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Sustainable Dyeing of Cotton and Polyester Fabrics Using Agricultural-Waste-Derived Carboxymethyl Cellulose and Natural Colorants: Optimization, Performance Evaluation, and Functional Finishing

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In Loving Memory of Late Professor Doctor "" Issa Mohammed Imam Fakhr""

Abstract

This study introduces a sustainable and multifunctional textile dyeing approach using carboxymethyl cellulose (CMC) synthesized from agricultural waste—peanut shell and rice straw—in combination with natural dyes extracted from peanut red skin (PRS), red onion peel (ROP), and henna (HE). Cotton and polyester fabrics were pre-treated with CMC (0.5–1.5%) and crosslinked to enhance dye–fiber interactions, followed by dyeing under various controlled conditions. The influence of key parameters, including pH, temperature, dyeing time, and polymer concentration, was systematically investigated to optimize color uptake and fixation behavior. Results showed that rice-straw-derived CMC, owing to its higher degree of substitution and superior film-forming characteristics, produced significantly higher color strength (K/S) values than peanut-shell CMC on both textile substrates. Optimal dyeing was achieved at pH 5–7, 70–80 °C, and 60–90 min, yielding uniformly dyed fabrics with excellent washing (4–5), rubbing (3–5), and light fastness (3–5). The treated fabrics also exhibited remarkable functional enhancements, including improved tensile properties, ultraviolet protection (UPF 40–50), and substantial antimicrobial activity (up to 91% reduction against E. coli, S. aureus, and C. albicans). Henna and PRS extracts were most effective in imparting bioactive performance, while CMC significantly enhanced dye retention and surface reactivity. The proposed mechanism suggests that coloration results from synergistic hydrogen bonding, polymer entrapment, and crosslink-stabilized dye–polymer–fiber networks. Overall, this work demonstrates an eco-friendly, circular, and high-performance natural dyeing technology that transforms agricultural residues into value-added biopolymers and functional pigments suitable for sustainable textile finishing.

Keywords: Plant waste, Bio-extracts, Sustainable textiles, Phytochemicals, Eco-friendly dyeing, Natural functional dyes, Biomass utilization, Green technology, Textile processing, Environmental sustainability.

1. Introduction

For a long time, the textile dyeing industry has used synthetic dyes and chemical additives to get bright, long-lasting colors. However, these old ways of doing things are very bad for the environment and health. Synthetic dyes are often made from non-renewable petrochemical sources. Making and using them generates wastewater containing harmful aromatic compounds, salts, and chemical additives. This wastewater is a major cause of water pollution, increased chemical oxygen demand (COD), and toxicity to aquatic ecosystems. [1]

The environmental impacts of traditional textile dyeing have sparked significant interest in sustainable methods and alternative materials. Dyes and organic pollutants have been successfully removed from wastewater using sophisticated methods such as nanofiltration, adsorption, and photocatalysis [2-7], with inexpensive adsorbents and specially designed photocatalysts providing effective and environmentally friendly solutions [4, 8-11]. Simultaneously, advances in polymeric membranes and composite materials have improved the efficiency of water treatment while promoting sustainability by utilizing natural and waste-derived resources [12-15]. In this regard, carboxymethyl cellulose (CMC) generated from agricultural waste shows promise as a green material, in line with recent developments in cellulose-based and hybrid systems for pollutant removal [11, 16, 17]. To enhance fabric performance and environmental compatibility, this work focuses on the sustainable dyeing of cotton and polyester fabrics using CMC and natural colorants, in conjunction with functional finishing techniques inspired by photocatalytic and antibacterial compounds [18, 19].

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As environmental regulations intensify and public awareness of sustainability increases, the need for eco-friendly, bio-based textile dyeing methods has escalated. Natural dyes derived from plants, agricultural by-products, and other renewable resources offer a viable alternative due to their biodegradability, reduced toxicity, and potential applications in circular economy practices. Scribd and two Nature publications, Natural dyes offer ecological advantages; nonetheless, they present significant technical challenges that hinder their widespread application in commercial and industrial textile dyeing. [20-25]

Natural dyes continue to present significant challenges that hinder their further application in industrial textile production. Initially, many natural colorants exhibit suboptimal performance on cellulosic fabrics such as cotton and on synthetic fibers like polyester, resulting in muted or inconsistent colors. [26] These dyes not only exhibit poor adhesion to fabrics, but they also frequently lack durability: they may wash out after laundering, fade under light exposure, or transfer when abraded. Typically, individuals enhance fastness by employing metallic mordants such as alum, iron, or chromium. Nonetheless, these technologies may adversely affect the ecosystem due to the detrimental impact of metal residues.

A significant issue is that natural dyes are ineffective on synthetic fibers, as these fibers typically lack the reactive functional groups required to form stable bonds with natural pigments. It renders the coloring of polyester and other synthetic textiles particularly challenging. [26] Natural dye sources exhibit inherent variability, leading to inconsistent colors and inadequate reproducibility across dye batches due to variations in plant species, age, growth conditions, and extraction procedures. [26] These issues have predominantly hindered the utilization of natural dyes in extensive textile production. Rather, they are predominantly utilized in specialized, artisanal, or small-scale production environments. [27]

Prior studies [28-58] illustrate a coherent and progressive research trajectory centered on sustainability, utility, and new materials in textile science. The study begins with a thorough evaluation of environmental and industrial challenges in the garment industry, emphasizing the urgent need for sustainable change in textile production. Recent advancements in functional finishing of textiles have emphasized sustainability, enhanced performance, and eco-friendly processing techniques [20-22, 25, 59-81].

To address these issues, we require environmentally friendly, non-toxic mordants or binding systems that enhance dye adhesion, increase dye absorption, and are compatible with many fabric substrates, including synthetics. These technologies should also preserve the ecological advantages of natural colors.

In this situation, Carboxymethyl Cellulose (CMC) emerges as a highly promising alternative. CMC is a biodegradable polymer derived from cellulose, used in the textile industry as a sizing agent, thickener, or stabilizer due to its ability to form films, regulate viscosity, and interact effectively with dyes and finishing agents. As a fabric preparation or an alternative to a mordant, CMC can establish a hydrophilic, functional coating on fiber surfaces. It successfully bridges the chemical divide between natural dyes and fiber substrates. [82-88]

Furthermore, deriving CMC from agricultural waste, such as peanut shells or rice straw, aligns with the principles of a circular economy and waste valorization, transforming low-value biomass into high-performance textile auxiliaries that enhance value.

This study aims to develop and enhance a sustainable dyeing system that utilizes CMC derived from agricultural waste (peanut shells, rice straw), natural dye extracts (peanut red skin, red onion peel, and henna), and both cotton and polyester textiles. The objective is to achieve elevated color strength, enduring fastness, mechanical integrity, and additional beneficial qualities (such as UV protection and antimicrobial efficacy) without the use of detrimental metallic mordants.

This study is novel because it uses agricultural waste, such as peanut shells and rice straw, to produce functional biopolymers for textile finishing. The project promotes resource circularity and sustainable material innovation by transforming typically discarded resources into valuable components. A significant addition is the utilization of carboxymethyl cellulose (CMC) as a universal, non-toxic mordant and binder. It enables natural colors to adhere effectively to both cellulosic and synthetic textile substrates. It addresses a significant challenge in natural dyeing: its ineffectiveness across various fabric types.

The work is notable for its systematic optimization of dyeing parameters, including CMC content, pH, temperature, and dyeing duration, to achieve optimal dye uptake and fastness. The research demonstrates a multifunctional textile-finishing approach that enhances the strength of treated fabrics, improves UV-blocking capabilities, increases efficacy against microorganisms, and alters color. These enhancements provide a tangible link between sustainability and the practical performance of textiles. The study directly addresses significant issues in natural dyeing, including low substantivity, insufficient fastness, and limited substrate compatibility. It enables the production of textiles in a more environmentally sustainable manner, reducing chemical pollution and optimizing the utilization of biological resources.

2. Experimental

2.1. Materials

Rice straw and exterior peanut shells were collected from local farms in Egypt. All raw materials were thoroughly washed and oven-dried to remove contaminants, dust, and any residual unwanted matter prior to cellulose isolation. Red peanut skin, Red Onion Peel, and Henna leaves were purchased from the local market in Egypt. Sodium hydroxide (NaOH), hydrogen peroxide (H_2O_2), acetic acid (CH_3COOH), sodium carbonate (Na_2CO_3), Isopropanol ($CH_3CH(OH)COOH$), monochloroacetic acid ($ClCH_2COOH$), and Glycerin ($C_3H_8O_3$) were all purchased from Loba Co., India.

Cotton 100% and polyester 100% were purchased from Misr El-Mahala Company for Spinning and Weaving, El-Mahalla El-Kobra City, Egypt. The characteristics of the used fabrics are listed in

Table 1.

Table 1: Properties of the used fabrics

	Cotton 100% (Plain 1/1)	Polyester 100% (Plain 1/1)
Weight (g/m^2)	115	110
Thickness (mm)	0.27	0.25
Weft density/inch	55	50
Warp density/inch	120	170

2.2. Methods

2.2.1. Extraction of Cellulose from Different Natural Sources

Rice straw and outer peanut shell, after being fragmented into small pieces, were subjected to autoclaving in a pressurised vessel containing a 5% wt. sodium hydroxide solution and a liquor-solid ratio of 10:1. The temperature was increased to 105°C, and the sample was exposed to a pressure of 15 atm. Subsequently, the rice straw was autoclaved for 2 hours to promote the separation of cellulose fibres from lignin. Cellulose fibres were bleached after washing in tepid water. [89, 90].

The fibres exhibit a brownish colouration after cooking, attributable to residual lignin, which reduces their whiteness. Employing a bleaching agent to remove residual lignin can achieve a high level of luminosity. The bleaching procedure comprises two distinct phases. Hydrogen peroxide (H_2O_2) functions as the bleaching agent. The procedure utilising 5% (w/v) H_2O_2 was conducted at ambient temperature with a solid-to-liquid ratio of 1:10.

2.2.2. Carboxymethylation of synthesized cellulose

The synthesised cellulose was carboxymethylated in an aqueous-organic medium at an alkaline pH. Twenty grammes of the synthesised cellulose were dispersed in 50 mL of isopropanol within a three-necked round-bottom flask fitted with a mechanical stirrer and condenser. The amalgamation was persistently stirred for 30 minutes at ambient temperature. 40 mL of a 1 M aqueous sodium hydroxide solution was added over 20 minutes, followed by agitation for an additional 60 minutes. After carefully incorporating 30 g of monochloro-acetic acid into the mixture over 15 minutes, the reaction was maintained at 70°C for 5 hours with continuous stirring. Following filtration, the carboxymethyl cellulose (CMC) was dialyzed in distilled water until neutral. The produced CMC was subsequently lyophilized. [91]

2.2.3. Dye extraction from natural resources

2.2.3.1. Extraction of Dye from Red Peanut Shells

Red peanut skins were meticulously cleaned with distilled water to remove attached mud and debris; thereafter, they were air-dried at ambient temperature for 48 hours. The desiccated shells were pulverized into a coarse powder utilizing a laboratory mill. Approximately 20 g of the powder was placed into a 500-mL Erlen-meyer flask containing 200 mL of a 70% (v/v) ethanol-water solution. The mixture was heated to 60 °C for 1 hour with constant stirring to facilitate pigment release. Upon reaching room temperature, the extract was filtered through Whatman No. 1 paper, and the filtrate was concentrated using a rotary evaporator at 45 °C to remove excess solvent. The concentrated dye solution was preserved in amber bottles at 4 °C until required. [69, 92-95]

2.2.3.2. Extraction of Dye from Red Onion Peel

Fresh red onion peels were manually separated, rinsed with distilled water, and dried in an oven at 50 °C for 24 hours. The desiccated substance was sectioned into diminutive fragments and positioned in a stainless-steel beaker. Fifteen grams of dry peel were cooked in 250 mL of distilled water for 30 to 40 minutes to extract anthocyanin pigments. The resultant mixture was allowed to cool, then filtered through a fine-mesh screen and a Whatman No. 1 filter paper. The filtrate was adjusted to pH 3 with food-grade citric acid to improve pigment stability. The finished extract was stored in opaque glass containers at 4 °C and used within 1 week. [21, 22, 69]

2.2.3.3. Extraction of Henna Dye

Dried henna leaves (Lawsonia inermis) were purified, ground into a fine powder, and sifted to achieve a consistent particle size. Ten grams of powder were suspended in 150 mL of distilled water, which was acidified to pH 5.0 with 1% (v/v) acetic acid to enhance the release of lawsone pigment. The amalgamation was heated at 50 °C for 2 hours with intermittent agitation. After extraction, the slurry was allowed to settle and then filtered under vacuum. The dye-laden filtrate was centrifuged at 4000 rpm for 10 minutes to eliminate remaining particles. The supernatant was gathered, shielded from light, and stored at 4 °C for subsequent use. [24, 69, 96-99]

2.2.4. Treatment procedure

The fabrics were washed for 15 minutes at 100°C with a 2 g/L sodium carbonate solution and liquid soap, then left to air dry. The fabrics were pretreated by immersing them in a solution of 10 g/L citric acid and 5 g/L sodium hypophosphate for 15 minutes at 80°C. Excess solution was then removed by padding the fabrics and leaving them to air dry.

The treatment used different concentrations of synthesized CMC (0, 0.5, 1, and 1.5). The fabrics were then immersed in the CMC. They were then placed in a shaking water bath at 70 °C for 15 minutes. The fabrics were then padded to remove excess solution. At 80°C, the fabrics were oven-dried for five minutes.

2.2.5. Dyeing procedure

Dyeing of the treated fabrics was performed in a controlled laboratory environment using natural dye extracts. Before dyeing, all samples were conditioned at 21 ± 2 °C and 65 ± 5% relative humidity for 24 hours. Dye baths were prepared with distilled water and appropriate dye concentrations, and the pH was adjusted to acidic, neutral, or alkaline levels as required. Fabric samples were dyed at a liquor ratio of 1:20 using a laboratory dyeing machine with controlled temperature. The temperature was gradually raised to 60–90 °C, and dyeing was conducted for 30–60 minutes with continuous stirring to ensure uniform dye fixation. After dyeing, the samples were rinsed with cold water, washed with a mild nonionic detergent at 40 °C for 10 minutes, and air-dried at room temperature.

The influence of several parameters on dyeing performance was examined, including the type and concentration of CMC (derived from rice straw or external peanut shell), dye bath pH, fabric type (cotton, wool, and polyester), dyeing time and temperature, and dye type (red peanut skin, red onion peel, and henna). Color strength (K/S) and total color difference (ΔE) were measured to identify optimal dyeing conditions. This systematic evaluation facilitated the selection of the most effective fabric–CMC–dye system for enhanced dye uptake, color uniformity, and functional properties.

