JSIANE Vol. 6 Issue 1 (2026) 115–117 eISSN No-2583-2093

Journal of Science Innovations and Nature of Earth

International, Double-Blind, Quarterly, Peer-Reviewed, Refereed, Edited and Open Access Research Journal
Journal homepage: https://jsiane.com/index.php/files

Botanical Natural Dyes as Antimicrobial Biofinishes for Medical Textiles: A Review of Sources, Mechanisms and Translational Challenges

Megha Sharma[1], Ambrish Kumar[1], Hina Farheen[1], Preetika Sharma[1], Devesh Kumar[1], Kalpana Singh[1], Saroj Singh Chahar*[1]

[1]*Department of Botany, Raja Balwant Singh College, Affiliated to Dr. Bhimrao Ambedkar University Agra- 282002, Uttar Pradesh, India*

* Corresponding author. E-mail- chaharsaroj555@gmail.com

DOI- https://doi.org/10.59436/jsiane.v6i1.25.2583-2093

ARTICLE INFO

Article history:
Received 15 December 2025
Received in revised form
17 January 2026
Accepted 1 March 2026
Available online 04 March 2026

Keywords:
Natural dyes;
antimicrobial textiles;
medical textiles;
botanical colorants;
mordanting; curcumin;
henna;
pomegranate peel

ABSTRACT

Natural dyes are being reconsidered in medical textile research not merely as colourants, but as plant-derived bioactive finishes capable of adding antibacterial, antifungal, ultraviolet-protective and skin-compatible functions to textile substrates. This review examines botanical natural dyes relevant to antimicrobial medical textiles, with emphasis on turmeric (*Curcuma longa*), henna (*Lawsonia inermis*), pomegranate peel (*Punica granatum*), madder (*Rubia tinctorum*), annatto (*Bixa orellana*), indigo (*Indigofera tinctoria*) and berberine-containing plants such as Coptis species. The paper synthesizes literature on phytochemical classes, antimicrobial mechanisms, extraction and dyeing approaches, mordanting strategies, evaluation standards and application areas including wound dressings, hospital linens, gowns, compression textiles and reusable protective materials. The review also identifies major barriers to translation: variability in botanical raw material, insufficient wash durability under clinical laundering, possible toxicity of metallic mordants, limited standardization and a shortage of clinical evidence linking treated textiles to reduced healthcare-associated infection risk. Current evidence supports natural dye systems as promising sustainable biofinishes, provided that future development prioritizes standardized extraction, bio-mordants, validated antimicrobial testing and safety assessment before medical deployment.

Introduction

The textile surface is a convenient ecological niche for microorganisms because fibres can retain moisture, nutrients and body-derived organic matter. In healthcare settings, this concern becomes more serious: gowns, bandages, bed linens, masks and patient garments may come into repeated contact with vulnerable skin, wounds or contaminated environments. Conventional antimicrobial finishes frequently depend on synthetic biocides, metallic nanoparticles or halogenated agents. These systems can be effective, but they also raise questions about durability, discharge into wastewater, skin compatibility and ecological persistence. Humanity, having first invented infection and then hospital laundry, is now rediscovering plants with all the surprise of someone finding an umbrella in a rainstorm.

Natural dyes derived from plants, microbes, minerals and animals historically served as major textile colourants before synthetic dyes became dominant. In contemporary research, their value is increasingly linked to functional chemistry rather than colour alone. Many botanical dyes contain phenolics, tannins, quinones, flavonoids, alkaloids and carotenoids. These compounds may interfere with microbial membranes, enzymes, proteins and oxidative balance. As a result, selected natural dyes can function as dual-purpose agents: they colour fibres and simultaneously impart antimicrobial or protective effects. This review is based on a synthesis of published literature and the supplied reference project on natural dyes as antimicrobial agents in medical textiles. It does not present new experimental data. Its objective is to frame a professional, review-based account of the botanical sources, dye chemistry, processing methods, antimicrobial evaluation and translational challenges that determine whether natural dye-treated textiles can realistically move from laboratory demonstrations to dependable medical textile products.

