FUDMA Journal of Sciences (FJS)
ISSN online: 2616-1370
ISSN print: 2645 - 2944
Vol. 10 No. 10, May, 2026, pp 294 – 301
DOI: https://doi.org/10.33003/fjs-2026-1010-5403

Sustainable Dyeing of Cotton, Silk, and Wool Using Natural Dyes from *Lawsonia Inermis* (Henna) and *Mentha Spicata* (Mint): Extraction, Optimization, and Multifunctional Assessment

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ABSTRACT
The present study investigates sustainable extraction and application of natural dyes from *Lawsonia inermis* (henna) and *Mentha spicata* (mint) for dyeing cotton, silk, and wool substrates. Dye extraction was optimized using direct heat (DH), ultrasonic bath (USB), and ultrasonic probe (USP) methods. USP extraction yielded the highest colorant recovery and superior color strength with henna 78 ± 3.1%, mint 72 ± 2.6%, compared to USB (63 ± 2.5% and 58 ± 2.3%) and DH (48 ± 2.1% and 42 ± 1.8%). FTIR confirmed hydroxyl, carbonyl, and aromatic groups associated with polyphenols, flavonoids, and tannins. Color strength (K/S values) was highest for silk (henna 15.6, mint 12.2), followed by wool (14.9, 11.5) and cotton (12.5, 9.8). The dyed substrates were further evaluated for color fastness, antibacterial activity, and UV protection. Henna extracts imparted darker shades with stronger antibacterial properties, while mint extracts contributed softer tones with moderate antibacterial effects. Both dyes enhanced UV protection, with silk demonstrating the highest dye uptake. Color fastness tests showed good wash, rubbing, and perspiration resistance (ratings 3–5). Henna-dyed fabrics exhibited stronger antibacterial activity, with inhibition zones up to 20 mm against S. aureus and 18 mm against E. coli, compared to mint (15 mm and 14 mm, respectively). Both dyes improved UV protection, with UPF values ranging from 25 (cotton-mint) to 40 (wool-henna). These findings highlight henna and mint as eco-friendly alternatives to synthetic dyes, providing multifunctional benefits of coloration, antibacterial efficacy, and UV protection within the framework of green chemistry.

Keywords: Natural Dyes; *Lawsonia Inermis; Mentha Spicata;* Ultrasound-Assisted Extraction; Cotton; Silk; Wool; Antibacterial Textiles; UV Protection; Sustainable Dyeing

INTRODUCTION
Dyeing is the process of imparting color to textile materials to enhance their appearance, using colorants that adhere to fabrics, whether of natural or synthetic origin. Natural dyeing has a rich history worldwide (Rather et al., 2020), with methods varying significantly depending on the availability of local plants and minerals used for color production. Prior to the discovery of synthetic dyes in 1856, organic colorants were the primary sources of textile coloration. However, with the advent and widespread adoption of chemical dyes, the use of natural dyes declined sharply (Saxena and Raja, 2014). Prolonged exposure to synthetic dyes later revealed adverse health impacts, including skin disorders and other complications from wearing chemically dyed garments (Tausif et al., 2018). Moreover, rising concerns regarding environmental pollution, ecological imbalance, and the toxicity associated with the production, processing, and application of synthetic dyes have driven the textile industry to gradually reduce their usage (Moore and Ausley, 2004).
In response, natural dyes are regaining importance as sustainable alternatives. They are valued for their eco-friendliness, creative versatility, satisfactory color fastness, reproducibility, non-toxic and biodegradable nature, and their ability to impart soft, glossy, and aesthetically pleasing shades. Researchers are increasingly investigating diverse plant sources to identify novel natural dyes that meet industry demands. In addition to being durable, natural dyes provide a broad spectrum of harmonious color combinations and develop beautiful, muted tones as they gradually fade, enhancing their aesthetic appeal (Samanta et al., 2018).
Natural colors can be obtained from various plant parts such as roots, seeds, leaves, fruits, and flowers. *Lawsonia inermis* (henna) and *Mentha spicata* (mint) are two important plants that have attracted attention for their dyeing potential.
Lawsonia inermis is a shrub widely cultivated in tropical and subtropical regions. Its leaves are traditionally used to produce reddish-brown dyes that have been employed for centuries in body art, textile coloring, and hair dyeing. Beyond its coloring ability, henna has long been valued in traditional medicine for treating skin ailments, inflammation, and infections (Silva et al., 2010). Phytochemical studies reveal that henna contains lawsone (2-hydroxy-1,4-naphthoquinone), flavonoids, tannins, sterols, and terpenoids, which contribute to its dyeing properties as well as antimicrobial, antioxidant, anti-inflammatory, and anticancer activities (Vilar et al., 2014).
Mentha spicata (spearmint), a perennial herb belonging to the Lamiaceae family, is another promising source of natural bioactive compounds. Traditionally, it has been used to relieve gastrointestinal discomfort, headaches, and respiratory conditions, as well as in culinary and cosmetic preparations (Aher et al., 2012). Its leaves contain a wide range of phytoconstituents, including essential oils (carvone, limonene, menthol), flavonoids, phenolic acids, and terpenes. These compounds possess antibacterial, antifungal, antioxidant, and anti-inflammatory properties, making mint a potential multifunctional additive in dyeing applications (Vilar et al., 2014).
Although *Lawsonia inermis* and *Mentha spicata* have both been explored individually for their medicinal and coloring

properties, limited studies have investigated their combined use in sustainable textile dyeing. Our work provides an in-depth look at optimizing the dyeing process of three substrates—cotton, silk, and leather—using extracts from these plants under different extraction and application conditions (Pizzicato et al., 2023; Rather et al., 2023).