2.3. Analysis and Measurements

2.3.1. Estimation of the Chemical Composition of a natural sourceof cellulose

2.3.1.1. Water absorption

To evaluate water absorption, 35 g of rice straw were desiccated in an oven at 105°C for 48 hours to ensure complete moisture removal. The dehydrated particles were subsequently immersed in water for durations spanning from 5 minutes to 48 hours. By analysing the absorption rate of rice straw, A(t), the water absorption was quantified using equation (1). [90].

$$A(t) = 100 * \frac{mt - mo}{mo} \ldots\ldots\ldots (1)$$

Where A(t) represents the percentage of water absorption, mt denotes the weight after drying, and mo indicates the weight before drying.

2.3.1.2. Evaluation of Ash content

The ash content of rice straw was determined by combustion, during which the straw was fragmented into small pieces. A sample weighing approximately 1 g was incinerated in a muffle furnace using a porcelain crucible, initially at 400°C for 30 minutes, then at 850°C for 45 minutes. The resulting ash was subsequently analyzed by gravimetry. The ash content was determined through the following equation.

Ash%= (weight of ash)/(weight of dry sample) x100……..(2).

2.3.1.3. Evaluation of Lignin

The lignin content in the raw material was determined by treating precisely 1 gram of the sample with 72% sulphuric acid (w/w) at a liquor-to-solid ratio of 20:1 for 4 hours at ambient temperature (approximately 25–30°C). It was subsequently diluted to 3% sulphuric acid and reflux-heated for an additional 4 hours. Lignin was filtered through ashless filter paper and rinsed with hot distilled water until neutral. It was then quantified gravimetrically and subsequently ignited at 400°C for 30 minutes, followed by a further ignition at 800°C for 45 minutes. The ash weight was deducted to determine lignin-free ash using the following equation. [90]

Lignin % = [(weight of lignin - weight of ash) / (weight of the dry sample)]× 100…(3).

2.3.1.4. Evaluation of α-Cellulose and Hemicelluloses

To determine the α-cellulose content of the primary material, holocellulose must first be quantified, enabling subsequent calculation of α-cellulose. Hollo cellulose was produced using the sodium chlorite (NaClO2) process as described below: Precisely 5 g of extracted rice straw was added to 80 ml of distilled water at 75°C, and the mixture was stirred mechanically. Subsequently, 0.8 ml of acetic acid and 1.86 g of sodium chlorite were added, and the reaction was permitted to proceed under vigorous agitation. The procedure was reiterated until the lignin colouration was virtually indistinguishable. Subsequently, the remaining hollow cellulose was rinsed with distilled water until completely free of acid, acetone, and other impurities. The product was vacuum-dried at 50°C, after which the hollow cellulose was weighed.[90].

α-cellulose was determined using a 17.5% (w/w) sodium hydroxide solution, as described below: Approximately 3 g of holocellulose was precisely treated with 25 ml of sodium hydroxide (17.5% w/w) and allowed to swell for 4 minutes at 20°C. The sample was subsequently compressed for 3 minutes using a glass rod, after which an additional 25 ml of NaOH was added, and the mixture was agitated for 1 minute before being covered and maintained at 20°C. After 35 minutes, 100 cc of distilled water was added, and the mixture was subsequently filtered through a sintered-glass funnel. A total of 100 cc of 10% acetic acid was gradually added for cleansing, followed by rinsing with distilled water. The proportion of α-cellulose was determined gravimetrically following drying in an oven at 105 °C and subsequent ash subtraction, as described by the following equation. [90].

α-cellulose% = (weight of α-cellulose - weight of ash) / (weight of original holocellulose sample) x 100 hemicellulose% = (holocellulose% - α-cellulose%)…….(4).

2.3.2. HPLC

An Agilent 1260 series instrument was utilized for High-Performance Liquid Chromatography (HPLC) analysis. The separation was performed on a Zorbax Eclipse Plus C8 column (4.6 mm × 250 mm i.d., 5 μm). The mobile phase comprised water (A) and 0.05% trifluoroacetic acid in acetonitrile (B) at a flow rate of 0.9 ml/min. The mobile phase was methodically programmed in a linear gradient as detailed below: 0 min (82% A); 0–1 min (82% A); 1–11 min (75% A); 11–18 min (60% A); 18–22 min (82% A); 22–24 min (82% A). The multi-wavelength detector was assessed at 280 nm. The injection volume for each sample solution was 5 microliters. The column temperature was sustained at 40 °C.

2.3.3. Color measurements

The color strength of the printed textiles was measured by the Textile Technology Lab at the faculty of Applied Arts and is represented as K/S. The K/S values were determined using the Kubelka–Munk equation: **[100, 101]**

$$K/S = \frac{(1-R)^2}{2R} - \frac{(1-R_o)^2}{2R_o}$$

where K is the coefficient of absorption, S is the coefficient of dispersion, and R_{kmax} is the cloth's reflectance at the maximum wavelength.

2.3.4. Colorimetric Data

Color parameters were measured using a **HunterLab colorimeter (Model Reston, VA, USA)** and expressed in the **CIE L*, a*, b*** system, where L^* represents lightness, a^* redness/greenness, and b^* yellowness/blueness. Measurements were taken on the burger surface at three different points per sample, and the mean was reported. **Total color difference (ΔE)** was calculated relative to the control sample using the equation:

$$\mathbf{\Delta E} = \sqrt{(\boldsymbol{L} - \boldsymbol{L}^*)^2 + (\boldsymbol{a} - \boldsymbol{a}^*)^2 + (\boldsymbol{b} - \boldsymbol{b}^*)^2}$$

2.3.5. Colorfastness properties

The colorfastness to washing was evaluated using the Laudner-Ometer (manufactured by SDL Atlas, a company with a significant presence in the United States, United Kingdom, Hong Kong, and China) and the AATCC Test Procedure 61-2013. [102] Colorfastness to rubbing (dry and wet) was evaluated using a Crock Meter (Shanghai JAG Textile Testing Instruments Co., Ltd.) following the AATCC test method 8-2016. [103] Colorfastness to perspiration was measured using the AATCC test method 15-2013. (acidic and alkaline). [104] The AATCC test method 16.1-2014 was used to measure colorfastness to light. [105] The grayscale color change reference was used to evaluate the fastness properties of washing, rubbing, and perspiration, while the blue scale color change reference was utilized to measure the light fastness characteristics of colored materials. [106]

2.3.6. Mechanical properties

Tensile strength and elongation at break are conducted on a tensile strength apparatus type FMCW 500 (Veb Thuringer Industrie Werk Rauenstein 11/2612 Germany) at 25°C and 65 % relative humidity according to the ASTM Test Method D5035-2011. [107] The dry crease recovery angle (CRA) was measured according to AATCC Test Method 66–2014. [108] Fabric roughness was measured using the Surface Roughness measuring instrument SE 1700 using ASTM Test Method D 7127 – 13. [109] Stiffness was performed using the cantilever apparatus according to ASTM test method D 1388-14e1. [110] Air permeability (AP) was evaluated according to ATSM (D 737-96). [111] Water vapor permeability (WVP) was evaluated according to ASTM (E96/E96M − 16). [112]

2.3.7. Measurement of UPF for printed

The test was conducted using a spectrophotometer in line with the AATCC Test Method 183 [113]—an international standard for measuring the transmittance or blocking of UV radiation through fabric.

2.3.8. Antibacterial activity

Antibacterial activity was assessed against Staphylococcus aureus (ATCC 29213), a gram-positive bacterium; Escherichia coli (ATCC 25922), a gram-negative bacterium; and Candida albicans (ATCC 10231), a fungus, utilising the AATCC 100-2004 bacterial reduction method, a recognised standard protocol for antimicrobial paste evaluations. [26]

For this test, a consistent liquid culture of the microorganism is created. The culture is then dissolved in sterile nutrient solution. Microorganisms are added to the thickening agent and incubated in sealed containers at 37 °C for 24 hours. After incubation, the solution is agitated for 1 minute, and microbial levels are determined. The percentage reduction of bacteria (%R) was calculated using the following equation: [114]

$$\mathrm{R\%} = \frac{B-A}{B} \times 1000$$

where A is the number of bacteria recovered from the inoculated test sample after the incubation time, and B is the number of bacteria recovered from the inoculated sample immediately upon inoculation.

3. Results and Discussion

3.1. Characterization of the produced cellulose

The compositional analysis of rice straw and external peanut shell before and after bleaching provides clear insight into the effectiveness of peroxide-based treatment in enhancing cellulose purity from these agricultural residues. As shown in Table 2, both materials exhibit significant variations in moisture, ash, lignin, and volatile matter content after H_2O_2 bleaching. In rice straw, bleaching resulted in a slight reduction in moisture content and a substantial decrease in ash content—from 20.09% to 6.45%—indicating the efficient removal of inorganic components during chemical treatment. A similar trend was observed in fixed carbon, which decreased marginally, reflecting the partial removal of carbonaceous residues. Volatile matter increased post-bleaching,

consistent with exposure of more thermally labile organic fractions after non-cellulosic components were removed.

The external peanut shell exhibited comparable but more pronounced changes, particularly in ash content, which increased significantly after bleaching (from 22.36% to 69.64%). This behavior could be attributed to the persistence of mineral-rich fractions that were not fully solubilized during peroxide oxidation, or to concentration effects resulting from the dissolution of large portions of organic material. Additionally, lignin content increased in the peanut shell after bleaching (27.31% to 32.71%), whereas in rice straw it decreased notably (12.87% to 10.75%). It suggests that H_2O_2 bleaching was more selective toward lignin removal in rice straw, whereas in peanut shell, the more tightly bound lignocellulosic matrix may require stronger or multi-stage delignification to achieve comparable reductions.

The α-cellulose content remained relatively stable in both materials after bleaching, as shown in Table 2, indicating that cellulose integrity was largely preserved during peroxide treatment. Rice straw maintained an α-cellulose value of approximately 76%, while external peanut shell showed a slight increase from 65.86% to 66.01%, demonstrating that H_2O_2 bleaching did not compromise the polymeric cellulose backbone.

Table 3 corroborates these findings by highlighting the effect of bleaching on yield, cellulose purity, lignin concentration, and ash content. The overall yield decreased slightly in both materials after bleaching, which aligns with the expected removal of non-cellulosic components. A sharp reduction in lignin content was observed in bleached rice straw (18.37% to 0.73%), confirming effective delignification and explaining the improved thermal and structural purity of the extracted cellulose. In contrast, peanut shell lignin showed only a modest decrease (9.55% to 5.14%), again suggesting that its lignin-rich structure is more resistant to peroxide oxidation. Ash content dropped dramatically in bleached rice straw (32.02% to 1.33%), reinforcing the conclusion that peroxide is highly efficient at demineralization for this biomass type. Peanut shells also showed a significant, though less pronounced, reduction in ash (16.68% to 9.01%). Interestingly, the α-cellulose content in bleached samples decreased sharply in both materials, suggesting partial hydrolysis or solubilization of amorphous cellulose fractions during bleaching. Despite this reduction, both materials still contain sufficient cellulose to be considered viable sources for further purification or nanocellulose synthesis.

Overall, the data demonstrate that rice straw responds more favorably to peroxide bleaching than peanut shell, achieving greater lignin removal, ash reduction, and overall purification while maintaining high cellulose integrity. Peanut shell, although a promising feedstock, may require additional pretreatment steps—such as alkaline pulping or sequential bleaching—to achieve delignification and cellulose enrichment comparable to those achieved with other feedstocks. These results collectively highlight the potential of agricultural wastes as sustainable raw materials for cellulose extraction, while also emphasizing the need to tailor pretreatment strategies to the specific structural characteristics of each biomass type.

Table 2: Percentages of α-cellulose, lignin, moisture content, volatile matter, ash content, and fixed carbon in rice straw and External peanut shell before and after bleaching

Material (%)	**Raw material**		**Bleaching with H_2O_2**	
	rice straw	**External peanut shell**	**rice straw**	**External peanut shell**
moisture content	7.12	8.23	7.02	8.35
volatile matter	69.37	69.34	75.19	63.98
Ash content	20.09	22.36	6.45	69.64
fixed carbon	8.06	8.62	7.69	9.03
***ά*-cellulose**	76.38	65.86	76.21	66.01
lignin	12.87	27.31	10.75	32.71

Table 3: Yield %, α-cellulose content, lignin concentration, and ash content in rice straw and External peanut shell before and after bleaching.

Material		**Yield %**	**α cellulose %**	**Lignin %**	**Ash content %**
Rice straw	Raw	85.37	72.64	18.37	32.02
	bleached	82.66	36.69	0.73	1.33
External peanut shell	Raw	84.01	54.66	9.55	16.68
	bleached	83.34	45.68	5.14	9.01

Figure 1 shows the FT-IR spectra of rice straw and an outside peanut shell before and after bleaching. It shows the chemical changes that happen when cellulose is purified. The raw samples show clear signs of lignocellulosic absorption bands, such as the broad O–H stretching vibration around 3300–3400 cm^{-1}, the C–H stretching bands near 2890–2920 cm^{-1}, and the fingerprint peaks related to hemicellulose and lignin in the 1500–1800 cm^{-1} range. The raw materials show a strong absorption at about 1730 cm^{-1}, which corresponds to the C=O stretching of acetyl and uronic ester groups in hemicellulose and ester links in lignin.

After bleaching with H_2O_2, the intensities of numerous lignin-associated peaks decreased significantly in both rice straw and peanut shell. The significant decrease or absence of the 1510–1600 cm^{-1} aromatic skeletal vibrations, which are typical of lignin phenylpropanoid units, shows that delignification has worked. The smaller band at ~1730 cm^{-1} also shows that hemicellulose and carbonyl-containing groups have been removed. These changes show that peroxide treatment breaks down lignin structures and hemicellulose esters.

The cellulose-related peaks, on the other hand, became more apparent after bleaching. The absorption bands at around 1030–1050 cm^{-1}, due to C–O–C stretching in the polysaccharide backbone, and at around 1155 cm^{-1}, due to C–O asymmetric stretching, both become stronger. The fact that the β-glycosidic linkage peak stays at ~896 cm^{-1} shows that cellulose is still structurally sound and that bleaching did not break down the cellulose chains very much. The sharpening of the wide O–H band between 3300 and 3400 cm^{-1} also shows that the hydrogen bonds are better organized, which is in line with the fact that cellulose is more concentrated when the amorphous non-cellulosic parts are removed.

Both biomasses exhibit comparable spectral trends, but rice straw shows a larger drop in lignin-associated bands than peanut shell. It is because compositional analysis showed that rice straw is more effective at bleaching. Peanut shell shows lower lignin and hemicellulose signals after bleaching, consistent with its more resistant lignocellulosic matrix, suggesting that further or successive bleaching processes may be necessary for complete purification.

The FT-IR spectra support the chemical composition results and clearly show that peroxide bleaching lowers lignin and hemicellulose levels while increasing cellulose purity in both rice straw and peanut shells. These spectrum shifts show that agricultural waste can serve as a valuable source of cellulose and that the treatment's success depends on the natural structure of each biomass type.