Botanical Dye Sources and Bioactive Phytochemistry- Botanical natural dyes are chemically diverse. Their antimicrobial potential depends less on the visual shade and more on the functional groups present in the dye molecule. Curcuminoids from turmeric contain phenolic hydroxyl groups and conjugated diketone structures. Lawsone from henna is a naphthoquinone. Alizarin and purpurin from madder are anthraquinones. Pomegranate peel is rich in hydrolysable tannins and ellagic acid derivatives. Berberine is a cationic isoquinoline alkaloid, while annatto seeds contain carotenoid pigments such as bixin and norbixin. Indigo, mainly indigotin, is structurally distinct and is valued more for substantivity and colour durability than for strong intrinsic antimicrobial action.

These phytochemical classes act through multiple mechanisms. Phenolic compounds can disturb cell wall and membrane integrity, alter permeability and precipitate microbial proteins. Quinones can participate in redox cycling and may interact with cellular proteins through electrophilic reactions. Tannins can bind proteins and polysaccharides, limiting microbial adhesion and enzyme function. Alkaloids such as berberine are reported to interact with bacterial membranes and nucleic acid-related processes. Because these mechanisms are broad rather than single-target, natural dye systems may reduce the likelihood of narrow resistance selection. That does not make them magic, obviously; bacteria are not politely waiting to be defeated by a pretty yellow fabric. It does mean that the chemistry deserves systematic attention.

Extraction and Dyeing Considerations- The performance of a natural dye finish begins with extraction. Conventional aqueous extraction remains common because it is simple, inexpensive and compatible with many plant materials. Plant parts are usually cleaned, dried, crushed or powdered, then extracted in water or aqueous solvent at controlled temperature and pH. Solvent extraction, acidic or alkaline extraction, microwave-assisted extraction, ultrasound-assisted extraction and pressurized liquid extraction have also been investigated to improve yield, reduce extraction time or recover less water-soluble compounds.

However, higher extraction yield is not automatically equivalent to superior antimicrobial performance. A crude plant extract may contain colouring molecules, inactive carbohydrates, proteins, minerals and degradation products. The concentration of active compounds varies with plant cultivar, maturity, season, geography and storage. For a medical textile application, therefore, extraction must be paired with quality control. UV-Visible spectrophotometry, thin-layer chromatography or high-performance liquid chromatography can help monitor batch consistency, although such analytical controls are not yet routine in small-scale natural dyeing.

Dyeing behaviour also varies by fibre type. Protein fibres such as wool and silk contain amino and carboxyl groups that can interact with many natural dyes. Cellulosic fibres such as cotton, viscose and linen are harder to dye durably because cellulose is relatively anionic and lacks strong binding sites for many botanical colourants. Synthetic fibres such as polyamide may accept selected dyes, but often require surface activation or optimized dyeing conditions. Medical textiles often use cotton, viscose, polyester, polypropylene, nylon or blended substrates, so dye-fibre compatibility is not a minor technical footnote; it is the gatekeeper of whether the antimicrobial finish survives use and laundering.

Mordanting: Performance Enhancement and Safety Trade-off- Mordanting is the application of a chemical bridge between dye and fibre. In natural dyeing, mordants improve dye uptake, colour strength and fastness by forming complexes with dye molecules and textile functional groups. Pre-mordanting treats the fabric before dyeing, meta-mordanting combines mordant and dye in a single bath and post-mordanting applies the mordant after dyeing. Pre-mordanting frequently gives stronger and more even shades, while one-bath methods can reduce water, time and energy consumption. Post-mordanting can deliberately shift shade, especially with iron salts.

The medical context makes mordant choice especially important. Traditional metallic mordants such as alum, iron salts, copper salts, tin salts and chromium compounds can improve colour fastness, but their toxicological and environmental profiles differ sharply. Chromium and tin mordants are unsuitable for a safety-first medical textile philosophy. Alum is often treated as comparatively safer, but even relatively benign metal mordants require residue control and effluent management.

Bio-mordants are therefore central to current research. Chitosan, tannin-rich extracts, myrobalan, pomegranate rind, gallnut and henna-derived systems can enhance dye-fibre binding while contributing their own antimicrobial activity. Chitosan is especially promising because it is cationic, film-forming and antimicrobial, allowing it to improve the adhesion of anionic or weakly substantive dyes to cotton and other cellulosic materials. The best future systems are likely to be dye-biomordant combinations in which colour, microbial control and biocompatibility support each other rather than fighting like committee members over a grant budget.

