	2	60	4	4	4	4/5	4/5	4	4/5
pre-7	4	20	4/5	4/5	4/5	4/5	4/5	4/5	4
pre-8	4	40	4	4	4	4/5	4/5	4	4/5
pre-9	4	60	4	4	4	4/5	4/5	4	4/5
pre-10	8	20	3/4	3/4	4	4/5	4/5	4	4/5
pre-11	8	40	3/4	3/4	4	4/5	4/5	4	4/5
pre-12	8	60	3/4	3/4	4	4/5	4/5	4	4
meta-1	1	20	4/5	4/5	4/5	4/5	4/5	4/5	4/5
meta-2	1	40	4/5	4/5	4/5	4/5	4/5	4/5	4/5
meta-3	1	60	4	4	4	4/5	4/5	4/5	4/5
meta-4	2	20	4	4	4	4/5	4/5	4	4/5
meta-5	2	40	4	4	4	4/5	4/5	4/5	4/5
meta-6	2	60	4/5	4/5	4/5	4/5	4/5	4/5	4/5
meta-7	4	20	4	4	4	4/5	4/5	4	4/5
meta-8	4	40	4	4	4	4/5	4/5	4	4/5
meta-9	4	60	4	4	4	4/5	4/5	4	4/5
meta-10	8	20	4	4	4	4/5	4/5	4	4/5
meta-11	8	40	4	4	4	4/5	4/5	4	4/5
meta-12	8	60	4	4	4	4/5	4/5	4	4/5
post-1	1	20	4/5	4/5	4/5	4/5	4/5	4/5	4/5
post-2	1	40	4/5	4/5	4/5	4/5	4/5	4/5	4/5
post-3	1	60	4/5	4/5	4/5	4/5	4/5	4/5	5
post-4	2	20	4/5	4/5	4	4/5	4/5	4/5	5
post-5	2	40	4/5	4/5	4/5	4/5	4/5	4/5	4/5
post-6	2	60	4/5	4/5	4	4/5	4/5	4/5	4/5
post-7	4	20	4	4	4/5	4/5	4/5	4/5	5
post-8	4	40	¾	4	4	4/5	4/5	4	5
post-9	4	60	4	4	4	4/5	4/5	4	4/5
post-10	8	20	4	4	4	4/5	4/5	4	5
post-11	8	40	4	4	4	4/5	4/5	4	4/5
post-12	8	60	4/5	4/5	4/5	4/5	4/5	4/5	4/5

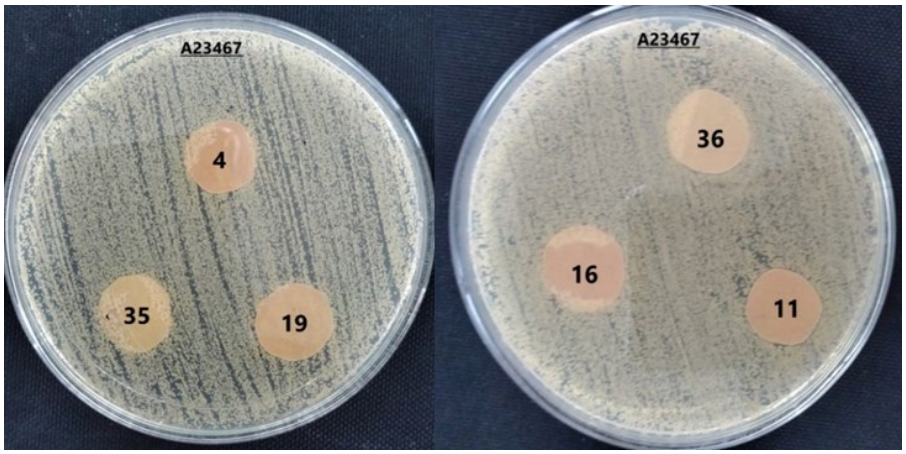

Figure 4: Antibacterial activity of pre-, meta- and post-mordanted dyed cotton fabric on Petri plates

Rubbing fastness

Color fastness to rubbing, for different shade depths of cotton fabric samples dyed with turmeric and citric acid, is given in Table 4. Dyed samples show excellent fastness to dry rubbing and good fastness to wet rubbing. Specimens dyed using the pre- and meta-crosslinking methods exhibit excellent fastness to dry rubbing and near-excellent fastness to wet rubbing, with ratings of 5 and 4/5 on the grey scale, respectively. The meta-crosslinked dyed fabric also shows similar results to pre-crosslinked fabric, with excellent dry rubbing fastness and near-excellent wet rubbing fastness. This may be due to the higher reactivity of citric acid in pre- and meta-crosslinking of the dye molecules into the cellulosic fabric. Cotton fabric dyed using the post-crosslinking method demonstrates very good dry rubbing fastness, rated 5 on the grey scale, and moderate wet rubbing fastness, rated 4.