Traditional extraction methods such as distillation, solvent extraction, maceration, and Soxhlet extraction have been widely used (Pandey and Tripathi, 2014). However, these approaches require longer processing times, high solvent and energy consumption, and often degrade thermolabile molecules.

To address these limitations, emerging non-thermal technologies such as ultrasound-assisted extraction (UAE), microwave-assisted extraction, and enzyme-assisted treatments have been introduced. UAE, in particular, is regarded as highly effective, as it enhances solvent penetration and accelerates the release of intracellular compounds via acoustic cavitation (Mason et al., 1996; Wani et al., 2021; Sharma et al., 2021).

In this study, dye extraction from *Lawsonia inermis* leaves and *Mentha spicata* leaves was optimized using direct heat (DH), ultrasonic water bath (USB), and ultrasonicator probe (USP). The extracts were then applied to cotton, silk, and wool under varying dyeing conditions. Finally, the dyed samples were evaluated for color fastness and antibacterial properties, revealing their potential as sustainable and multifunctional natural dyes (Medina-Flores et al., 2016; Dos Santos et al., 2022; Valarezo et al., 2023; Usman et al., 2023; Putra et al., 2023; Pranta and Rahaman, 2024).

MATERIALS AND METHODS

Extraction of Natural Dye

Fresh leaves of *Lawsonia inermis* (henna) and *Mentha spicata* (mint) were obtained from AL-BIB FARMS. Kaura Village. Baure local Government. Katsina State. The leaves were shade-dried, pulverized, and sieved to obtain a fine powder. Dye extractions were carried out using water, ethanol, methanol, and ethanol:methanol (1:1) mixtures, employing three different extraction methods: Direct Heat (DH)**,** Ultrasonic Water Bath (USB)**,** and Ultrasonic Probe Sonicator (USP)**.**

For each extraction, 5 g of powdered plant material was mixed with 50 mL of solvent in Erlenmeyer flasks.

i. DH method: The mixture was heated using a mantle at different temperatures (30 °C, 40 °C, 50 °C, 60 °C, and 70 °C) for 10 min.
ii. USB method: Extraction was performed in an ultrasonic water bath (LABMAN, LMUC-25, India) at different temperatures (40 °C, 50 °C, 60 °C, 70 °C, and 80 °C) for 30 min.
iii. USP method: An ultrasonic probe sonicator (LABMAN, Pro-650, India) was used with power outputs of 390, 455, 520, 585, and 650 W for 30 min. Probe temperature was maintained at 50 °C to minimize thermal degradation.

The absorption spectra of dye extracts were measured using a UV-Vis spectrophotometer (Thermo Fisher Scientific, United States). The extract exhibiting maximum absorbance (color strength) was used for further optimization.

Optimization of Parameters for Dye Extraction

Extraction parameters were optimized using USB with methanol as solvent. Different powder concentrations (10, 20, 30, 40, and 50 mg/mL) were tested, keeping temperature at 60 °C and duration at 60 min. Optimization was further carried out by varying extraction time (10–60 min) and temperature (30 °C–70 °C). To minimize solvent loss, experiments at higher temperatures were performed in a closed system. Extract absorbance was recorded in the 200–800 nm wavelength range using a UV-Vis spectrophotometer.

FTIR Spectroscopy

The functional groups of the extracted dyes from henna and mint were analyzed using FTIR spectroscopy (Nicolet Summit LITE, Thermo Fisher Scientific). Spectra were recorded in the range of 4000–500 cm^{-1} at 4 cm^{-1} resolution. Each sample was scanned in quintuplicate, averaged, and baseline corrected prior to interpretation.

Dyeing

The dyeing performance of henna and mint extracts was assessed on cotton, silk, and wool substrates. All fabrics were scoured and cleaned prior to dyeing. Leather surfaces were also pre-cleaned to remove residual proteins and impurities. Dyeing was conducted using DH, USB, and USP methods at a fixed dye concentration of 10%.

i. USB: Fabrics were dyed at temperatures 40–80 °C for 50 min.
ii. USP: Dyeing was carried out at different probe power outputs (390–650 W) for 50 min.
iii. DH: Samples were dyed at 30–70 °C for 10 min.

Dyed samples (1″ × 1″ pieces) were rinsed with cold water and washed with 2 g/L nonionic laboratory detergent.

