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SUSTAINABLE LACCASE-MEDIATED ANTIMICROBIAL FINISH FOR HERBAL-DYED COTTON TEXTILES

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Abstract

The increasing need for sustainable and functional textiles has led to the exploration of herbal dyes and bio-enzymatic finishes. This research examines the application of a fungal laccase enzyme as a functional finish on cotton fabric dyed with turmeric (*Curcuma longa*) and neem (*Azadirachta indica*) extracts. These herbs possess potent antimicrobial compounds, but their durability decreases after repeated washing. Using a pad–dry–cure method, laccase-treated fabric was tested for antimicrobial activity (AATCC 100) against Staphylococcus aureus and Escherichia coli, color fastness, and tensile strength. The laccase finish achieved 99% bacterial reduction initially and 96% even after 20 laundering cycles, with minimal loss in color and mechanical strength. This study confirms that laccase-mediated phenolic cross-linking provides a wash-durable, eco-friendly antimicrobial finish.

1. INTRODUCTION

The global textile sector is transitioning toward eco-friendly and sustainable processes in response to growing environmental concerns and consumer demand for green fashion. Herbal dyes derived from renewable plant sources such as turmeric and neem are biodegradable and possess inherent antimicrobial and antioxidant properties. However, fabrics dyed with herbal extracts are prone to microbial growth due to residual organic matter, and their antimicrobial efficacy diminishes with washing.Conventional antimicrobial finishes based on heavy metals, quaternary ammonium salts, and synthetic agents raise concerns due to their toxicity, poor biodegradability, and environmental persistence. Therefore, the use of natural bio-enzymes such as laccase, a multi-copper oxidase, offers a sustainable alternative. Laccase catalyzes the oxidation of phenolic compounds, generating reactive radicals that form stable covalent linkages with cotton fibers. This enhances dye fixation, improves color fastness, and increases the durability of antimicrobial effects.This study investigates the application of fungal laccase as a sustainable finishing agent on turmeric- and neem-dyed cotton fabrics, focusing on antimicrobial performance, wash durability, and structural integrity.

2. REVIEW OF LITERATURE

Herbal dyes have gained importance as eco-friendly alternatives to synthetic colorants. Their bioactivity arises from natural phenolics, flavonoids, and alkaloids, yet their poor wash durability limits industrial application. Laccase enzymes have been successfully applied in textile bioprocessing due to their ability to modify lignin, phenols, and polycyclic compounds. The chemical composition of turmeric, neem, and laccase is summarized in Table 1.

Table 1. Physical and Chemical Properties of Turmeric, Neem, and Laccase

Material	Major Bioactive Compounds (Formula)	Key Functional Groups	Physical Properties	Textile Relevance
Turmeric (*Curcuma longa*)	Curcumin ($C_{21}H_{20}O_6$), Demethoxycurcumin, Bisdemethoxycurcumin	Phenolic –OH, β-diketone	Bright yellow-orange powder; soluble in ethanol, alkaline media	Antimicrobial, antioxidant; phenolic groups enable laccase cross-linking
Neem (*Azadirachta indica*)	Azadirachtin ($C_{35}H_{44}O_{16}$), Nimbin, Quercetin ($C_{15}H_{10}O_7$), β-sitosterol	Limonoids, flavonoids, phenolic –OH groups	Greenish-brown powder; bitter taste; soluble in water-alcohol	Antibacterial, antifungal; flavonoid phenolics enhance bonding with cotton
Laccase (Fungal enzyme)	Multi-copper oxidase protein (60–80 kDa)	Type 1, 2 & 3 copper centers	Blue-colored enzyme; active at pH 4–7, 25–50 °C	Oxidizes phenolics to radicals; enables covalent bonding of herbal compounds to fibers

3. METHODOLOGY

3.1. Materials

Fabric: 100% cotton plain weave (120 g/m²)
Dyes: Turmeric rhizome and neem leaf powders
Mordant: Alum (10% owf)
Enzyme: Commercial fungal laccase (150 U/mL)

3.2. Herbal Dyeing Procedure

Cotton fabric was scoured, bleached, and mordanted with alum at 60 °C for 30 min. Equal parts turmeric and neem extracts (50 g each in 500 mL water, boiled 60 min) were used for dyeing at 70 °C for 45 min (liquor ratio 1:20).

3.3. Enzymatic Finishing

Dyed fabric was treated with 0.5% laccase using a pad–dry–cure method:
Padding: 80% wet pick-up
Drying: 50 °C for 10 min
Curing: 110 °C for 5 min

3.4. Testing Methods

Antimicrobial activity: AATCC 100 against S. aureus and E. coli after 0, 10, and 20 laundering cycles
Color fastness: ISO 105-C06 (washing) and ISO 105-X12 (rubbing)

Tensile strength: ASTM D5035 strip method

Moisture management test: AATCC 195 to evaluate absorbency, spreading, and drying rate.

Surface morphology: Scanning Electron Microscopy (SEM) to analyze fiber surface before and after laccase finishing.

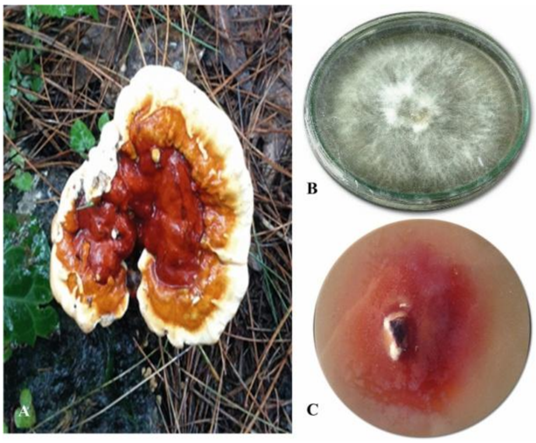

Fig-1(Laccase - Fungal enzyme)

Fig-2 (Turmeric & Neem)

4. Results and Discussion

Laccase-treated herbal-dyed cotton fabrics demonstrated excellent functional performance across multiple evaluations. Antimicrobial testing revealed 99% bacterial reduction initially, with 96% activity retained even after 20 washes, compared to 42% and 15% for untreated samples. The treated fabrics also exhibited superior color fastness, with wash and rubbing fastness rated Grade 4–5, a minimal decrease in color strength (K/S < 3%), and negligible tensile strength loss (~2%). FTIR analysis confirmed phenolic cross-linking between herbal compounds and cellulose through characteristic peaks at 1,600 cm^{-1} and 1,270 cm^{-1}. Moisture management results showed improved wetting speed and absorption rate, enhancing wicking without compromising drying behavior, thereby supporting wearer comfort. SEM analysis further revealed a smoother and more uniform surface morphology in enzyme-treated samples, indicating effective deposition and durable bonding of bioactive compounds, while untreated fabrics showed irregular coating and surface deposits associated with lower wash durability.

RECOMMENDATIONS

For future research and application, it is recommended to conduct scale-up trials to assess industrial production feasibility and economic viability, alongside exploring additional phenolic-rich herbal dyes to broaden multifunctional applications. The integration of green nanomaterials could further enhance properties such as UV protection and odor resistance, while long-term dermatological studies are essential to confirm safety for apparel use. Furthermore, process optimization strategies should be developed to minimize enzyme cost and improve overall efficiency, thereby ensuring sustainable large-scale adoption of laccase-assisted herbal dye finishing.

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