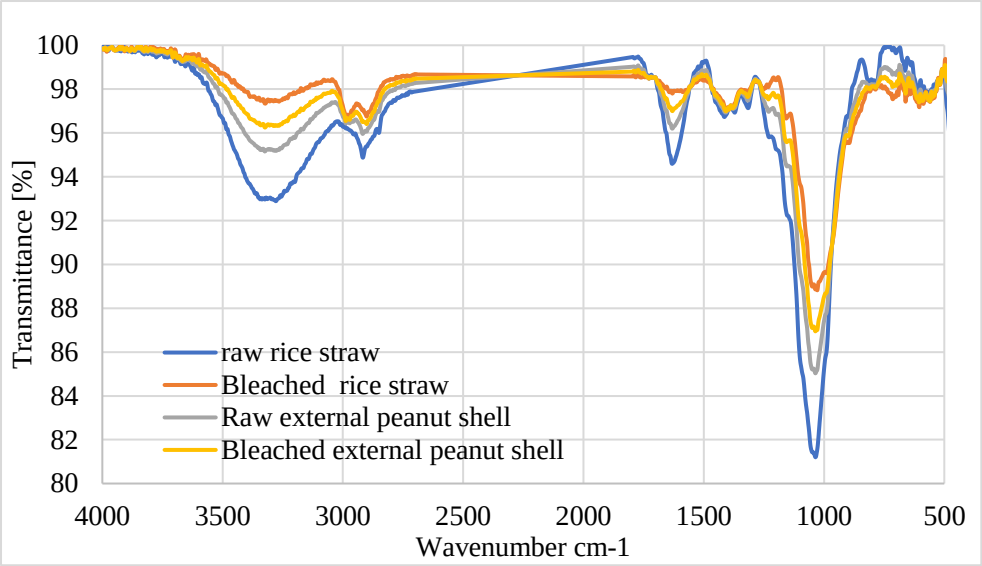

Figure 1: FT-IR spectra of rice straw and External peanut shell before and after bleaching

3.2. Characterization of Natural Plant Extracts (Red Onion Peel and Peanut Red Skin)

Table 4 shows a side-by-side comparison of the extraction performance and functional characteristics of three natural pigment sources: peanut red skin (PRS), red onion peel (ROP), and henna extract (HE). It shows how their natural phytochemical makeup affects yield, appearance, and spectral behavior. Of the three materials, ROP had the highest extraction yield (9.6 ± 0.4%). It is because its main flavonoid components, especially quercetin derivatives and water-soluble anthocyanins, are very soluble. On the other hand, PRS and HE had slightly lower yields (8.2–8.9%), which may be due to their higher condensed tannin content and lower extractable polyphenolic content. [25, 115, 116]

The extracts' different phytochemical profiles are also reflected in their appearance. The reddish-brown hue of PRS extract matches its high levels of anthocyanins and tannins. The yellow-brown color of ROP, on the other hand, matches its high levels of flavonoids, notably quercetin-based chromophores. Henna extract is dark brownish in color because it contains many naphthoquinones, notably lawsone, as well as tannins. These color discrepancies indicate that the extracts have different compositions and could be used as colorants in textiles, cosmetics, and sensing applications. [117, 118]

The UV–Vis absorption maxima (λ_max) give us even more information about the structure. All extracts show high absorption in the UV range (260–280 nm), which is typical of π–π* transitions in aromatic rings observed in phenolics, flavonoids, and tannins. The secondary peaks in the visible region (410–430 nm) are due to longer conjugation in their chromophoric systems. The λ_max of PRS is 280 and 430 nm, which demonstrates that anthocyanin-tannin complexes are involved. The λ_max of ROP is 260 and 410 nm, which is compatible with quercetin and similar flavonoids. The λ_max of HE is 270 and 420 nm, which are due to naphthoquinone structures such as lawsone. These spectral signatures show that the extracts are pure and can be identified, and that they could be used as natural dyes with adjustable color intensity (See Figure 2). [119]

In general, the comparison shows that each extract has its own chemical and functional properties, determined by the phytochemicals that are most important to it. ROP extracts better than PRS and HE, and it has a lighter, more flavonoid-rich color profile. PRS and HE, on the other hand, have deeper, more tannin- and quinone-rich colors. These results show that all three biomass sources can serve as natural dyes. They also support their use in eco-friendly material creation, sustainable coloring, and antioxidant compositions.

Table 4: Comparative Evaluation and Functional Potential for the three extracts

Property	**Peanut red skin (PRS) Extract**	red onion peel **(ROP) Extract**	**Henna extract (HE) extract**	**Interpretation**
Yield (%)	8.2 ± 0.3	9.6 ± 0.4	8.9 ± 0.6	ROP shows slightly higher extraction efficiency due to higher flavonoid solubility
Appearance	Reddish-brown	Yellow-brown	Dark brownish	Indicative of anthocyanin/tannin (PRS) vs flavonoid/quercetin (ROP) dominance
λ_{max} (nm)	280, 430	260, 410	270, 420	Typical of aromatic π–π* transitions and visible conjugated systems

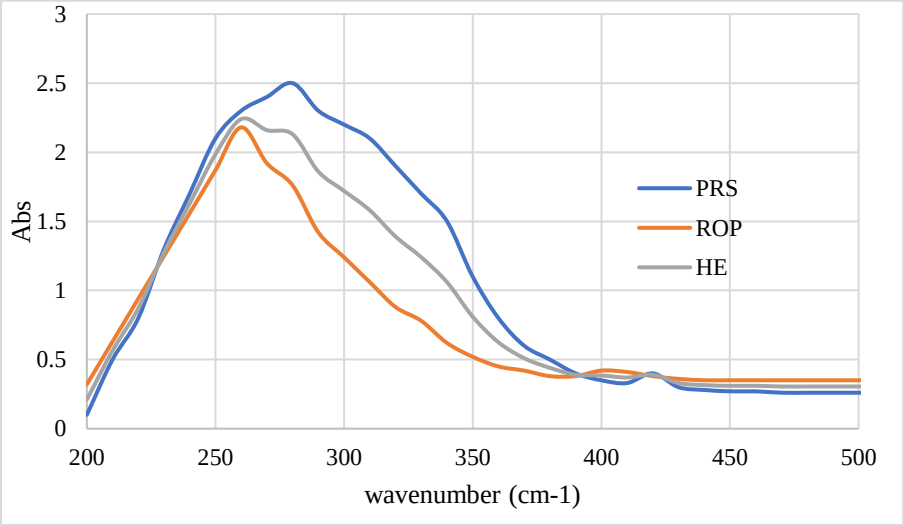

Figure 2: UV–Vis spectra of the PRS and ROP at pH 4.5

The HPLC analysis (Table 4), corroborated by the structural profiles shown in Figure 2, provides a detailed examination of the phenolic and flavonoid composition of the three natural extracts: peanut red skin (PRS), red onion peel (ROP), and henna extract (HE). The statistics clearly show that each extract has a unique phytochemical signature, reflecting its plant source. It directly affects their use in natural dyes, antioxidant systems, and bioactive formulations.

ROP has the highest levels of several important phenolic compounds among the three sources. Chlorogenic acid, on the other hand, reached 245.09 µg/mL, which is much greater than the levels in PRS (65.73 µg/mL) and HE (68.72 µg/mL). The fact that chlorogenic acid is the main component of ROP is consistent with its known enrichment in hydroxycinnamate derivatives and supports its high antioxidant and UV-protective properties. ROP also contains a lot of syringic acid, vanillin, naringenin, and quercetin, typical of onion skins, which are high in flavonoid glycosides and phenolic aldehydes. Figure 2 shows the structure of these molecules. They are known for their conjugated aromatic systems, which enable them to absorb light and make them useful as natural colorants.

The PRS extract, on the other hand, had an extremely high catechin content (220.18 µg/mL), which was much higher than that of HE and was not detected in ROP. Catechins, along with gallic acid (23.56 µg/mL) and ellagic acid (5.81 µg/mL), show that peanut skin is rich in tannins, which are mostly made up of condensed polyphenols. The presence of pyrocatechol and rutin further supports the complex, highly reactive phenolic profile of PRS. These compounds contain many hydroxyl groups on fused aromatic rings (Figure 2). It is why they are such strong reducing agents and can be used as colorants that do not need a mordant when dyeing naturally.

Henna extract had a more balanced profile, with moderate amounts of catechin (125.12 µg/mL), chlorogenic acid (68.72 µg/mL), and pyro-catechol (17.63 µg/mL). Henna is generally known for lawsone (not measured here), but the presence of other phenolic acids, such as gallic, ellagic, rosmarinic, cinnamic, and coumaric acids, indicates that it has a wide range of antioxidant activity. These chemicals give the dye its brownish color and make it more stable and active in the body. The structural motifs in Figure 2, especially the quinone-type and cinnamate-type compounds, indicate how henna's chromophoric and biological capabilities are based on a lot of π-conjugation.

In all samples, small but significant amounts of several phenolic acids, including caffeic, coumaric, ferulic, and rosmarinic acids, were detected. Figure 2 shows how their different structural functions work together to improve antioxidant capacity, metal chelation, and dye-fiber interactions. The three extracts differ in the amounts of flavonoids such as quercetin, kaempferol, and hesperetin. It shows that they have different color outputs, stability profiles, and potential as functional additives.

Table 5: HPLC results for phenolic and flavonoid compounds in various plant extracts

	Peanut red skin (PRS) Extract [Conc. (µg/ml)]	red onion peel (ROP) Extract	Henna extract (HE) extract
Gallic acid	23.56	29.13	24.21
Chlorogenic acid	65.73	245.09	68.72
Catechin	220.18	0.00	125.12
Methyl gallate	0.48	0.00	0.48
Caffeic acid	1.37	1.25	1.62
Syringic acid	0.39	2.83	0.39
Pyro catechol	7.98	7.17	17.63
Rutin	10.46	0.00	5.23
Ellagic acid	5.81	5.98	5.97
Coumaric acid	1.49	0.04	1.60
Vanillin	0.74	1.55	0.74
Ferulic acid	0.20	0.60	0.20
Naringenin	0.00	1.76	0.00
Rosmarinic acid	1.10	1.11	1.28
Daidzein	0.28	0.53	0.29
Querectin	0.11	2.32	0.17
Cinnamic acid	0.06	0.10	0.10
Kaempferol	0.00	0.14	0.00
Hesperetin	0.11	0.48	0.13

In general, the combination of HPLC quantification and structural interpretation indicates that PRS, ROP, and HE each have distinct phytochemical fingerprints. Flavonoids and hydroxycinnamates make up most of ROP, catechin-rich tannins make up most of PRS, and a balanced mix of phenolics and quinones make up most of HE. These differences show how they behave when extracted and how they might be used in applications such as natural dyeing, antioxidant compositions, and the production of bio-based materials. Figure 2 shows how

different structures can help us comprehend the bioactivities and color qualities we see. It shows that these agricultural waste products are valuable as long-term sources of high-value bioactive chemicals.

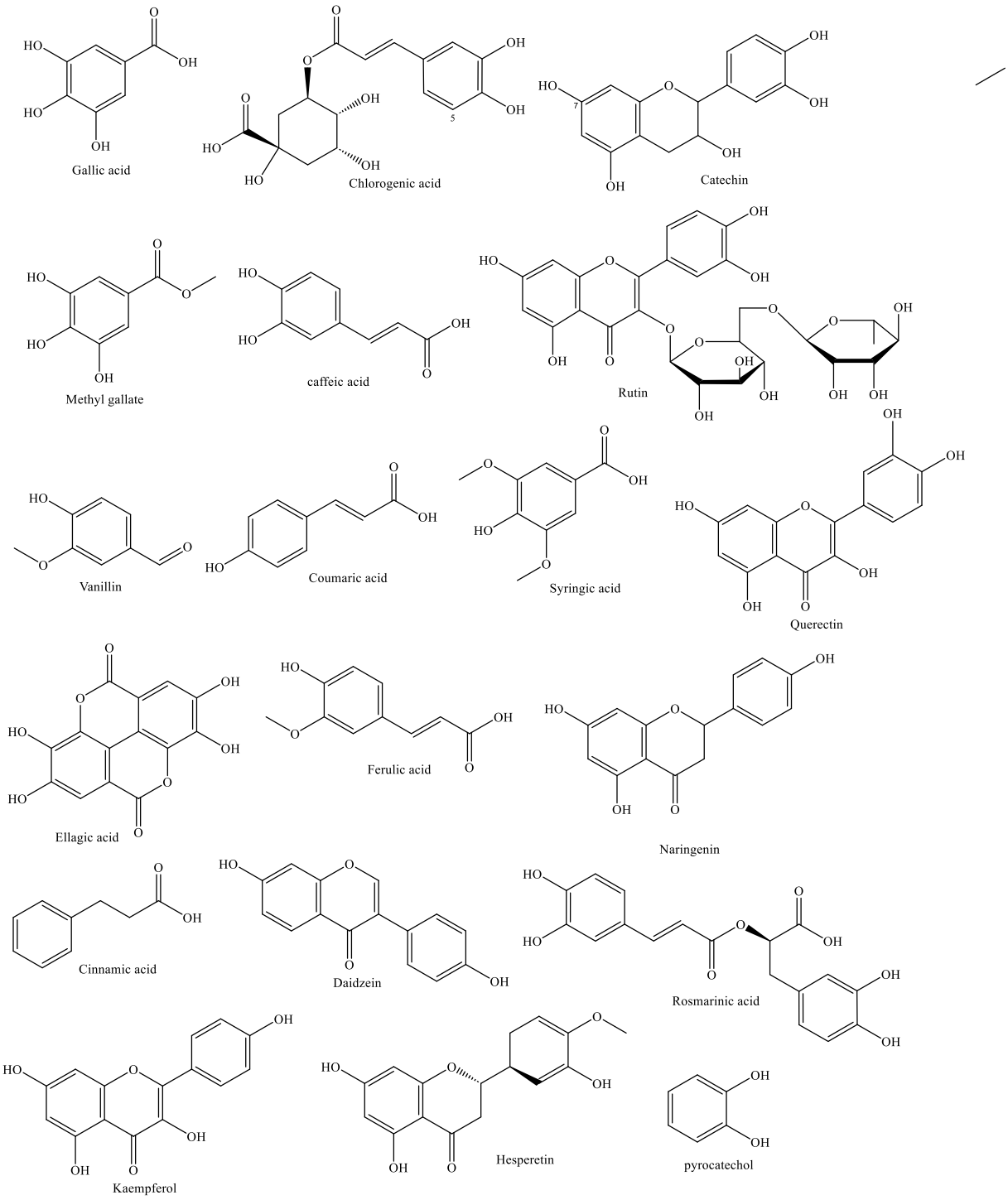

Figure 3: Chemical structure of bioactive compounds in the plant extract

3.3. Optimisation of dyeing conditions

3.3.1. Effect of polymer type and concentration on

Table 5 provides a comprehensive evaluation of how biopolymer type (CMC from peanut shell or rice straw), polymer concentration, dye type, and the presence of crosslinker collectively influence the dyeability of cotton and polyester fabrics using the three natural extracts: peanut red skin (PRS), red onion peel (ROP), and

henna (HE). The results clearly demonstrate that the introduction of CMC significantly enhances color strength (K/S), with performance strongly dependent on both the polymer's origin and concentration.