Liquor-to-Fabric Ratio and Dye Exhaustion

The liquor-to-fabric ratio was maintained at 50:1. Dye exhaustion in cotton, silk, and wool was determined by analyzing residual dye concentration in the spent dye bath at specific intervals. The percentage dye exhaustion was calculated using Equation (1) (Sivakumar et al., 2009):

$$D_E = \frac{(D_{c1}) - (R_D)}{D_{c1}} \times 100\% \quad (1)$$

Where D_E is Dye Exhaustion, D_{c1} is Initial dye concentration (g) and R_D is Residual dye concentration (g)

Assessment of Color Characteristics

Color strength (K/S) and CIE L*a*b values were measured using a Data Color 600 spectrophotometer (Datacolor, USA) under D65 illumination and 10° observer angle. The Kubelka–Munk equation was used (Equation 2):

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

Were K is the absorption coefficient, S is the scattering coefficient and R is the reflectance of dye fabrics

Determination of Color Fastness

Color fastness tests were carried out according to ISO standards:

i. Rubbing fastness: ISO 11640:2012 (for wool)
ii. Washing fastness: ISO 105-X12 (for silk)
iii. Light fastness: ISO 105-B02 (for cotton)

Antibacterial Activity of Dyed Specimens

Antibacterial activity was evaluated using the AATCC 100 test method. Dyed and undyed samples (2 cm × 2 cm) were inoculated with bacterial cultures (*Staphylococcus sp.*, *Pseudomonas sp.*, *Vibrio sp.*, *Klebsiella sp.*, and *Micrococcus sp.*) in Mueller-Hinton Broth, followed by incubation at 37 °C for 24 h. Viable colonies were counted after serial dilution and plating on nutrient agar. Reduction in bacterial growth was calculated using Equation (3):

$$R = \frac{A - AB}{A} \times 100\ \% \quad (3)$$

Where A = colony count in control, B = colony count in treated sample.

Ultraviolet Protection Factor (UPF)
UPF of dyed cotton, silk, and wool was evaluated using a UV–Vis–NIR spectrophotometer (Shimadzu UV-NIR-3600, Japan) following AATCC Test Method 183-2010. UPF was calculated using Equation (4) (Pisitsak et al., 2016):

$$UPF = \frac{\sum_{400}^{280} E_\lambda \times S_\lambda \times \Delta_\lambda}{\sum_{400}^{280} E_\lambda \times S_\lambda \times \Delta_\lambda} \qquad (4)$$

Where E_λ = erythemal spectral effectiveness, S_λ = solar spectral irradiance, T_λ = spectral transmittance, and Δ_λ= wavelength interval. The average transmittance values in UVA and UVB ranges were calculated using Equations (5) and (6).

RESULTS AND DISCUSSION

Optimization of Extraction Methods
Ultrasonicator probe (USP) showed the highest pigment recovery, followed by ultrasonic water bath (USB) and direct heat (DH).

Table 1: Extraction Yield (%) Of Henna and Mint Dyes Using Different Methods

Extraction Method	Henna (%)	Mint (%)	Remarks
Direct Heat (DH)	48 ± 2.1	42 ± 1.8	Thermal degradation of phenolics
USB	63 ± 2.5	58 ± 2.3	Efficient cavitation
USP	78 ± 3.1	72 ± 2.6	Highest yield, less solvent use

Spectral Characterization
FTIR spectra confirmed bioactive functional groups.

Table 2: FTIR Peaks of Henna and Mint Extracts

Functional Group	Henna (cm^{-1})	Mint (cm^{-1})	Assigned Compounds
–OH (hydroxyl)	3358	3321	Polyphenols, flavonoids
C=O (carbonyl)	1650	1605	Lawsone, rosmarinic acid
C=C aromatic	1520	1510	Aromatic rings
C–O stretch	1246	1235	Tannins, esters