Perspiration fastness

Table 5 presents the perspiration fastness of dyed cotton fabric samples at different dye concentrations (1%, 2%, 4%, and 8%) using pre-, meta-, and post-crosslinking techniques. Pre-crosslinked fabrics show excellent perspiration fastness, with a rating of 4/5 on the grey scale, decreasing to 4 as shade depth increases. Meta-crosslinked fabrics have good to near-excellent fastness, rated 4/5. Post-crosslinked fabrics exhibit the best perspiration fastness, of nearly 5 on the grey scale, outperforming both pre- and meta-crosslinked samples.

Antibacterial performance

The agar disk diffusion method was used to evaluate the antibacterial activity of the samples, as shown in Figure 4. Samples 35 and 36 represent post-crosslinked dyed cotton fabric, samples 4 and 11 represent meta-crosslinked dyed cotton fabric, and samples 16 and 19 represent pre-crosslinked dyed cotton fabric. The antibacterial activity was tested against the gram-positive bacteria *Staphylococcus aureus*. Although no clear zone of inhibition was observed around the fabric samples, no visible bacterial growth was detected on the fabric surface, suggesting a contact-based antibacterial effect. This indicates that the treated fabrics inhibit bacterial proliferation upon direct contact, rather than through diffusion of antibacterial agents. Thus, the naturally dyed textile fabric showed activity against the gram-positive bacteria *Staphylococcus aureus*, likely due to the combined effects of curcuminoid compounds in turmeric and citric acid.[33]

Mechanism of crosslinking

Crosslinking is a simple method that uses covalent bonding or supramolecular interactions to join polymer chains. The low cost, wide availability and non-toxicity of citric acid have attracted great attention. As shown in Figure 5, crosslinking of cellulose with citric acid is done through esterification processes, based on anhydride intermediate production. Crosslinking begins when citric acid becomes cyclic anhydride. Three carboxylic groups interact, releasing a water molecule. In cellulose, cyclic anhydride interacts with a hydroxyl group to form an ester. The same constituent creates another cyclic anhydride to react with the second hydroxyl group, completing crosslinking.[34]

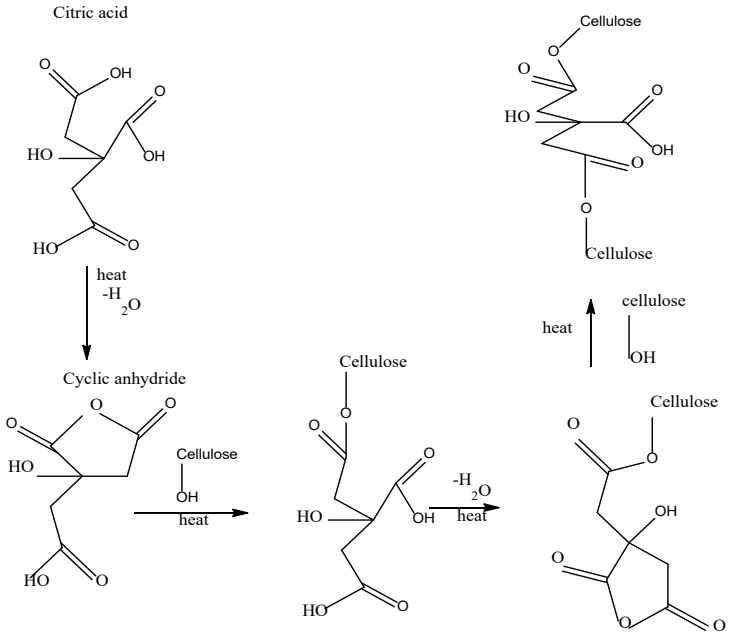

Figure 5: Crosslinking reaction of citric acid with cellulose

CONCLUSION

This research aimed to dye cotton with a natural bio-based dye and a green mordant (crosslinker) using turmeric and citric acid for an eco-friendly approach. Turmeric proved to be a cost-effective, compatible, and antibacterial natural colorant. Dyeing was conducted using pre-, meta-, and post-crosslinking methods, and the results were compared for color strength, shade, and fastness properties. The pre-crosslinking method increased the shade depth of cotton fabrics, achieving the highest color strength (K/S) value of 3.814 with 8% dye concentration and citric acid. The fastness properties, including washing, perspiration, rubbing, and light, were excellent. Fabric dyed with the post-mordanting method showed antibacterial activity, evidenced by no bacterial growth on the fabric samples. This study highlights the potential of natural dyes to complement synthetic dyestuffs effectively.

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