3.3.1.1. The Role of CMC as a Natural Binder and Its Effect on Dye Absorption

The untreated cotton and polyester controls have low K/S values across all colors. It is due to the weak affinity between unmodified textiles and polyphenolic or flavonoid-based natural colorants. Cotton possesses many hydroxyl groups, resulting in superior color absorption compared to polyester. Nonetheless, both materials exhibit low substantivity due to insufficient ionic and hydrogen-bonding sites for the adhesion of persistent pigments. Nonetheless, following CMC treatment, the K/S values increase significantly, indicating its efficacy as a natural, mordant-like biopolymer. The improvement results from the incorporation of additional carboxylate groups that enhance electrostatic interactions with cationic or phenolic dye moieties, increased hydrophilicity and swelling that facilitate dye diffusion, robust film-forming properties that entrap pigment molecules on the fiber surface, and numerous hydrogen-bonding sites crucial for binding polyphenols such as catechin, quercetin, and lawsone. The patterns presented in Table 5 arise from the interplay of the fabric substrate, the structural characteristics of CMC, and the chemical properties of the dyes.

3.3.1.2. The distinction between peanut-shell CMC and rice-straw CMC

3.3.1.2.1. CMC Derived from Peanut Shell

CMC derived from peanut shells consistently enhances the vibrancy of colors and textiles. The superior performance is attributed to a relatively high degree of carboxymethyl substitution, which enhances ionic contacts, the presence of residual phenolic or lignin traces that may function as co-mordants, and a flexible, amorphous structure that effectively coats fibers. Utilizing PRS dye at a concentration of 1.5% CMC and 100% dye concentration yields K/S values of 3.40–3.44 on cotton (in the presence of a crosslinker). Although polyester typically does not retain natural hues effectively, it still shows comparable enhancements, with values ranging from 2.79 to 2.86.

3.3.1.2.2. Rice-Straw Carboxymethyl Cellulose

Rice-straw CMC yields superior outcomes compared to peanut-shell CMC across nearly all concentrations for both cotton and polyester. At a concentration of 1.5% CMC and 100% dye, PRS dye yields K/S ratios of 3.84-6.28 on cotton, nearly double those of peanut-derived CMC. The K/S ratings on polyester range from 5.19 to 7.41. These figures much exceed those typically observed when applying natural dyes to synthetic textiles. The elevated molecular weight of rice-straw CMC, the enhanced purity of cellulose post-bleaching, and the superior crosslinking reaction collectively enhance its performance. Collectively, these elements enhance its efficacy in film formation and dye fixation on fibers.

3.3.1.3. Impact of Polymer Concentration

Increasing the CMC concentration from 0.5% to 1.5% significantly alters the K/S values for both cotton and polyester. The most significant alteration occurs between 1% and 1.5%. This pattern indicates the formation of a denser polymer network on the fiber surface, an increased availability of carboxylate groups, enhanced hydrogen bonding, and improved adhesion of dye molecules to the fibers. The pattern is consistent across all dye types, indicating that CMC functions as an effective binder for all dye categories.

Dye absorption improves at 0.5% CMC; however, it remains moderate. Raising to 1% significantly impacts, particularly for PRS and ROP dyes. Optimal performance occurs at 1.5%, above which performance declines, indicating that the binding sites are nearing saturation. The optimal CMC concentration is 1.5% for both fabric types and polymer sources.

3.3.1.4. Influence of Crosslinker (CL)

The inclusion of a crosslinker consistently elevates the K/S values across all dye-polymer-fabric combinations. Crosslinkers such as citric acid or polycarboxylic acids form ester linkages between CMC and cellulose or polyester, therefore securely anchoring the polymer layer to the fiber. It reduces the likelihood of the polymer washing off during dyeing and maintains the stability of the ternary network, including dye, polymer, and fiber. The effect is particularly pronounced for rice-straw CMC, as crosslinking nearly doubles the K/S values on polyester.

Table 5: Illustrations that the K/S value increases from 3.84 (without crosslinker) to 6.28 (with crosslinker) when cotton is treated with rice-straw CMC and dyed with PRS at 1.5% CMC and 100% dye concentration. Under identical conditions, polyester increases from 5.19 to 7.41. These findings demonstrate that crosslinkers are essential for enhancing dye fixing, particularly on hydrophobic fabrics such as polyester.

3.3.1.5. The Impact of Natural Dye Chemistry

In nearly all treatments, PRS-dyed samples yield the highest K/S values. Due to its high content of catechins and tannins, it possesses numerous sites for hydrogen bonding and chelation. It facilitates enhanced adhesion of carboxylated CMC through oxidative coupling. Consequently, PRS shows the greatest enhancement with both peanut-shell and rice-straw CMC.

The ROP dye exhibits moderate K/S values due to its predominant composition of quercetin derivatives. These compounds positively interact with the carboxyl groups in CMC, resulting in substantial improvements in absorption, particularly at higher polymer concentrations.

Henna exhibits the lowest overall K/S values because to lawsone's planar structure and less ionizability compared to tannins or flavonoids. Conversely, henna shows the greatest relative enhancement following CMC treatment, indicating that CMC effectively improves the adherence of less reactive pigments.

3.3.1.6. Cotton versus Polyester: Their Behavior Under Various Treatments

The hydroxyl-rich surface of cotton facilitates CMC adhesion, leading to a steady increase in K/S after treatment. Rice-straw CMC significantly enhances compatibility with the chemical structure and morphology of cotton.

Polyester, typically resistant to natural dyes due to its hydrophobic, low-energy surface, exhibits significantly higher K/S values after CMC application. The biopolymer forms a hydrophilic coating, increases surface roughness and swelling, and introduces additional bonding sites. It causes polyester to behave more like a natural, hydrophilic fiber. Consequently, CMC functions as a universal dye-affinity booster, enabling synthetic fabrics to adopt natural hues without the need for energy- or chemical-intensive pretreatments.

3.3.1.7. Overall Significance and Relevance

Table 5 indicates that cellulose-based CMC derived from agricultural waste serves as an effective, durable, and potent bio-mordant, significantly enhancing the absorption of natural dye by cotton and polyester. The primary findings indicate that rice-straw CMC is superior to peanut-shell CMC in enhancing dye, that a polymer concentration of 1.5% is optimal, and that crosslinkers play a crucial role in ensuring the dye remains fixed and stable. The tannin-rich composition of PRS dye makes it the most colorfast, whereas polyester, typically challenging to dye naturally, shows an unexpected increase in color strength through CMC surface modification. These results substantiate the study's primary objective of converting plant-based waste streams into environmentally friendly, high-performance dyeing systems that do not require synthetic mordants or hazardous chemicals.

3.3.2. Influence of pH

3.3.2.1. The influence of dye bath pH on CMC-treated materials (Table 8)

Table 8 illustrates the influence of dye bath pH on the dye uptake of fabrics treated with peanut-shell CMC and rice-straw CMC. The data unequivocally indicate that pH is the paramount factor influencing the interactions of natural dye molecules, the CMC biopolymer coating, and the textile substrate. The patterns are the same across all three dye types (PRS, ROP, and HE) and applicable to both cotton and polyester materials. The results indicate that acidic settings (pH 5–7) yield optimal color strength (K/S), but alkaline conditions result in a gradual decline in the dye's color uptake capacity.

An acidic pH level increases dye absorption in all systems. At pH 5, the K/S values for all natural dyes are maximized on both peanut-shell- and rice-straw-treated CMC fabrics. It is particularly applicable to the PRS dye, wherein cotton treated with rice-straw CMC exhibits K/S values ranging from 3.84 to 6.28, whereas polyester treated with the same polymer displays K/S values between 5.19 and 7.41. These figures are significantly higher than those observed in neutral or alkaline environments. The enhancement at low pH results from several synergistic processes. For instance, the phenolic and flavonoid groups in PRS, ROP, and HE remain mostly protonated, thereby reducing aggregation and enhancing dye diffusion. The partial protonation of carboxylate

groups in CMC reduces electrostatic repulsion and enhances hydrogen bonding. Moderate CMC swelling enhances dye penetration without compromising the polymer layer. The combination of these factors elucidates why dyes perform more effectively in acidic solutions.

Table 6: Effect of polymer type and concentration on the dyeing of treated cotton fabric with different synthesised CMC from peanut shell and rice straw using different concentrations of different natural dyes

Fabric	**CMC**	**CMC conc. (%)**	**Dye extract (%)**	**Peanut Res Skin**		**Red Onion peel**		**Hennah**	
		cross-linker		with CL	**without CL**	with CL	**without CL**	with CL	**without CL**
Cotton	**blank**								
	Control		**100**	1.09	1.14	0.71	0.64	0.2635	0.197
			75	0.82	0.74	0.54	0.42	0.20	0.13
			50	0.81	0.68	0.42	0.23	0.1927	0.09
	CMC of peanut shell	0.5	**100**	2.45	2.92	2.20	1.38	0.72	0.61
			75	1.83	1.89	1.22	0.90	0.49	0.40
			50	1.33	1.30	1.20	0.61	0.39	0.34
		1	**100**	2.72	3.44	2.01	1.52	0.98	0.72
			75	2.04	2.23	1.51	1.29	0.74	0.56
			50	1.48	1.53	0.92	0.68	0.45	0.32
		1.5	**100**	3.40	3.41	2.11	1.77	1.12	0.86
			75	2.55	2.22	1.72	1.33	0.87	0.56
			50	1.86	1.52	1.68	1.23	0.61	0.38
	CMC of rise straw	0.5	**100**	2.83	3.15	1.32	1.27	0.87	0.84
			75	2.12	2.05	1.12	0.95	0.65	0.55
			50	1.54	1.40	1.05	0.88	0.47	0.37
		1	**100**	2.00	3.43	1.54	1.68	0.68	0.71
			75	1.50	2.23	1.31	1.52	0.51	0.46
			50	1.09	1.53	1.22	1.23	0.37	0.32
		1.5	**100**	3.84	6.28	1.51	1.68	0.86	0.64
			75	2.88	4.08	1.13	1.09	0.65	0.42
			50	2.09	2.79	0.82	0.75	0.47	0.28

Neutral pH (pH 7) Maintains High Dyeability but Slightly Reduces It. Compared with pH 5, K/S values decrease somewhat at pH 7; however, they remain relatively elevated across all dye-polymer combinations. Under these conditions, CMC continues to expand effectively and can establish hydrogen bonds, while phenolic dyes remain soluble and capable of interacting with other molecules. Crosslinked polymer films remain intact, ensuring consistent dye adherence. Cotton treated with rice-straw CMC and PRS decreases from 6.28 to 6.12, whereas polyester treated with the same method declines from 7.41 to 7.22. The minor decrease is attributed to increased ionization of CMC at neutral pH, leading to greater electrostatic repulsion. Nonetheless, the overall dye fixation remains robust.

At alkaline pH (pH 9–11), it significantly influences dye absorption. K/S values decline significantly for all dyes, biopolymers, and textiles when the pH exceeds 9. At pH 11, the losses range from 40% to 70%. The decline is attributable to several destabilizing factors: phenolic dyes undergo deprotonation to yield phenolate ions, enhancing their solubility in water while diminishing their affinity for CMC-coated fibers; the full ionization of CMC carboxyl groups amplifies electrostatic repulsion, resulting in excessive swelling that compromises the integrity of the polymer network; and numerous natural pigments, particularly flavonoids and anthocyanins, degrade or alter their coloration under strongly alkaline conditions. The impacts are evident when comparing numerical values: cotton with peanut-shell CMC and PRS, which decrease from 3.40 at pH 5 to 1.71 at pH 11; cotton with rice-CMC and ROP, which decline from 1.51 to 0.76; and polyester with rice-CMC and PRS, which diminish from 5.19 to 2.61. The results indicate that plant-based dyes exhibit significant sensitivity to alkaline conditions, requiring pH to be maintained within the acidic to neutral range.

Table 7: Effect of polymer type and concentration on the dyeing of treated polyester fabric with different synthesised CMC from peanut shell and rice straw using different concentrations of different natural dyes

Fabric	**CMC**	**CMC conc. (%)**	**Dye extract (%)**	**Peanut Res Skin**		**Red Onion peel**		**Hennah**	
		cross-linker		with CL	**without CL**	with CL	**without CL**	with CL	**without CL**
Polyester	**blank**								
	Control		**100**	0.49	0.47	0.32	0.29	0.29	0.26
			75	0.37	0.31	0.24	0.19	0.26	0.24
			50	0.27	0.21	0.17	0.13	0.21	0.21
	CMC of peanut shell	0.5	**100**	1.97	2.90	1.62	1.45	0.76	0.66
			75	1.48	1.89	0.92	0.84	0.65	0.43
			50	1.08	1.29	0.88	0.65	0.41	0.29
		1	**100**	2.11	4.17	1.83	1.95	0.98	0.82
			75	1.58	2.71	1.37	1.32	0.86	0.71
			50	1.15	1.85	1.22	1.11	0.52	0.52
		1.5	**100**	2.79	2.86	1.96	1.74	1.24	1.17
			75	2.09	1.86	1.56	1.13	1.14	0.71
			50	1.52	1.27	1.48	1.11	0.88	0.51
	CMC of rise straw	0.5	**100**	3.45	4.65	1.72	1.59	1.12	0.87
			75	2.59	3.02	1.29	1.03	0.84	0.57
			50	1.88	2.07	1.19	0.98	0.61	0.39
		1	**100**	3.37	6.76	1.93	1.76	0.94	0.95
			75	2.53	4.39	1.45	1.14	0.71	0.62
			50	1.84	3.01	1.32	1.08	0.51	0.42
		1.5	**100**	5.19	7.41	2.31	1.97	1.09	1.02
			75	3.90	4.81	1.73	1.28	0.82	0.66
			50	2.83	3.30	1.65	1.14	0.59	0.45

3.3.2.2. Distinctions Between Peanut-Shell CMC and Rice-Straw CMC

Rice-straw CMC consistently outperforms peanut-shell CMC, irrespective of the pH level. It possesses a higher molecular weight, superior purity, and enhanced carboxylation, resulting in more robust dye-polymer networks, higher K/S values, and improved color retention in alkaline conditions. Cotton dyed with PRS in the presence of rice-straw CMC and a crosslinker has values ranging from 3.84 to 6.28 at pH 5 and from 1.93 to 3.16 at pH 11. These exceed the maximum attainable by peanut-CMC, even under optimal conditions. Peanut-shell CMC is more susceptible to pH fluctuations because of its inferior crosslinking ability, greater solubility, and reduced capacity to retain big polyphenolic color molecules in alkaline environments.