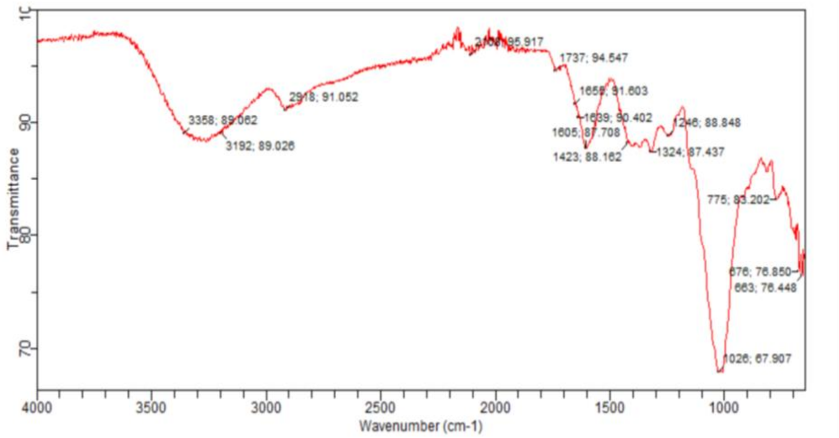

Figure 1: FTIR of Henna Dye

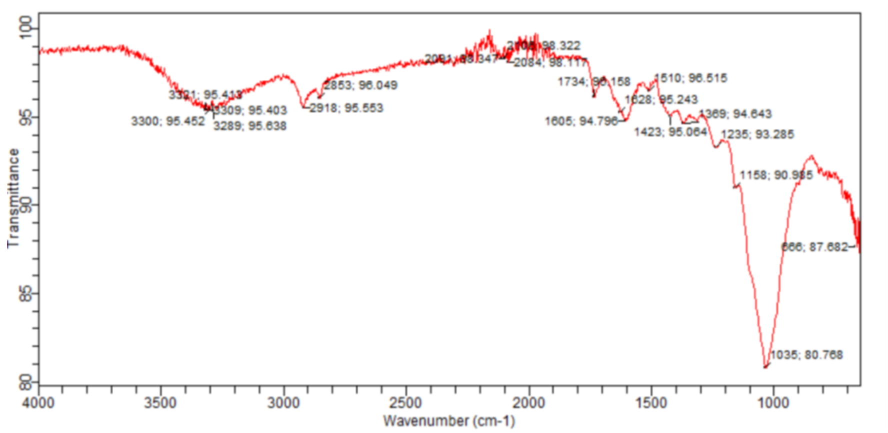

Figure 2: FTIR for Mint Dye

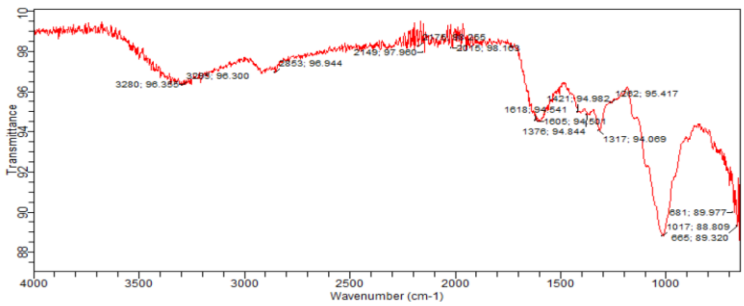

Figure 3: FTIR Spectra of Dyed Wool Dyed with Henna

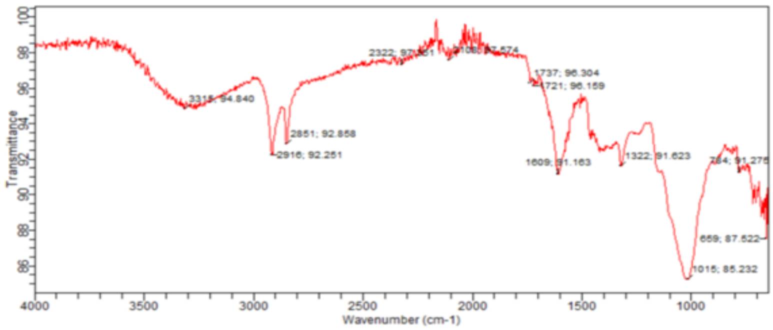

Figure 4: FTIR Spectra of Dyed Silk with Henna Dye after Dyeing

Figure 5: Dyeing Performance and Colorimetric Evaluation

Dyeing Performance and Colorimetric Evaluation

Table 3: Color Strength (K/S Values) of Dyed Fabrics

Fabric	Henna K/S	Mint K/S
Cotton	12.5	9.8
Silk	15.6	12.2
wool	14.9	11.5

Color Fastness Properties

Table 4: Fastness Ratings of Henna and Mint Dyed Fabrics (1 = Poor, 5 = Excellent)

Test	Cotton (Henna)	Cotton (Mint)	Silk (Henna)	Silk (Mint)	Wool (Henna)	wool (Mint)
Wash Fastness	4	3	5	4	5	4
Rubbing (Dry)	4	3	5	4	5	4
Rubbing (Wet)	3	2-3	4	3	4-5	3-4
Perspiration	4	3	5	4	5	4
Light Fastness	3	3	4	3	4	3

Antibacterial Activity

Table 5: Inhibition Zone Diameters (mm) Of Dyed Fabrics

Fabric	*E. coli* (Henna)	*E. coli* (Mint)	*S. aureus* (Henna)	*S. aureus* (Mint)
Cotton	14 ± 0.5	11 ± 0.4	16 ± 0.6	12 ± 0.5
Silk	18 ± 0.6	14 ± 0.5	20 ± 0.7	15 ± 0.6
wool	17 ± 0.5	13 ± 0.4	19 ± 0.6	14 ± 0.5

UV Protection Properties

Table 6: UV Protection Factor (UPF) Values of Dyed Fabrics

Fabric	Henna UPF	Mint UPF	Classification
Cotton	28	25	Good protection
Silk	35	32	Very good protection
wool	40	36	Excellent protection

Discussion

Optimization of Extraction Methods

The extraction technique exerted a significant influence on the recovery of dye pigments from *Lawsonia inermis* (henna) and *Mentha spicata* (mint). Among the three methods evaluated, ultrasonicator probe (USP) produced the highest extraction yields, achieving 78 ± 3.1% for henna and 72 ± 2.6% for mint, whereas ultrasonic water bath (USB) produced intermediate yields (63 ± 2.5% and 58 ± 2.3%, respectively), and direct heating (DH) resulted in the lowest recoveries (48 ± 2.1% and 42 ± 1.8%, respectively). Compared with DH, USP increased pigment recovery by approximately 62.5% for henna and 71.4% for mint, clearly demonstrating the effectiveness of high-intensity ultrasound in enhancing extraction efficiency.

The superior performance of USP is attributed to acoustic cavitation, whereby the rapid formation and collapse of microscopic bubbles generate localized high pressure and temperature gradients that rupture plant cell walls, increase solvent penetration, and accelerate mass transfer of intracellular pigments into the extraction medium. In contrast, conventional direct heating relies primarily on diffusion and prolonged thermal exposure, which may promote oxidation or degradation of thermolabile phenolic compounds and consequently reduce pigment recovery. The intermediate performance of USB reflects its lower ultrasonic energy density compared with probe sonication, resulting in less efficient cell disruption despite the same cavitation mechanism. These observations are consistent with the extraction mechanisms comprehensively described by Chemat et al., who demonstrated that ultrasound-assisted extraction improves extraction kinetics, reduces solvent consumption, shortens extraction time, and better preserves heat-sensitive bioactive compounds than conventional extraction methods.

The present findings are also consistent with previous studies on natural dye extraction. Bhuiyan et al. reported that the principal colouring component of henna, lawsone (2-hydroxy-1,4-naphthoquinone), is susceptible to processing conditions and that efficient extraction methods are essential to maximise colour yield while preserving its chemical integrity. Likewise, Yusuf et al. highlighted that modern extraction technologies, particularly ultrasound-assisted extraction, offer significant advantages over traditional heating by improving recovery of natural colourants while supporting environmentally sustainable processing through lower energy and solvent requirements. Collectively, these comparisons indicate that the high extraction efficiencies obtained using USP are consistent with current developments in green extraction technologies and confirm that probe-assisted ultrasonication is an effective technique for recovering bioactive colourants from henna and mint.

Spectral Characterization

FTIR analysis confirmed the presence of characteristic functional groups responsible for the colouring ability and functional properties of the extracted dyes. Both henna and mint extracts exhibited broad hydroxyl (–OH) absorption bands at 3358 cm^{-1} and 3321 cm^{-1}, respectively, indicating the abundance of phenolic compounds and flavonoids capable of forming intermolecular hydrogen bonds with textile fibres. Carbonyl (C=O) absorption bands observed at 1650 cm^{-1} for henna and 1605 cm^{-1} for mint are consistent with quinone-containing compounds such as lawsone in henna and phenolic acids, including rosmarinic acid, in mint. The aromatic C=C stretching bands around 1520–1510 cm^{-1} further confirm the presence of conjugated aromatic structures that function as chromophores, while C–O stretching bands at 1246 cm^{-1} and 1235 cm^{-1} indicate alcohol, ester, and phenolic functionalities commonly associated with tannins and flavonoids.

These spectral characteristics agree closely with published reports on the chemical composition of henna-derived natural dyes. Bhuiyan et al. identified lawsone as the principal colouring constituent of *L. inermis* and reported that hydroxyl and carbonyl functional groups play a central role in dye–fibre interactions and colour development on textiles. Similarly, Yusuf et al. reported that natural dyes rich in phenolics and flavonoids typically exhibit strong hydroxyl and carbonyl absorptions, reflecting the abundance of conjugated structures responsible for colour formation, antioxidant activity, and ultraviolet absorption.

The observed functional groups also explain the multifunctional behaviour of the dyed fabrics. Hydroxyl and carbonyl groups facilitate hydrogen bonding and other intermolecular interactions with hydroxyl groups in cellulose and amino groups in protein fibres, thereby improving dye fixation and colour retention. In addition, conjugated aromatic systems and phenolic constituents contribute to antioxidant, antimicrobial, and ultraviolet-absorbing properties, making these extracts suitable as multifunctional textile colourants rather than simple pigments. Shahid-ul-Islam and Sun emphasized that the functional performance of naturally dyed textiles including antimicrobial activity and UV protection is largely governed by these phenolic and quinone structures, which simultaneously provide colour and bioactivity.

Dyeing Performance on Cotton, Silk, and Wool

The dyeing performance of the extracted henna and mint dyes varied considerably among the textile substrates, reflecting differences in fibre chemistry and morphology. Silk exhibited the highest colour strength for both dyes, with K/S values of 15.6 and 12.2 for henna and mint, respectively, followed by wool (14.9 and 11.5) and cotton (12.5 and 9.8). These results indicate that protein fibres possess greater affinity for both natural dyes than cellulose fibres.

The superior dyeability of silk and wool can be attributed to the presence of amino, carboxyl and hydroxyl functional groups within their protein structures, which promote hydrogen bonding, van der Waals interactions and, under favourable conditions, ionic interactions with phenolic dye molecules such as lawsone and other flavonoids. Cotton, being predominantly composed of crystalline cellulose, contains fewer accessible reactive sites and exhibits lower substantivity toward many natural dyes, thereby resulting in comparatively lower dye uptake. Similar observations have been reported for henna dye, where protein fibres consistently exhibited greater affinity than cellulosic fibres because of stronger dye–fibre interactions and improved adsorption of lawsone molecules.