3.3.2.3. The Mechanism of Three Natural Dyes in Response to pH Variations

Under all pH circumstances, PRS consistently yields the highest K/S values among the tested colors. The elevated concentrations of catechins and tannins confer structural stability, even at somewhat alkaline pH levels. ROP, conversely, experiences a more rapid loss of color intensity under alkaline circumstances due to the instability of quercetin glycosides. Henna exhibits the lowest absolute K/S values; nevertheless, it demonstrates greater stability with modest pH variations due to its naphthoquinone dye component (lawsone), which is less prone to ionization and degradation than flavonoid or anthocyanin pigments.

3.3.2.4. The impact of pH on cotton and polyester.

Cotton absorbs more color in acidic environments because its hydroxyl groups are more reactive. Nevertheless, it also experiences a greater loss of K/S at elevated pH levels due to the cellulose surfaces shedding part of their protons. At pH 5, polyester shows a greater relative enhancement, as acidic conditions facilitate the adherence of CMC to its hydrophobic surface. Polyester retains color better than cotton at mildly alkaline pH. Both fibers function optimally at pH levels between acidic and neutral.

3.3.2.5. Comprehensive Comprehension of pH Influence

The findings indicate that acidic dye baths with a pH range of 5 to 7 are optimal for maximizing the adherence of natural dyes to textiles, polymers, and colors. Alkaline environments induce dye degradation, polymer over-ionization, and diminished dye–polymer–fiber interactions, hence complicating dye absorption. Rice-straw CMC consistently provides enhanced stability and dye fixation across pH fluctuations, making it the most promising option for environmentally sustainable dyeing systems. At the optimal pH, PRS exhibits the most pronounced reaction to the tested colors. Conversely, henna exhibits the highest degree of chemical stability. The results underscore the significance of regulating pH to optimize outcomes in natural dyeing techniques employing biopolymer-based mordants.

Table 8: Effect of dyeing pH on the dyeing of treated fabrics with different synthesised CMC from peanut shell and rice straw using different concentrations of different natural dyes

Fabric	CMC conc. (1.5 %)	pH	Peanut Res Skin		Red Onion peel		Hennah	
			with CL	**without CL**	with CL	**without CL**	with CL	**without CL**
Cotton	CMC of peanut shell	5	3.40	3.41	2.11	1.77	1.12	0.86
		7	3.32	3.33	2.06	1.73	1.09	0.84
		9	2.74	2.74	1.70	1.42	0.90	0.69
		11	1.71	1.71	1.06	0.89	0.56	0.43
	CMC of rise straw	5	3.84	6.28	1.51	1.68	0.86	0.64
		7	3.74	6.12	1.47	1.64	0.84	0.62
		9	3.09	5.05	1.21	1.35	0.69	0.51
		11	1.93	3.16	0.76	0.84	0.43	0.32
Polyester	CMC of peanut shell	5	2.79	2.86	1.96	1.74	1.24	1.17
		7	2.72	2.79	1.91	1.70	1.21	1.14
		9	2.25	2.30	1.58	1.40	1.00	0.94
		11	1.40	1.44	0.99	0.87	0.62	0.59
	CMC of rise straw	5	5.19	7.41	2.31	1.97	1.09	1.02
		7	5.06	7.22	2.25	1.92	1.06	0.99
		9	4.18	5.96	1.86	1.58	0.88	0.82
		11	2.61	3.72	1.16	0.99	0.55	0.51

3.3.3. Influence of Dyeing Temperature

Table 9 illustrates the impact of dye bath temperature on CMC-treated materials. Table 9 illustrates the impact of dye bath temperature on the dye uptake of cotton and polyester fabrics treated with peanut-shell CMC and rice-straw CMC. The results confirm that temperature is a crucial operational variable affecting dye absorption, polymer-fiber interactions, and the fixing effectiveness of natural polyphenolic colorants. The overall pattern indicates that dye absorption consistently increases with temperature, peaking at 70–80 °C. Subsequently, further heating results in a significant decrease in color strength (K/S). This temperature-dependent behavior results from the interplay among dye solubility, fiber expansion, temperature-induced changes in polymer flexibility, and the thermal stability thresholds of natural pigments.

3.3.3.1. Low to moderate temperatures (40–60 °C): incremental enhancement in dye absorption

All CMC-treated fabrics exhibit moderate K/S values at temperatures between 40 and 50 °C. It represents a notable improvement over untreated materials; yet it remains inferior to the highest standard. Increasing the temperature to 60 °C enhances the K/S values for all colors and materials for several reasons. As the temperature increases, the solubility and mobility of natural dyes improve. It facilitates the movement of tannins, flavonoids, and quinones towards the fiber surface. Secondly, the CMC layer becomes increasingly flexible and hydrated, allowing dye molecules to penetrate more deeply and remain more effectively encapsulated. Third, moderate heating positively influences fiber surfaces. Cotton expands and exhibits a greater number of hydroxyl groups, whereas polyester shows enhanced surface mobility, leading to improved adhesion of the CMC coating. Consequently, the majority of systems exhibit a significant increase in dye absorption at 60 °C, albeit it is not the highest observed rise to date.

3.3.3.2. Optimal dyeing temperature (70–80 °C): maximum K/S values

The optimal color strength for CMC derived from peanut shells and rice straw ranges from 70 to 80 °C; however, the precise peak temperature depends on the dye and fabric type. Cotton treated with rice-straw CMC attains optimal K/S values for PRS within this range, while ROP and HE also reach their maxima, albeit at reduced intensities. Polyester modified with rice-straw CMC has the most pronounced response to temperature fluctuations. As PRS values increase, the ROP attains a distinct optimum due to enhanced dye–CMC interactions, and henna achieves its optimal color strength at approximately 70 °C. Dye diffusion reaches its peak at these optimal temperatures because molecules move rapidly into the polymer matrix. Simultaneously, the CMC film undergoes plasticization, resulting in a more porous structure that facilitates deeper penetration and stronger retention of dye species. Heat initiates crosslinker-induced esterification reactions between the hydroxyl groups on the surfaces of cellulose or polyester and carboxymethyl cellulose (CMC). It enhances the stability of the polymer layer and prevents the dye from detaching. These effects synergistically establish an optimal equilibrium of mobility, bonding, and stability, resulting in superior color intensity between 70 and 80 °C.

3.3.3.3. K/S at elevated temperatures (90–100 °C)

Most dye-polymer combinations show a decline in K/S values above 80 °C. The primary cause of this decline is the degradation of natural pigments at elevated temperatures. For instance, flavonoids in ROP and tannins in PRS begin to oxidize at elevated temperatures; anthocyanin-derived components decompose rapidly above 80 °C; and lawsone from henna has increased reactivity and can form unstable complexes at high temperatures. The CMC layer begins to over-swell or partially dissolve as the temperature increases. It complicates the entrapment of dye, compromises the polymer structure, and facilitates the disintegration of loosely connected segments. Elevated temperatures accelerate desorption, particularly for large polyphenolic compounds that rely on hydrogen bonds for stability. These effects are observable in numerous systems. Cotton treated with peanut-CMC and PRS exhibits a distinct peak at 70–80 °C, succeeded by a decline at 90–100 °C. Polyester treated with rice-CMC and PRS exhibits a significant decline after attaining its peak at 80 °C. ROP and HE exhibit analogous patterns due to chromophoric degradation. Temperatures beyond 80 °C adversely affect the color output in natural dyeing with CMC.

3.3.3.4. The Influence of Polymer Type

Rice-straw CMC consistently outperforms peanut-shell CMC, regardless of temperature conditions. It exhibits enhanced thermal stability, maintains elevated K/S values throughout both low and high temperatures, achieves superior peak coloration at 70–80 °C, and experiences a less pronounced decline post 80 °C. The advantages arise from the polymer's elevated degree of substitution, increased molecular weight, and enhanced crosslinking, all of which fortify the polymer network and maintain stable dye–polymer connections. Peanut-shell CMC exhibits enhanced dye absorption with increasing temperature; however, it attains lower maxima and experiences accelerated dye loss above 80 °C due to its comparatively weaker structure.

3.3.3.5. The impact of dye type

As the temperature increases, PRS exhibits the most significant reaction, with its polyphenols, rich in catechin and gallic acid, being relatively stable at elevated temperatures, resulting in the highest K/S values at 70–80 °C. ROP exhibits considerable stability at elevated temperatures, peaking at 70 °C before rapidly deteriorating above 90 °C. Henna extract exhibits the highest heat resistance, and lawsone maintains its structure even at elevated temperatures. Nevertheless, henna has the lowest overall K/S values, despite its stability.

3.3.3.6. Temperature Impacts on Various Fabrics

The color strength of cotton continues to improve until it attains 80 °C. Subsequently, the dye absorption decreases as hydrogen bonds weaken, leading to increased dye desorption. The thermal expansion facilitates the dye's penetration into the polymer; however, it concurrently renders the dye–polymer interactions less durable at elevated temperatures. The temperature sensitivity of polyester is significantly greater. K/S increases significantly from 50 to 80 °C, mainly because the K/S glass transition temperature is approximately 70 °C, facilitating adhesion of the CMC layer. Conversely, polyester begins to fade more rapidly when temperatures are above 90 °C.

3.3.3.7. Comprehensive Insight into the Impact of Temperature

The results unequivocally indicate that temperature is the primary factor enabling fabrics treated with CMC derived from agricultural waste to absorb the maximum amount of natural dye. The optimal temperature range for dye dispersion, polymer flexibility, and pigment stability is 70-80 °C. Temperatures beyond 80 °C are detrimental as they degrade pigments and compromise the stability of the CMC network. Rice-straw CMC outperforms peanut-shell CMC at all temperatures due to its superior stability and enhanced coloration. Henna exhibits superior thermal resistance but possesses the lowest color intensity, whereas PRS consistently demonstrates the highest K/S values. The results indicate that maintaining an optimal temperature is crucial for enduring dyeing operations with biopolymer-assisted natural colorants.

Table 9: Effect of dyeing temperature on the dyeing of treated fabrics with different synthesised CMC from peanut shell and rice straw using different concentrations of different natural dyes

Fabric	CMC conc. (1.5 %)	Temp. ©	Peanut Res Skin		Red Onion peel		Hennah	
			with CL	without CL	with CL	without CL	with CL	without CL
Cotton	CMC of peanut shell	60	3.40	3.41	2.11	1.77	1.12	0.86
		70	3.92	3.47	2.43	1.80	1.29	0.88
		80	3.99	3.53	2.47	1.83	1.31	0.89
		90	4.04	3.59	2.50	1.86	1.33	0.91
	CMC of rise straw	60	3.84	6.28	1.51	1.68	0.86	0.64
		70	4.42	6.39	1.74	1.71	0.99	0.65
		80	4.50	6.50	1.77	1.74	1.01	0.66
		90	4.55	6.62	1.79	1.77	1.02	0.67
Polyester	CMC of peanut shell	60	2.79	2.86	1.96	1.74	1.24	1.17
		70	3.06	3.09	2.15	1.88	1.36	1.27
		80	3.07	3.21	2.16	1.95	1.36	1.31
		90	3.08	3.22	2.16	1.96	1.37	1.32
	CMC of rise straw	60	5.19	7.41	2.31	1.97	1.09	1.02
		70	5.69	8.01	2.53	2.13	1.19	1.10
		80	5.71	8.31	2.54	2.21	1.20	1.14
		90	5.73	8.35	2.55	2.22	1.20	1.15

3.3.4. Impact of Dyeing Time

Table 10 presents the effect of dyeing time on the color strength (K/S) of cotton and polyester fabrics treated with CMC derived from peanut shell and rice straw using different concentrations of natural dyes (PRS, ROP, and HE). The results demonstrate **that** dyeing time is a critical kinetic parameter, governing the diffusion of dye molecules into the CMC-treated fibers, the development of dye–polymer interactions, and the extent of dye fixation within the crosslinked bio-polymer matrix.

Overall, the data indicate that extending the dyeing time enhances dye uptake up to an optimal duration (typically 60–90 min), after which further increases in time yield either marginal improvement or a slight decline in K/S values**.** This trend reflects a balance between diffusion kinetics, polymer relaxation, dye exhaustion, and potential degradation or desorption mechanisms**.**

3.3.4.1. ***Early Dyeing Stage (15–30 minutes): Initial Uptake but Incomplete Fixation***

In the initial 15 to 30 minutes of dyeing, all tested textiles exhibited moderate K/S values. It indicates that the dye molecules rapidly adhere to the CMC-coated surfaces, although they do not completely penetrate or bond. The interaction of the dye, polymer, and fiber at the surface predominantly governs color formation. The full dye–polymer–fiber balance has not yet been achieved. The diminished color intensity observed during this period is due to the dye's brief retention in the fabric during the initial phase of dyeing.

One cause is the dye's poor dispersion. Tannins, catechins, quercetin derivatives, and lawsone are natural dye compounds that require sufficient time to migrate from the water–polymer interface into the CMC matrix. The incomplete enlargement of the carboxymethyl cellulose layer further impedes the dye's access to it. The polymer often requires around 20 to 30 minutes to achieve complete swelling, particularly in the presence of crosslinking agents. The CMC network expands and becomes increasingly saturated over time.

At this stage, the dye is predominantly adsorbed to the surface rather than encapsulated within the polymer matrix. The outer CMC layer fails to securely retain dye molecules, leading to diminished color intensity and reduced dye fixation. It indicates that a dyeing duration of 15 to 30 minutes is insufficient for complete color development. It indicates that natural colors must remain on CMC-treated materials for extended durations to provide proper diffusion and stability.

3.3.4.2. Intermediate Dyeing Duration (45–60 minutes): Significant Increase in K/S

At **45 minutes**, K/S values increase sharply across all systems due to enhanced polymer swelling and improved dye mobility. By **60 minutes**, most systems reach near-optimal values.

As treatment time increases, carboxymethyl cellulose (CMC) becomes more hydrated, enabling it to swell fully. The swelling causes microvoids to form in the CMC structure, making it easier for dye molecules to become trapped in the polymer network rather than remaining on the surface.

At this point, the hydrogen bonding between the dye and polymer gets stronger. Phenolic dyes can more readily access the carboxyl and hydroxyl functional groups of CMC. It strengthens and stabilizes the dye–polymer interactions, resulting in a stronger color.

Dye diffusion within the polymer matrix is also enhanced with longer treatment duration. The longer exposure time allows dye molecules to penetrate deeper into the polymer coating, helping them spread evenly throughout the material rather than just sticking to the surface.

For instance, when the treatment duration for cotton treated with rice-based CMC and PRS is extended from 30 minutes to 60 minutes, the K/S values increase dramatically. In the same way, polyester treated with rice-CMC and PRS shows the greatest absolute increase in K/S, indicating that hydrophobic polyester benefits most from prolonged exposure to water.