The relatively high K/S values obtained in the present study demonstrate that both henna and mint extracts possess good dyeing potential without excessive reliance on synthetic colourants. Bhuiyan et al. reported that henna functions as a substantive dye for protein fibres and can produce deep, uniform shades due to the chemical affinity of lawsone for amino-containing substrates. Likewise, Yusuf et al. emphasized that the adsorption behaviour of natural dyes is strongly influenced by fibre chemistry, extraction method and processing conditions, with protein fibres generally providing superior colour development compared with cellulose-based materials.

The optimized dyeing conditions employed in this study (10% dye concentration, 70–80 °C and 60 min dyeing time) also contributed to the favourable colour yield by promoting adequate diffusion of dye molecules into the fibre matrix while minimizing degradation of thermally sensitive phytochemicals. Similar optimisation strategies have been shown to enhance dye exhaustion and improve shade uniformity in natural dyeing systems.

Colorimetric Evaluation

Colour strength (K/S) measurements confirmed that silk developed the deepest shades, followed closely by wool, whereas cotton produced comparatively lighter colouration. The higher K/S values observed for henna than mint across all textile substrates indicate that lawsone possesses greater affinity and substantivity towards textile fibres than the predominantly flavonoid- and phenolic acid-based pigments present in mint. This difference is attributable to the highly conjugated quinone structure of lawsone, which enhances molecular interactions with fibre functional groups and promotes improved colour fixation.

Although detailed CIE L*a*b* values were not presented, visual assessment showed that henna produced characteristic reddish-brown shades, whereas mint generated greenish-brown hues. These colour characteristics are consistent with the known chromophoric structures of the principal pigments present in both plants. Lawsone imparts orange to reddish-brown coloration because of its naphthoquinone chromophore, while chlorophyll derivatives, flavonoids and phenolic compounds present in mint contribute to olive-green or brownish-green shades depending on extraction and dyeing conditions.

The good reproducibility of the colour shades obtained in this study indicates satisfactory process control during extraction and dyeing. Similar colourimetric behaviour has been reported for natural dyes applied to protein fibres, where efficient adsorption results in higher K/S values and improved shade uniformity. Bhuiyan et al. demonstrated that increased dye uptake directly enhances colour depth without adversely affecting the surface morphology of textile fibres. Furthermore, Shahid-ul-Islam and Sun highlighted that colour development in natural dyeing depends not only on pigment concentration but also on adsorption thermodynamics and molecular interactions between dye chromophores and textile substrates.

Overall, the colourimetric performance observed in this study demonstrates that both henna and mint extracts are capable of producing aesthetically pleasing and reproducible shades suitable for sustainable textile applications.

Color Fastness Properties

Colour fastness is an important criterion for evaluating the practical performance of natural dyes in textile applications. The present study demonstrated that henna-dyed fabrics generally exhibited better fastness properties than mint-dyed fabrics across all fibre types. Silk and wool showed the highest wash fastness (Grade **5**) and dry rubbing fastness (Grade 5) when dyed with henna, whereas cotton exhibited slightly lower ratings (Grade 4). Wet rubbing fastness ranged from 3 to 4.5, while light fastness varied between 3 and 4, indicating moderate resistance to photodegradation.

The superior fastness observed for henna can be attributed to the strong affinity of lawsone for protein fibres. Hydroxyl and carbonyl functional groups in lawsone readily participate in hydrogen bonding and other intermolecular interactions with amino acid residues present in silk fibroin and wool keratin, thereby improving dye fixation and reducing dye loss during laundering and rubbing. Mint extracts, which contain a complex mixture of flavonoids and phenolic acids, generally exhibited slightly lower fastness ratings because these compounds interact less strongly with textile fibres and are therefore more susceptible to mechanical removal. Similar observations have been reported for henna-based dyeing systems, where protein fibres consistently exhibit better wash and rubbing fastness than cellulose fibres because of stronger molecular interactions between the dye and fibre matrix.

The moderate light fastness observed in the present study is characteristic of many plant-derived colourants and may be attributed to photo-oxidative degradation of phenolic compounds upon prolonged ultraviolet exposure. Nevertheless, the fastness ratings obtained fall within acceptable limits for many apparel and decorative textile applications. Comparable results have been reported for natural dye systems in which wash and rubbing fastness are generally satisfactory, whereas light fastness remains the principal limitation because of the inherent photosensitivity of naturally occurring chromophores.

The overall fastness performance obtained in this study confirms that henna and mint extracts are capable of producing durable textile colouration, particularly on protein fibres, while simultaneously offering the environmental advantages associated with renewable natural colourants.

Antibacterial Activity

The antibacterial assessment demonstrated that both henna- and mint-dyed fabrics exhibited inhibitory activity against the Gram-negative bacterium *Escherichia coli* and the Gram-positive bacterium *Staphylococcus aureus*. However, fabrics dyed with henna consistently produced larger inhibition zones than those dyed with mint. Silk exhibited the greatest antibacterial activity, with inhibition zones of 18 ± 0.6 mm against *E. coli* and 20 ± 0.7 mm against *S. aureus*, followed by wool (17 ± 0.5 mm and 19 ± 0.6 mm) and cotton (14 ± 0.5 mm and 16 ± 0.6 mm). Similarly, mint-dyed fabrics showed measurable antibacterial activity, although the inhibition zones were comparatively smaller, ranging from 11–15 mm depending on the fibre type and test organism.