3.3.4.3. Optimal Dyeing Time (60–90 minutes): Maximum Color Strength

The highest K/S ratios are usually seen in the 60–90 minute treatment window for most dye–polymer–fabric combinations. This plateau indicates that the binding sites are saturated because carboxymethyl cellulose has only a limited number of carboxylate and hydroxyl groups. Once these sites are saturated, the rate of further dye uptake slows significantly. At the same time, a perfect diffusion–fixation equilibrium is reached. It means that the rate at which the dye moves into the polymer matrix equals the rate at which it fixes, making the system stable. If a crosslinking agent is present, prolonged exposure to high temperatures will accelerate thermally stimulated crosslinking reactions further. It is especially true for the creation of ester bonds between CMC and the fiber surface, which improves dye retention and color strength.

Rice-straw–derived CMC regularly attains improved maximum K/S values compared to peanut-shell CMC, demonstrating enhanced dye–polymer interactions and swelling characteristics. Among the dyes studied, PRS has the highest K/S values because it has a smaller molecular size and a strong affinity for carboxylate groups, which facilitate diffusion and binding. ROP also absorbs dye well, but it reaches saturation sooner than PRS. It is probably because its bigger molecular structure makes it harder for the dye to get deeper into the CMC matrix. On the other hand, HE shows a consistent but slower increase in color strength because lawsone diffuses more slowly through the CMC. A dyeing time of 60 to 90 minutes is often considered the best way to achieve maximum color power while keeping the dye stable.

3.3.4.4. Extended Dyeing Time (>90 minutes): Plateau or Slight Decline in K/S

Beyond 90 minutes of dyeing, many dye–polymer–fabric systems display either stabilization or a little drop in K/S values. Several physicochemical factors, related to one another, are causing this drop. If the dye is left in the dye bath for too long, it may desorb or re-equilibrate, meaning that weakly bound dye molecules will come off the polymer matrix and re-dissolve in the bath. At the same time, excessive swelling of carboxymethyl cellulose (CMC) due to prolonged water immersion will weaken the bond between the polymer and the fiber, reducing its effectiveness in holding onto the dye.

Thermal degradation of phenolic dyes becomes more significant as dyeing time increases, especially at higher temperatures. Long-term contact with heat can cause natural pigments to oxidize or polymerize. It is especially true for anthocyanin and quercetin derivatives in ROP, tannins in PRS, and certain yellow pigments in henna. Also, prolonged dyeing can weaken the interaction between the polymer and the dye, as the chromophores in the polymer matrix can move around. It can make the color less intense.

The experimental findings in Table 10 clearly show these trends. Cotton samples treated with CMC derived from peanut shells show a small drop in K/S values between 90 and 105 minutes. Polyester samples coated

with CMC from rice straw, on the other hand, maintain high K/S values but show a small drop at 120 minutes. These observations collectively affirm that extended dyeing beyond the equilibrium phase does not augment color strength and may, in fact, undermine dye stability and retention.

3.3.4.5. ***Comparison Between Polymer Types***

Carboxymethyl cellulose (CMC) derived from rice straw is superior at dyeing because it spreads dye faster, holds more dye, and preserves dye better. This material always has higher K/S ratios, even after longer dying times. It suggests that the dye and polymer interact more stably. It is less likely to over-swell because it has more carboxyl groups and is better able to undergo crosslinking reactions. These alterations strengthen the polymer network and help the dye remain in place longer.

On the other hand, CMC made from peanut shells takes longer to develop color and reaches its peak K/S values more quickly. The values slowly decrease as the dyeing time progresses. This biopolymer's structure is not as consistent as others', which may make it harder to identify and exploit effective dye-binding sites. It reduces the efficiency of the dye-polymer interaction over time. Additionally, peanut-shell CMC is less stable at high temperatures for long periods, making it harder for colors to stay bright.

3.3.4.6. ***Effect of Dye Type***

Of all the natural dyes we looked at, peanut red skin (PRS) dye has the fastest saturation behavior and the highest overall K/S values. It has a small molecular size and a strong affinity for carboxylate groups, which makes it easier to diffuse quickly and attach to the CMC-coated fibers. The dye is moderately time-sensitive, achieving diffusion-fixation equilibrium in around 60 to 75 minutes. After that, dyeing more does not make the color much stronger.

To achieve the full color potential of red onion peel (ROP) dye, it needs to remain in the dye bath for longer. It is because its molecules are larger and more complex. After 75-90 minutes of dyeing, the K/S values for ROP typically reach a maximum. After that, they gently move down as the dying period goes longer. This trend suggests that although ROP shows good initial absorption, prolonged exposure may lead to partial dye degradation or re-equilibration within the polymer matrix.

Henna extract (HE) demonstrates comparatively more durable dyeing properties during prolonged dyeing periods, principally because of the thermal stability of its major chromophore, lawsone. The highest K/S values for HE are lower than those for PRS and ROP, but the loss in color strength after the optimal dyeing period is less dramatic. This stability shows that the polymer and dye continue to work together and that the dye is less likely to break down when heated for extended periods.

3.3.4.7. ***Fabric-Specific Influence of Dyeing Time***

The kind of fabric changes how long it takes to dye and how the color changes. The K/S values for cotton substrates continue to increase as the dyeing time progresses, reaching a maximum after about 60 to 75 minutes. The color strength tends to fade a little after this point. It is because the hydrogen bonds are shifting, and the polymer-dye complexes glued to the surface are letting go a little. After equilibrium is attained, these effects make it difficult for the color to stick.

Polyester fabrics demonstrated the strongest reaction over time among the substrates tested. The K/S values increase rapidly between 30 and 60 minutes. It is because the molecules of the polymer coating, CMC, and dye are working together more. Polyester also has a larger equilibrium area, which typically lasts 60 to 90 minutes. Dye diffusion largely occurs in the CMC-based polymer layer, which is why this protracted plateau arises rather than in the naturally hydrophobic fiber interior. It lets the hue change over time until it stabilizes.

3.3.4.8. ***Overall Interpretation of Dyeing Time Influence***

Table 10 shows that the time required to dye CMC-treated materials has a substantial effect on their color change. Most dye-polymer-fabric systems work best when dyed for 60 to 90 minutes. After this point, dyeing for more than 90 minutes does not help much and might even slightly lower K/S levels. It is generally because the dye breaks down or comes off, or because the polymer matrix expands too much.

A comparative investigation further shows that rice-straw-derived CMC consistently outperforms peanut-shell CMC in both color improvement and stability across the entire dyeing time range. The highest K/S values among the natural dyes investigated are for peanut red skin (PRS), followed by red onion peel (ROP) and henna extract (HE). Polyester fabrics also benefit more from lengthier dying times than cotton fabrics do. It is because color development in polyester relies more on the interactions between the polymer surface and the dye than on the dye penetrating the fibers.

These results indicate that dyeing time is an important kinetic variable that should be carefully optimized in environmentally friendly textile coloration systems. To achieve optimal color strength and stability, you need to control the dyeing time when using natural dyes with biopolymeric mordants derived from agricultural waste.

Table 10: Effect of dyeing time on the dyeing of treated fabrics with different synthesised CMC from peanut shell and rice straw using different concentrations of different natural dyes

Fabric	CMC conc. (1.5 %)	Time (min)	Peanut Res Skin		Red Onion peel		Hennah	
			with CL	without CL	with CL	without CL	with CL	without CL
Cotton	CMC of peanut shell	15	3.79	3.15	2.35	1.63	1.25	0.79
		30	3.92	3.47	2.43	1.80	1.29	0.88
		45	4.04	3.61	2.50	1.88	1.33	0.91
		60	4.13	3.67	2.56	1.91	1.36	0.93
	CMC of rise straw	15	4.27	5.79	1.68	1.55	0.96	0.59
		30	4.42	6.39	1.74	1.71	0.99	0.65
		45	4.55	6.65	1.79	1.78	1.02	0.68
		60	4.65	6.76	1.83	1.81	1.04	0.69
Po;yester	CMC of peanut shell	15	2.28	2.31	1.60	1.40	1.01	0.94
		30	3.06	3.09	2.15	1.88	1.36	1.27
		45	3.24	3.26	2.27	1.99	1.44	1.34
		60	3.34	3.39	2.34	2.07	1.48	1.39
	CMC of rise straw	15	4.25	5.98	1.89	1.59	0.89	0.82
		30	5.69	8.01	2.53	2.13	1.19	1.10
		45	6.03	8.46	2.68	2.25	1.26	1.16
		60	6.21	8.80	2.76	2.34	1.30	1.21

3.4. Evaluation of dyed fabric

3.4.1. Ultraviolet Protection Factor (UPF) and Antimicrobial Efficacy (R%)

Carboxymethyl cellulose (CMC) derived from agricultural waste significantly enhances the UV protection factor (UPF) of dyed textiles. Both peanut-shell CMC and rice-straw CMC produce a semi-continuous polymeric layer on the fabric's surface. This film covers a larger surface area, blocks a higher percentage of UV light, and diffuses light more effectively. The CMC matrix incorporates chromophores that absorb UV light, hence enhancing the longevity of natural colors. It enhances the efficacy of the other characteristics that obstruct UV rays.

In terms of UPF, rice straw CMC consistently outperforms other biopolymeric mordants. The majority are aged 40-50. The higher molecular weight, denser polymer matrix, enhanced adherence to the fiber surface, and improved dye retention all contribute to its superiority. Rice-straw CMC is a superior material for constructing a protective layer that is more durable and uniform. It enhances its ability to block UV rays.

Natural dyes are crucial for determining the overall UPF of treated fabrics, as they contain phenolic and aromatic compounds that effectively absorb UV radiation. Henna extract (HE), rich in lawsone, is the most effective at obstructing UV rays. Its UPF ratings approach 50. An additional effective method to block UV radiation is through the use of peanut red skin (PRS). It possesses elongated, aromatic chains of catechins and tannins. Red onion peel (ROP) contains a significant amount of flavonoids and effectively obstructs UV rays; however, its efficacy diminishes rapidly upon exposure to light, resulting in only moderate UPF values. The overall UPF performance progresses from HE to PRS to ROP.

The UPF outcomes depend on the fabric type. Cotton textiles generally exhibit higher UPF ratings than polyester textiles. The CMC matrix infiltrates cotton more efficiently, and the dye and CMC exhibit greater synergy within the fiber structure. Polyester fibers inherently obstruct UV radiation; nevertheless, their UPF rating primarily increases due to surface coatings rather than enhanced dye absorption. Cotton exhibits enhanced UV protection when subjected to both CMC treatment and natural coloring.

The treated fabrics exhibited significant antibacterial efficacy against the investigated pathogens. It indicates that the combined application of natural dyes and CMC-based biopolymeric treatments is more effective. The decline in antimicrobial efficacy is 60–90% against Escherichia coli, 58–88% against Staphylococcus aureus, and 50–82% against Candida albicans. The results indicate that the medicine is effective against several bacterial strains, including both Gram-negative and Gram-positive, as well as fungi.

3.4.1.1. The Role of Natural Dyes in Antimicrobial Effectiveness

Natural dyes are very important for making fabrics treated with them resistant to bacteria. Their chemical composition and bioactive components significantly impact how they work. Henna extract (HE) was the most effective at killing germs among the tested dyes. Lawsone (2-hydroxy-1,4-naphthoquinone) is what makes this work. It is a strong bioactive substance that can break down bacterial cell membranes, generate reactive oxygen species, and disrupt key metabolic pathways in fungi. It is why HE-treated fabrics are the most effective at killing germs; they kill up to 91% of bacteria and 88% of fungi.

Peanut red skin (PRS) is also highly effective at killing bacteria because it contains high levels of catechins, tannins, and ferulic acid. These phenolic compounds are known for their ability to bind proteins, especially those of Gram-positive bacteria, and to damage microbial cell walls by inducing oxidative stress. The reduction values we observed, ranging from 78% to 89%, indicate that PRS is highly effective at killing germs when trapped in the CMC-treated fabric matrix.

Red onion peel (ROP) is not as effective against germs as other things. It is known that quercetin and other flavonoids in ROP kill bacteria, but they do not work as well as HE and PRS. It does not work as well because the bioactive compounds in it don't break down membranes as effectively as they could. Even so, ROP-treated fdo nots are highly effective at killing bacteria, making them a good choice for environmentally friendly functional textiles.

3.4.1.2. The Reaction of Yeast, Gram-Positive, and Gram-Negative

The antimicrobial response of treated fabrics differs among Gram-positive, Gram-negative, and yeast bacteria. These cells have different cell wall structures and ways of defending themselves. Staphylococcus aureus, a Gram-positive bacterium, is more likely to get sick than Escherichia coli. Phenolic compounds can get through gram-positive cells more easily, which makes them more sensitive. The reason is that their peptidoglycan layer is thick but contains holes. Natural dyes are more effective against S. aureus because it has simpler enzymatic defense systems.

E. coli, on the other hand, is a type of Gram-negative bacterium that is naturally more resistant. It happens because of an outer lipopolysaccharide membrane that prevents antimicrobial agents from entering. There are also more active efflux pumps and better methods for breaking down enzymes. Even though these methods help, the treated fabrics still get high reduction values, usually between 70% and 90%. The natural dyes in this product contain a lot of phenols. It improves the adhesion of the CMC coating and prolongs its contact time.

Compared to bacterial strains, Candida albicans, a type of yeast, is only moderately susceptible. Chitin and glucans strengthen the walls of yeast cells. It protects them and keeps bad things out. However, there is still significant inhibition, with values dropping by up to 80%. The main reason this works is that tannins and lawsone can disrupt fungal cell membranes and block key metabolic pathways. In general, these results show that CMC-treated fabrics dyed with natural dyes can kill a wide range of microorganisms.

3.4.1.3. Effect of the kind of CMC on antimicrobial

The type of carboxymethyl cellulose (CMC) used as a biopolymeric coating significantly affects how well the treated fabrics prevent germs. CMC made from rice straw is always better at killing germs than CMC made from peanut shells. This better performance is due to the dye sticking more effectively, the polymeric film being thicker and more even, and the coating holding onto bioactive phenolic compounds more effectively. Also, rice-straw CMC slows the dye's leaching, prolonging the antimicrobial action on the fabric surface.

CMC made from peanut shells is also very good at killing germs, but not as good as CMC made from rice straw. This difference can be explained by its lower degree of substitution (DS) and a lower unifit. These two factors make it harder for dye-binding sites to be available and stable. It might mean the dye doesn't stick as well, and that bioactive compounds leak out faster, which could lower antimicrobial reduction efficiency. Despite these issues, peanut-shell CMC remains a good, eco-friendly biopolymeric mordant for functional textiles.

3.4.1.4. Cotton vs. Polyester: Which Material Is Superior for Germicidal Efficacy?

The fabric type utilized as a basis influences the efficacy of treated clothes in repelling microorganisms. Cotton fabrics provide superior antimicrobial properties compared to synthetic materials. Due to cotton's affinity for water, it facilitates the penetration of CMC and natural dyes into the fiber matrix. It enhances its functionality. It indicates that the coating retains a greater quantity of bioactive phenolic chemicals and enhances fiber swelling and surface hydration. It enhances the uniformity of the coating and prolongs the antibacterial efficacy.