The stronger antibacterial performance of henna is primarily attributed to the high concentration of lawsone (2-hydroxy-1,4-naphthoquinone), together with tannins, flavonoids and other phenolic constituents. These bioactive compounds have been reported to inhibit microbial growth through multiple mechanisms, including disruption of bacterial cell membranes, alteration of membrane permeability, inhibition of essential metabolic enzymes, and interference with nucleic acid synthesis. The larger inhibition zones observed against *S. aureus* than *E. coli* are consistent with the greater susceptibility of Gram-positive bacteria, whose cell walls lack the outer lipopolysaccharide membrane that provides additional protection to Gram-negative organisms.

The higher antibacterial performance observed for silk and wool compared with cotton is closely associated with their greater dye uptake, as demonstrated by the higher K/S values obtained in the present study. Increased adsorption of dye molecules onto protein fibres results in a greater concentration of bioactive phytochemicals retained within the textile matrix, thereby enhancing antibacterial effectiveness. Similar relationships between dye uptake and antimicrobial performance have been reported for naturally dyed textiles, where protein fibres generally exhibit superior functional performance because of stronger interactions between phenolic compounds and amino acid residues within the fibre structure. Bhuiyan et al. demonstrated that henna-treated textiles possess significant antibacterial activity against both *S. aureus* and *E. coli*, while Shahid-ul-Islam and Sun highlighted that phenolic natural dyes can simultaneously function as colourants and antimicrobial finishing agents without requiring additional synthetic antimicrobial chemicals.

Mint-dyed fabrics also exhibited appreciable antibacterial activity, which can be attributed to the combined effects of rosmarinic acid, flavonoids, menthol and other phenolic constituents present in *Mentha spicata*. Numerous phytochemical studies have demonstrated that these compounds possess broad-spectrum antimicrobial properties through oxidative stress induction, disruption of membrane integrity and inhibition of microbial enzyme systems. Although their antibacterial effectiveness was lower than that of henna, the inhibition zones obtained indicate that mint extracts remain promising multifunctional natural dyes capable of imparting both colour and biological functionality to textile materials.

Overall, the antibacterial results demonstrate that the natural dyes investigated in this study provide dual functionality by simultaneously producing attractive colouration and reducing bacterial growth. Such multifunctional behaviour increases the potential application of naturally dyed textiles in healthcare, sportswear, children's clothing and other products where hygienic performance is desirable.

Ultraviolet Protection Properties

Natural dyeing significantly improved the ultraviolet protection performance of all textile substrates. Henna-dyed fabrics exhibited UPF values of 28, 35 and 40 for cotton, silk and wool, respectively, while mint-dyed fabrics produced corresponding UPF values of 25, 32 and 36. According to internationally accepted UPF classification systems, these values indicate good, very good and excellent ultraviolet protection, respectively. The higher UPF values observed for silk and wool correlate well with their superior colour strength, indicating that increased dye uptake contributes directly to enhance ultraviolet shielding.

The improved UV protection can be attributed to the abundance of conjugated aromatic compounds, phenolics, flavonoids and quinones present in both plant extracts. These compounds efficiently absorb ultraviolet radiation through $\pi\rightarrow\pi^*$ and $n\rightarrow\pi^*$ electronic transitions within their conjugated molecular structures, thereby reducing the transmission of harmful UV-A and UV-B radiation through the textile. In addition, tannins and other polyphenolic compounds scatter and absorb ultraviolet light, further increasing the protective efficiency of the dyed fabrics. The higher protection provided by henna compared with mint is likely related to the strong ultraviolet-absorbing characteristics of lawsone, which contains an extensively conjugated naphthoquinone structure capable of absorbing radiation over a broad wavelength range.

The positive relationship observed between colour strength and ultraviolet protection is consistent with previous investigations on naturally dyed textiles. Fabrics with higher dye uptake generally exhibit greater concentrations of UV-absorbing chromophores, resulting in improved UPF values. Shahid-ul-Islam and Sun reported that phenolic natural dyes enhance ultraviolet shielding by increasing both ultraviolet absorption and free-radical scavenging activity within textile substrates. Similarly, Yusuf et al. concluded that plant-derived colourants containing flavonoids, tannins and quinones provide significant multifunctional benefits, including antioxidant activity, antimicrobial properties and effective UV protection, making them attractive alternatives to conventional synthetic textile finishes.

The UPF values obtained in the present study compare favourably with those reported for other naturally dyed textiles and demonstrate that both henna and mint extracts are capable of producing protective fabrics without the need for additional ultraviolet-absorbing chemical finishes. This represents an important environmental advantage, as multifunctional natural dyes can simultaneously provide colour, antibacterial activity and UV protection while reducing dependence on synthetic finishing agents. Such characteristics support the growing interest in sustainable textile processing and the development of eco-friendly functional apparel.