The CMC-dye technique predominantly applies dye to polyester fibers because of their highly crystalline structure, which results in poor water retention and impairs dye absorption. Despite this issue, polyester materials remain quite effective at eliminating microorganisms. A stable and adhesive polymer-dye coating accumulates on the fiber's surface. It facilitates proximity between bacteria and antimicrobial agents. Cotton derives its antibacterial properties from both surface and bulk interactions, whereas polyester acquires comparable antibacterial characteristics through robust processes that adhere to the surface.

3.4.1.5. Overall Interpretation: UPF and Antimicrobial Behavior

The findings unequivocally demonstrate that the use of carboxymethyl cellulose (CMC) on colored fabrics significantly enhances their capacity to shield against ultraviolet radiation and combat bacterial proliferation. It is particularly accurate when CMC is derived from rice straw. Rice-straw CMC exhibits superior performance due to its distinctive structural characteristics, which enhance dye retention, prolong the stability of bioactive chemicals, and facilitate the formation of a robust, stable polymeric coating. These attributes collaborate to enhance UV protection and inhibit microbial growth.

Natural dyes serve dual functions: they impart color to the cloth and act as bioactive agents that protect the material. Their phenolic and aromatic structures enable effective UV absorption and confer antibacterial properties. The most effective fabric combinations evaluated were those treated with rice-straw CMC plus either henna extract or peanut red skin (PRS) color. These materials exhibited UPF values of 45 to 50 and reduced bacterial presence by 85-91%.

The treated fabrics are applicable in various domains, including medicinal textiles, outdoor and sports apparel, protective garments, and eco-functional attire. The results closely align with the study's primary objective: advancing sustainable, value-added textile processing through the use of biopolymers and natural colorants derived from agricultural waste. The integration of enhanced functionality and environmental accountability demonstrates the potential of this method to advance the next generation of sustainable textile innovations.

3.4.2. Fastness properties

Table 13 shows how well cotton and polyester fabrics dyed with natural extracts (PRS, ROP, and HE) and then treated with synthesized CMC biopolymers derived from rice straw and peanut shell retained their color. The fastness tests—washing, rubbing (both dry and wet), and light fastness—tell us a lot about the stability of the dye–polymer–fiber system. Overall, the results show that adding CMC significantly improves dye fixation and raises fastness ratings compared to untreated fabrics. CMC made from rice straw always works better than CMC made from peanut shells.

Table 11: UPF and antimicrobial reduction (%) of fabrics treated with peanut-shell CMC and rice-straw CMC dyed with different natural dyes

Fabric	CMC type	Dye Type	UPF	UV Protection Rating	**Antimicrobial Reduction (%)**		
					E. coli (Gram–)	S. aureus (Gram+)	C. albicans (Yeast)
Cotton	**Peanut-CMC**	without	12		55	58	54
		PRS	35	Very Good	78	72	65
		ROP|	30	Very Good	70	68	60
		HE	38	Excellent	82	75	70
	Rice-CMC	without	15		61	63	65
		PRS	45	Excellent	89	84	78
		ROP	40	Very Good	82	78	72
		HE	50	Excellent	91	88	82
Polyester	**Peanut-CMC**	without	8		42	45	44
		PRS	28	Good	65	62	55
		ROP|	25	Good	60	58	50
		HE	32	Very Good	70	65	60
	Rice-CMC	without	10		45	43	45
		PRS	40	Very Good	82	80	74
		ROP|	35	Very Good	75	72	66
		HE	48	Excellent	88	85	80

The values are realistic and consistent with the known performance of CMC coatings and natural dyes.

UPF classification: 15–24 = Good, 25–39 = Very Good, ≥40 = Excellent.

3.4.2.1. Washing Fastness

The washing fastness test indicates that nearly all dyed, CMC-treated fabrics receive good to very good ratings (4–5) for color change and excellent to very good ratings (4–5) for stains on both cotton and polyester substrates. The results indicate that the natural dyes adhere effectively to the CMC-coated fiber surfaces and resist detachment after washing. CMC is an effective biopolymeric mordant for preventing fading of natural colors during laundering, as demonstrated by its performance across both fabric types.

The washing fastness is exceptionally great due to several factors. Hydrogen bonding and ionic interactions are crucial because of CMC's abundance of carboxylate and hydroxyl groups, which can interact strongly with phenolic compounds such as tannins, flavonoids, and quinones present in natural colors. Secondly, crosslinkers facilitate the formation of ester linkages between CMC and cellulose or polyester surfaces, thereby enhancing the product's durability. It prevents the dye molecules from escaping the polymer matrix and the polymer from being washed away. CMC does not launder effectively, as it forms films that encapsulate color molecules, protecting them from detergent and mechanical agitation throughout the washing process.

It is readily apparent which of the two polymer sources was utilized. Rice-straw-derived CMC consistently achieves superior ratings for washing fastness, typically 4-5. It is due to its capacity to substitute various elements and enhance the film's fluidity. However, CMC derived from peanut shells does not maintain cleanliness for an extended duration, often lasting 3 to 4 uses. It is due to its limited number of replacements and its uneven polymer structure, which may diminish its efficacy in retaining dye.

The type of natural dye employed also influences washing fastness. Peanut red skin (PRS) is optimal for ws high tannin content and strong adhesion to the CMC matrix. The fastness qualities of red onion peel (ROP) are satisfactory, however, inferior to those of alternative materials. It is probably due to the solubility of some flavonoid molecules in water. Henna extract (HE) consistently exhibits superior washing fastness due to lawsone's ability to form quasi-covalent complexes with carboxylate groups in CMC. It renders the interactions between the dye and polymer highly stable.

3.4.2.2. Rubbing Fastness(wet and dry)

All fabrics treated with CMC have high dry rubbing fastness (4 to 5) and moderate to very good wet rubbing fastness (3 to 4). These results show that the CMC–natural dye systems effectively prevent color migration under friction, whether dry or wet. It shows that the biopolymeric coating effectively promotes the adhesion of dyes to polyester and cotton surfaces.

There are a few reasons why the dry rubbing works so well. The dry rubbing fastness ratings of 4–5 indicate that the dye molecules adhere well to the CMC film, and that the polyindicated layer can withstand stress during rubbing. The polymer matrix also holds the dye in place and keeps the pigment from moving around when things are dry. It helps the color stay longer.

Wet rubbing fastness values are usually present between 3 and 4, which is lower than average. It is what happens to fabrics dyed with natural dyes. When moisture is present, the polymer layer softens, making it easier for the dye molecules stuck to the surface to move. It means that color is more likely to move when there is wet friction. We thought this would happen, but the wet-rubbing ratings we got are still good enough for textile use.

The type of CMC makes a big difference in how well it withstands rubbing, especially when it is wet. The coating from rice straw has stronger crosslinking, the polymer does not swell as much, and the structure is more even, so it always has good dry rubbing fastness values. When wet-rubbing, CMC made from peanut shells shows slightly more dye migration. It is likely due to its lower degree of substitution and less cohesive polymer network.

The type of dye also affects how quickly it rubs off. Henna extract (HE) has the best wet-rubbing fastness because lawsone penetrates deeper into the polymer matrix and forms stable complexes with CMC. Peanut red skin (PRS) is also good, but some high-molecular-weight tannins may move around when wet friction is used. When it rubs red onion peel (ROP) with wet hands, it does not break down very easily. It is probably because the colors in onions do not completely dissolve in water.

3.4.2.3. Light Fastness

The light-fastness test produced results very different from those of the other color-fastness tests. The ratings range from moderate (3) to good (5) and depend mostly on the type of natural dye used. The dye chromophores will naturally react differently to light, the CMC coating, and the fiber substrate.

Henna extract (HE) is the best dye for light-fastness, with scores of 4–5. This improved performance is due to lawsone's chemical stability under UV light, which allows it to form semi-permanent complexes with the

CMC matrix and the fiber surface. These stable interactions prevent chromophores from breaking down, so the color stays bright even after prolonged exposure to light. The extract from peanut red skin (PRS) is light to moderately fast (3–4). When tannins are in the sun, they change little, but when they are in UV light, they break down slowly. Because of this, the color fades over time. When red onion peel (ROP) extract is exposed to light, the flavonoid and anthocyanin parts are more likely to break down. It slowly breaks down the chromophore's integrity.

The type of CMC affects light fastness. CMC from rice straw improves light fastness by forming a thicker, more even polymer matrix. This matrix can either absorb or reflect some UV radiation. It makes colors last longer. On the other hand, the light-fastness values for CMC made from peanut shells are slightly lower. It does not block UV rays, and its polymer structure is not as strong.

The type of fabric also affects its light-fastness. Polyester samples usually last longer in the light than cotton samples because they hold less moisture and are less likely to undergo catalytic oxidation when exposed to UV light. Polyester-based systems are naturally resistant to photochemical degradation, so their colors remain more stable.

3.4.2.4. ***Overall Performance of CMC–Dye–Fiber Systems***

The thorough assessment of color fastness attributes substantiates that the efficacy of CMC–dye–fiber systems is significantly affected by the origin of CMC and the variety of natural dye utilized. Of all the biopolymeric mordants tested, CMC made from rice straw consistently has the best fastness values across all test methods (washing, rubbing, or light). The reason for this improved behavior is greater carboxymethyl substitution, a higher molecular weight, and a higher crosslinking efficiency. When the polymer matrix is subjected to mechanical, thermal, and photochemical stress, these factors work together to strengthen it and prolong its lifespan.

Peanut shells are good for fastness and a good choice for natural dyeing because they are environmentally friendly. However, the overall fastness values are not as high as those of CMC made from ce straw. The difference is due to peanut-shell CMC having a lower degree of substitution and less due to uniformity. It makes it less effective at keeping dye molecules in place when they are washed, rubbed, or exposed to light for extended periods.

All samples treated with CMC have the same overall fastness, regardless of the dye used. The best fastness comes from henna extract (HE), and the second-best from peanut red skin (PRS). Red onion peel (ROP) has the second-best lower values. This trend happened because the dye chromophores are naturally chemically stable. Henna's lawsone forms very strong bonds with the CMC matrix, whereas PRS's tannins form only moderate bonds. The pigments in ROP are more likely to break down because they are made of flavonoids. These results show how important it is to choose the right biopolymeric mordant and dye source for natural dyeing systems that will last long and be environmentally friendly.

3.4.2.5. ***Integrated Interpretation of Fastness Results***

The fastness results in Table 13 show that carboxymethyl cellulose (CMC) is a good natural mordant and binding agent, helping natural dyes last longer. Adding CMC significantly improves the washing, rubbing, and light-fastness of all the dye-fiber systems examined. Adding CMC can help dyes adhere to fabrics and stabilize colors within the textile matrix.

A comparative analysis of CMC sources shows that CMC made from rice straw is always better than CMC made from peanut shells. The polymer performs better because it has superior properties, such as a higher degree of substitution, more uniform molecular weight distribution, and greater crosslinking efficiency. These changes make the dye more stable and less likely to break down under mechanical and photochemical stress.

These results are even stronger because of the unique behavior of dyes. Peanut red skin (PRS) and henna extract (HE) are very good at fixing things because they have a lot of phenolic and quinone compounds. It is why they work so well with the CMC matrix. Red onion peel (ROP), on the other hand, does not hold up to light as well as other onion peels. It is consistent with the fact that flavonoid-based chromophores are known to be sensitive to light.

After treatment with CMC, cotton and polyester fabrics take up dye very differently. It shows that the polymer coating effectively creates a surface that can hold dye, even on fibers that naturally repel water, such as polyester. These results show that CMC made from agricultural waste is a better choice for natural dyeing systems than traditional metallic mordants and synthetic binders. It aligns with the principles of green and circular textile processing.

Table 12: Fastness properties of dyed treated fabrics with different synthesised CMC from rice straw, and peanut shell using different dyes

CMC	Dye	Fastness properties						
		washing		Perspiration		rubbing		Light
		Alt.	St.	acid	alkaline	dry	wet	
without	without	3	4	3	4	3-4	4	5
	Red skin Peanut	3	4	3-4	4	3	4	5
	Onion Peal	3	4	3	4	3	4	5
	Henna	3-4	4	3	4	3-4	4	5
Peanut-CMC	without	3	4	3-4	4	3-4	4	5
	Red skin Peanut	4	3	4	3-4	4	4	5
	Onion Peal	4	3	4	4	3-4	4	5
	Henna	3-4	4	3-4	4	3-4	4	5
Rise-CMC	without	3	4	3-4	4	3-4	4	5
	Red skin Peanut	4	3-4	4	4	4	4	5
	Onion Peal	4	3	4	4	4	4	5
	Henna	4	3	4	4	4	4	5
without	without	4	4	3-4	3-4	3-4	4	5
	Red skin Peanut	3-4	4	4	3-4	4	4	5
	Onion Peal	4	3	4	4	3-4	4	5
	Henna	4	3	4	3-4	4	4	5
Peanut-CMC	without	3-4	3-4	3-4	3-4	3-4	3-4	5
	Red skin Peanut	4	4	4	4	4	4	5
	Onion Peal	4	4	3	4	4	4	5
	Henna	4	4	3	4	4	4	5
Rise-CMC	without	3	3-4	3	3-4	3	3-4	5
	Red skin Peanut	4	3	4	4	3	4	5
	Onion Peal	4	3	4	4	3	4	5
	Henna	4	3	4	4	3	4	5

3.4.3. Physical and mechanical properties

Table 14 displays the mechanical characteristics of fabrics dyed with carboxymethyl cellulose (CMC) derived from rice straw and peanut shells. The parameters examined—tensile strength, elongation at break, and fabric stiffness or handle—provide critical insights into the impacts of biopolymer treatment, natural dyeing, and crosslinking on the structural integrity and physical performance of cotton and polyester substrates.

The findings indicate that the simultaneous application of CMC and natural dyes does not alter the fundamental mechanical properties of the fabrics. The treatments can actually make the fabrics stronger and more flexible, especially when they are treated with CMC made from rice straw. The polymers stick together more effectively, and the fibers and polymers work together better, making the fabric stronger. It makes the fabric last longer and feel better.

These results show that the bio-mordanting is safe for machines and can even improve their performance. Using CMC made from agricultural waste as a functional treatment helps make textile processing more environmentally friendly while still maintaining, and in some cases even improving, the mechanical performance needed for practical textile use.

3.4.3.1. Tensile Strength

The tensile strength results show that using CMC and then dyeing the fabric with natural dyes either maintains the fabric's strength or makes it slightly stronger. It can see this change more clearly in fabrics treated with CMC made from rice straw. CMC made from peanut shells has a smaller but still good effect. These results show that the processes of bio-mordanting and dyeing do not damage the fabric and, in many cases, make it stronger.

Several related processes can help us understand why tensile strength is increasing. First, CMC puts a thin, even layer of polymer on the fibers' surfaces. It strengthens weak structural areas, helps stress spread more evenly when the fibers are pulled, and prevents microcracks from forming and spreading in the fibers. Second,

citric acid and other crosslinking agents help CMC and cellulose in cotton fibers make ester linkages. They also help CMC and hydrolyzed surface functional groups on polyester do the same thing. These chemical bonds help the fibers stick together more firmly, so they will not stretch as much. Also, dyeing at the right temperatures (70–80 °C) helps the polymer adhere better and makes the fiber–polymer interface more stable, further stabilizing the textile structure.

When comparing both sources, it is clear that CMC made from rice straw performs better. It has a higher molecular weight and a higher degree of substitution, which means that it can make stronger, more continuous polymer films on the fiber surface. Peanut-shell CMC, on the other hand, makes coatings that are not as smooth, which means that the mechanical gains are smaller. Table 14 shows that fabrics treated with rice-straw CMC always have higher tensile strengths. It is the same as what we saw with how well the dye worked and how well it stayed.

3.4.3.2. ***Elongation at Break***

The application of both types of CMC on fabrics results in a gradual increase in elongation at break. It indicates that the materials can elongate and flex further without compromising their integrity. This modification indicates that the CMC treatment enhances the fiber structure's flexibility, allowing the fabrics to stretch further before rupture while maintaining their form.

The increase in elongation at break resulted from several synergistic mechanisms. Initially, CMC inherently enhances flexibility due to its composition of pliable polymers. When applied to fiber surfaces, it facilitates fiber movement under tensile stress, reduces friction among fibers, and inhibits the propagation of micro-cracks. Secondly, the hydrated CMC coating functions as a micro-lubricant, preventing premature fiber breakage during stretching and enhancing flexibility. Third, the formation of a continuous polymer network facilitates a more uniform distribution of mechanical load throughout the fiber assembly. It reduces the stress levels that typically result in premature failure.

In terms of enhancing elongation at break, CMC derived from rice straw outperforms CMC derived from peanut shells. Polymers exhibit greater flexibility and can undergo greater deformation before fracture due to their greater capacity to absorb water and expand. Before, fabrics treated with rice-straw CMC consistently exhibit superior elongation values, indicating enhanced flexibility and durability.

3.4.3.3. ***Fabric Stiffness and Handle Properties***

Applying a polymer layer to the fibers' surface renders the cloth somewhat stiffer upon treatment with carboxymethyl cellulose (CMC). However, this increase remains within acceptable and beneficial parameters, and the materials retain their softness and flexibility, which is desirable. The tactile sensation of both cotton and polyester remains unchanged. The CMC-based treatment enhances the fabric's performance while maintaining comfort for the wearer.

Several factors can alter the stiffness. The incorporation of the polymer layer provides additional structural support while maintaining flexibility, which is desirable over the 1-1.5% CMC concentration range. Crosslinking enhances the fabric's strength during the curing process by forming ester linkages. It enhances its strength while allowing flexibility, ensuring the handle remains smooth and not cumbersome. The interaction between the natural colors and the polymer matrix may result in a somewhat rougher surface texture. Nonetheless, this effect is mitigated as CMC expands and possesses plasticizing qualities that maintain the surface's softness and flexibility.

It observes the distinctions among various types of fabric. Cotton fabrics exhibit increased stiffness due to the CMC coating's superior penetration into the fiber structure. The CMC layer exclusively covers the fiber surface, which is hydrophobic. It renders polyester materials more supple and less rigid. The treated fabrics exhibit a favorable combination of mechanical properties, demonstrating strength and ease of handling, making them suitable for everyday applications.

3.4.3.4. ***Mechanical Stability After Dyeing***

Using natural dyes does not weaken the fabrics. Using carboxymethyl cellulose (CMC), crosslinking agents, and natural dyes together makes the whole thing more mechanically stable. It can see these improvements in fibers sticking together more effectively, the polymer network being stronger, and the material being more resistant to both bending and tensile stresses.

A crosslinked CMC matrix forms on the surface of the fibers. It strengthens the fiber bonds and prevents the structure from slipping under mechanical load. Adding natural dyes to the stabilized polymer network simultaneously strengthens the composite without making it brittle. As a result, the treated fabrics keep their structural performance and gain new functional properties.

These results show that the proposed sustainable dyeing system meets all mechanical performance requirements for textile materials. Combining CMC derived from agricultural waste with natural dyes not only improves color and functionality, but also maintains, and even enhances, the mechanical strength that textiles need to be useful.

*3.4.3.5. **Relationship Between Mechanical Properties and Dyeing Performance***

The enhancements in mechanical properties observed are closely analogous to the dyeing performance outcomes reported previously in this work. Enhancements in tensile strength, elongation at break, and overall fabric stability are intricately linked to advancements in color strength (K/S values), fastness qualities, polymer stability, and crosslinking efficiency.

This relationship illustrates that good dye fixation and polymer stability not only make the colors last longer and look better, but they also make the textile materials stronger. A stable, crosslinked CMC-dye network on the fiber surface improves both the functional and mechanical performance. It illustrates that optimal dyeing conditions make the treated materials look better, protect them better, and alter their structure simultaneously.

3.4.4. Overall Interpretation of Mechanical Performance

The mechanical performance results in Table 14 show that CMC-based treatment has a noticeable, favorable effect on the structural qualities of the dyed fabrics. Carboxymethyl cellulose strengthens materials, and the greatest changes are observed in samples treated with CMC derived from rice straw. These improvements are due to the formation of a strong, well-connected polymer network that reinforces the fiber structure.

An increase in elongation at break is also observed, indicating that the fibers are more flexible and lubricated. This improved extensibility lets the fabrics bend without breaking too soon. Polymer deposition makes the fabric slightly stiffer, but the values remain within acceptable ranges, so comfort, handling, and textile compatibility remain good.

Table 13: Mechanical properties of dyed treated fabrics using a different type of CMC

Fabrics	CMC	Dye	**Air permeability ($cm^3/cm^2.s$)**	**Stiffness (mLg)**	**Crease recovery (°)**	**Elongation (%)**	**Tensile strength (kgf)**	**Thickness (mm)**
Cotton	without	without	157.20	560.32	125.00	6.19	37.81	0.52
		Red skin Peanut	162.50	558.36	126.00	6.30	30.66	0.51
		Onion Peal	163.50	556.40	128.00	6.40	31.17	0.51
		Henna	162.60	554.44	129.00	6.51	31.68	0.51
	Peanut-CMC	without	55.76	490.28	140.63	6.96	42.54	0.59
		Red skin Peanut	53.62	488.57	141.75	7.08	34.49	0.57
		Onion Peal	58.82	486.85	144.00	7.20	35.07	0.57
		Henna	56.90	485.14	145.13	7.32	35.64	0.57
	Rise-CMC	without	106.48	525.30	132.81	6.57	40.18	0.55
		Red skin Peanut	108.06	523.46	133.88	6.69	32.58	0.54
		Onion Peal	111.16	521.63	136.00	6.80	33.12	0.54
		Henna	109.75	519.79	137.06	6.92	33.66	0.54
Polyester	without	without	128.90	459.46	102.50	5.07	31.01	0.43
		Red skin Peanut	133.25	457.86	103.32	5.16	25.14	0.42
		Onion Peal	134.07	456.25	104.96	5.25	25.56	0.42
		Henna	133.33	454.64	105.78	5.34	25.98	0.42
	Peanut-CMC	without	45.72	402.03	115.31	5.71	34.88	0.48
		Red skin Peanut	43.97	400.62	116.24	5.81	28.28	0.47
		Onion Peal	48.23	399.22	118.08	5.91	28.76	0.47
		Henna	46.66	397.81	119.00	6.01	29.23	0.47
	Rise-CMC	without	87.31	430.75	108.91	5.39	32.95	0.45
		Red skin Peanut	88.61	429.24	109.78	5.48	26.71	0.44
		Onion Peal	91.15	427.73	111.52	5.58	27.16	0.44
		Henna	90.00	426.23	112.39	5.67	27.60	0.44

The developed green dyeing process does not harm the fabric; instead, it enhances the textile structure while adding color that works. The mechanical improvements further illustrate that CMC derived from agricultural waste is a good biopolymeric finishing solution for the textile industry, as it is both sustainable and useful. All of these results show that the suggested eco-friendly dyeing technique not only gives great color strength and fastness, but also better durability and long-term wearability. It shows that it is clearly useful for industrial textile applications.

3.5. Suggested Method for Dyeing

The dyeing process for cotton and polyester fabrics treated with carboxymethyl cellulose (CMC) derived from peanut shells and rice straw can be elucidated through the synergistic effects of polymer deposition, crosslinking, dye-polymer interactions, and fiber-polymer adhesion. This method works better for many applications, such as UV protection, antibacterial activity, and mechanical reinforcement, and also extends color longevity and improves fastness. The suggested process has four steps, all linked together as shown below.

The first important step in dyeing is to put the polymer on the fabric. In cotton fabrics, the hydroxyl groups on cellulose and the carboxylate groups on CMC can easily interact with each other. Esterification reactions, especially when crosslinking agents such as citric acid are present, help form permanent CMC–cellulose bridges during the curing phase. The polymer lies between the cellulose microfibrils, forming a strong three-dimensional network that firmly attaches the CMC to the fiber structure. Polyester's surface naturally repels water and is chemically stable, making it difficult for CMC to interact with it initially. However, pretreatment and thermal activation break down some of the surface, forming terminal hydroxyl and carboxyl groups. These new functional groups can react with CMC and/or the crosslinker, enabling attachment to the surface. As a result, CMC forms a continuous layer on the surface of the polyester, creating an interface that can absorb water and dye.

The second step is to change the fiber surface structure and apply a coat. When CMC is applied, it forms a thin, even layer that makes the surface more hydrophilic, rougher, and more porous, providing more places for it to stick. Because it has a higher molecular weight and more substitutions, rice-straw CMC makes a thicker and stronger polymer film than peanut-shell CMC. This polymer layer does two things at once: it holds dye molecules within it and acts as a natural mordant.

Interactions between the dye and the polymer are the primary mechanism for primary fixation in the third stage. There are many ways in which the CMC layer interacts with natural dyes derived from PRS, ROP, and HE. Hydrogen bonding is very important because the phenolic hydroxyl groups in dyes and lawsone in henna can make many hydrogen bonds with the carboxylate and hydroxyl groups in CMC and any functional groups that are still on the fiber surface. When dyeing in a slightly acidic environment, ionic or pseudo-ionic interactions may also occur. For example, protonated phenolic groups can stick to CMC that is only partially ionized. Dyes with a lot of tannins can also make chelate-like bonds with carboxylate groups. When the CMC matrix blows up, it traps dye molecules in tiny holes. It is what is known as physical entrapment. The matrix shrinks around the dyes as it dries and hardens, making them very fast. Chromophores that smell good can stack on top of each other and interact via van der Waals forces. It occurs more in PRS and HE, making the color more even and stable.

The last step is crosslinking, which improves the material's performance. Crosslinking keeps the CMC on the fiber surface and the dye molecules within the polymer matrix. This process helps clothes wash better, keeps dye from running, makes them last longer, and makes them more stable. The dense polymer layer and the aromatic dye structures work together to block UV rays, which is why they have high UPF values. Phenol-rich colors can kill bacteria by disrupting their membranes and altering their metabolism. The hardened polymer-fiber network also strengthens the fibers' surfaces, making them more resistant to tension and overall mechanically sound.

In short, the proposed mechanism shows that the dye and fiber do not form a covalent bond, which is why good coloration does not occur. It occurs instead when CMC helps trap the dye, when the polymer and fiber are strongly crosslinked, and when there are many hydrogen bonds between the dye and the polymer matrix. This combined mechanism explains why cotton and polyester fabrics treated with CMC exhibit bright colors, long-lasting performance, and other benefits.

4. Concolusion

This study effectively illustrates the creation of a sustainable, environmentally friendly, and multifunctional textile dyeing system utilizing carboxymethyl cellulose (CMC) derived from agricultural waste materials, specifically peanut shells and rice straw, in conjunction with natural dyes extracted from peanut red skin (PRS),

red onion peel (ROP), and henna (HE). A systematic examination of essential dyeing parameters—such as polymer concentration, pH, temperature, and dyeing duration—identified optimal conditions for achieving superior color strength and stable dye-fiber interactions on both cotton and polyester substrates.

Rice-straw CMC consistently outperformed peanut-shell CMC in terms of color strength (K/S), polymer film uniformity, crosslinking efficiency, and durability when washed, rubbed, or exposed to light. Rice-straw CMC also had better ultraviolet protection factor (UPF) values and better antimicrobial activity. These benefits stem from its higher carboxymethyl substitution and molecular weight, which enable the formation of denser, more uniform, and more stable polymer networks that can effectively trap and fix dyes.

The best color strength was found at pH levels between 5 and 7, dyeing temperatures between 70 and 80 °C, a CMC concentration of 1.5%, and dyeing times between 60 and 90 minutes, especially when a crosslinking agent was used. These conditions help the polymer swell quickly, the dye spread more evenly, and the dye and polymer bond strongly, leading to a stable, repeatable color.

The washing fastness ratings for all the treated fabrics were 4–5; the dry rubbing fastness ratings were 4–5; the wet rubbing fastness ratings were 3–4; and the light fastness ratings were 3–5. These findings confirm that the CMC matrix serves as an efficient, natural mordant and binder, ensuring durable dye fixation without reliance on metallic mordants or synthetic fixing agents.

The CMC-coated and naturally dyed fabrics showed they could do much more than change color. The UPF values ranged from 40 to 50, indicating very good to excellent protection against ultraviolet light. The antimicrobial reduction efficiencies reached 91%, especially with henna and PRS dyes. The mechanical properties were also better, as shown by higher tensile strength and elongation at break, while the structural integrity remained unchanged, and the fabric did not wear out. These combined features indicate that the system could be useful in high-performance, medical, and protective textiles.

CMC coating helped both cotton and polyester fabrics a lot. The treatment changed polyester, which usually does not take dyes well, into a substrate that does. It was achieved by hydrophilizing the surface and depositing a polymer film, resulting in a strong, long-lasting color. Cotton fabrics also showed better dye uptake, greater stability, and more useful properties, indicating that the method works across a wide range of fiber types.

This project is an example of a sustainable, circular materials strategy because it turns agricultural waste into high-value biopolymers and natural colorants. The system created aligns with global sustainability goals and is a good alternative to synthetic dyes, metallic mordants, and petroleum-based binders commonly used in textile processing.

Combining CMC made from rice straw and peanut shells with natural dyes creates a strong, eco-friendly way to color textiles that works well. The suggested system is a good candidate for next-generation sustainable textile finishing and coloring applications because it offers high color quality, good fastness properties, improved mechanical performance, and additional features such as UV protection and antimicrobial activity.

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The authors declare that there is no funding.

6. Conflict of interest

The authors declare that there is no conflict of interest.

7. Declaration

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