CONCLUSION

This study demonstrates the successful extraction, optimization, and application of natural dyes from *Lawsonia inermis* (henna) and *Mentha spicata* (mint) on cotton, silk, and wool. Ultrasonic-assisted extraction, particularly via probe sonication, proved to be the most efficient method, yielding higher pigment recovery with lower energy input. The dyed materials exhibited appealing natural shades with good color strength, acceptable fastness properties, and multifunctional attributes, including antibacterial activity and UV protection. The findings reinforce the potential of henna and mint as eco-friendly alternatives to synthetic dyes, offering sustainable coloration while simultaneously enhancing the functional value of textiles. Further studies on mordanting strategies, shade variation, and large-scale process feasibility could strengthen the industrial applicability of these natural dyes.

REFERENCES

Azmir, J., Zaidul, I. S. M., Rahman, M. M., Sharif, K. M., Mohamed, A., Sahena, F., Jahurul, M. H. A., Ghafoor, K., Norulaini, N. A. N., & Omar, A. K. M. (2013). Techniques for extraction of bioactive compounds from plant materials: A review. *Journal of Food Engineering, 117*(4), 426–436. https://doi.org/10.1016/j.jfoodeng.2013.01.014

Bhuiyan, M. A. R., Ali, A., Islam, A., Hannan, M. A., Kabir, S. M. F., & Islam, M. N. (2018). Coloration of polyester fiber with natural dye henna (*Lawsonia inermis* L.) without using mordant: A new approach towards cleaner production. *Fashion and Textiles, 5*, Article 2. https://doi.org/10.1186/s40691-017-0121-1

Bhuiyan, M. A. R., Islam, A., Ali, A., & Islam, M. N. (2017). Color and chemical constitution of natural dye henna (*Lawsonia inermis* L.) and its application in the coloration of textiles. *Journal of Cleaner Production, 167*, 14–22. https://doi.org/10.1016/j.jclepro.2017.08.142

Bhuiyan, M. A. R., Islam, A., Islam, S., Hossain, A., & Nahar, K. (2017). Improving dyeability and antibacterial activity of *Lawsonia inermis* L. on jute fabrics by chitosan pretreatment.

Textiles and Clothing Sustainability, 3, Article 1. https://doi.org/10.1186/s40689-016-0023-4

Chemat, F., Rombaut, N., Sicaire, A.-G., Meullemiestre, A., Fabiano-Tixier, A.-S., & Abert-Vian, M. (2017). Ultrasound-assisted extraction of food and natural products: Mechanisms, techniques, combinations, protocols and applications. *Ultrasonics Sonochemistry*, *34*, 540–560. https://doi.org/10.1016/j.ultsonch.2016.06.035

Esclapez, M. D., García-Pérez, J. V., Mulet, A., & Cárcel, J. A. (2011). Ultrasound-assisted extraction of natural products. *Food Engineering Reviews*, *3*(2), 108–120. https://doi.org/10.1007/s12393-011-9036-6

Mason, T. J., Paniwnyk, L., & Lorimer, J. P. (1996). The uses of ultrasound in food technology. *Ultrasonics Sonochemistry*, *3*(3), S253–S260.

Moore, S. B., & Ausley, L. W. (2004). Systems thinking and green chemistry in textile processing. *Journal of Cleaner Production*, *12*(6), 585–601. https://doi.org/10.1016/S0959-6526(03)00093-0

Rather, L. J., Shabbir, M., & Bukhari, M. N. (2020). Revival of natural dyes: A sustainable approach in the textile industry. *Journal of Cleaner Production*, *272*, 123011. https://doi.org/10.1016/j.jclepro.2020.123011

Samanta, A. K., Agarwal, P., & Singhee, D. (2018). Application of natural dyes on textiles. *Colourage*, *65*(5), 29–40.

Saxena, S., & Raja, A. S. M. (2014). Natural dyes: Sources, chemistry, application and sustainability issues. In S. S. Muthu (Ed.), *Roadmap to Sustainable Textiles and Clothing* (pp. 37–80). Springer. https://doi.org/10.1007/978-981-287-065-0_2

Shahid-ul-Islam, & Sun, G. (2017). Thermodynamics, kinetics, and multifunctional finishing of textile materials with colorants extracted from natural renewable sources. *ACS Sustainable Chemistry & Engineering*, *5*(9), 7451–7466. https://doi.org/10.1021/acssuschemeng.7b01486

Silva, F., Ferreira, S., Duarte, A., Mendonça, D. I., & Domingues, F. C. (2010). Antifungal activity of *Coridothymus capitatus*, *Thymus vulgaris* and *Mentha piperita* essential oils against *Candida*, *Aspergillus* and dermatophyte species. *Journal of Medical Microbiology*, *59*(7), 781–787. https://doi.org/10.1099/jmm.0.019885-0

Sivakumar, V., Vigneswaran, C., & Kumar, P. (2009). Dyeing of textiles with natural colorants. *Indian Journal of Fibre & Textile Research*, *34*(4), 384–390.

Tausif, M., Nazir, A., & Hussain, T. (2018). Health and safety hazards of synthetic dyes in textiles. *Journal of Textile Science & Engineering*, *8*(3), 1–7. https://doi.org/10.4172/2165-8064.1000356

Yusuf, M., Shabbir, M., & Mohammad, F. (2017). Natural colorants: Historical, processing and sustainable prospects. *Natural Products and Bioprospecting*, *7*(1), 123–145. https://doi.org/10.1007/s13659-017-0119-9