Major Botanical Dyes for Antimicrobial Medical Textiles- Turmeric (*Curcuma longa*) is one of the most widely studied botanical dyes for antimicrobial textile finishing. Curcumin and related curcuminoids provide yellow coloration and reported activity against selected Gram-positive and Gram-negative bacteria as well as fungi. On cotton, turmeric dyeing often benefits from chitosan or other pretreatments that improve uptake and wash durability. Curcumin also attracts interest for wound-contact textiles because the biomedical literature associates it with anti-inflammatory and wound-healing pathways, although textile claims must still be validated through appropriate safety and efficacy testing.

Henna (*Lawsonia inermis*) contains lawsone, a naphthoquinone dye with strong affinity for keratinous and protein-rich substrates. In textile research, henna has been explored both as a colourant and as a bioactive finish. The quinone structure of lawsone provides a plausible antimicrobial basis, and henna-dyed wool and cotton systems have been examined for bacterial reduction. Pomegranate peel (*Punica granatum*) is another strong candidate because it is an agricultural by-product rich in tannins. Its use supports waste valorisation while providing brown-yellow shades and antimicrobial activity linked to tannin-protein interactions.

Madder (*Rubia tinctorum*) provides anthraquinone dyes such as alizarin and purpurin. These compounds can complex with mordants and produce red to orange shades. Their antimicrobial value appears to depend strongly on mordant and substrate. Berberine-containing botanical sources offer a different approach: berberine is cationic, intensely coloured and associated with antimicrobial activity. It can be applied to wool, cotton, nylon or modified surfaces, especially where the fibre surface can attract or retain the alkaloid. Annatto (*Bixa orellana*) contributes carotenoid pigments and has been discussed in relation to UV protection and comfort-related functions. Indigo (*Indigofera tinctoria*) is important as a substantive vat dye; its antimicrobial action may be moderate, but it can be combined with stronger bioactive finishes in layered or blended systems.

Evaluation of Antimicrobial Activity- Antimicrobial claims in medical textiles require standardized evaluation. Qualitative agar diffusion methods show whether a treated fabric produces a zone of inhibition around the sample. These methods are visually intuitive but can favour agents that diffuse easily into agar and may underestimate non-leaching surface-bound finishes. Quantitative contact methods measure reduction in microbial count after defined contact time and are more appropriate for durable antimicrobial textiles. Commonly cited methods include AATCC 100 for antibacterial finishes on textile materials, AATCC 147 for parallel streak screening, ISO 20743 for antibacterial activity of textile products, JIS L 1902 for textile products and ASTM E2149 for dynamic contact testing of immobilized antimicrobial agents.

For medical relevance, testing should include clinically meaningful organisms such as Staphylococcus aureus, Escherichia coli, Klebsiella pneumoniae and Candida albicans where appropriate. Yet in vitro bacterial reduction alone is insufficient. A natural dye-treated bandage or gown must also meet requirements for cytotoxicity, irritation, sensitization, air permeability, absorbency, mechanical integrity, sterilization compatibility and laundering durability. In simpler words: killing bacteria in a petri dish is not the same as behaving safely on injured human skin. Science has standards because optimism, left unsupervised, tends to file false paperwork.

Medical Textile Applications- Wound dressings, gauze and absorbent pads are among the most relevant applications because they directly contact damaged tissue. A plant-derived antimicrobial finish may reduce microbial colonization, but it must not impair healing, release unsafe residues or produce excessive staining. Curcumin-chitosan and pomegranate-tannin systems are particularly relevant here because they combine antimicrobial potential with film-forming or protein-binding behaviour.

Hospital bed linen and patient garments represent another application area. They are repeatedly exposed to sweat, skin flora and laundering. Natural dye finishes for these products would need high wash fastness and resistance to thermal disinfection conditions. Surgical gowns, isolation gowns and reusable protective textiles require antimicrobial performance without compromising barrier properties, breathability or user comfort. Compression bandages and support garments are also promising because they are worn for long periods against warm skin, where microbial growth and odour may become concerns.

A reasonable translational pathway would not begin with the most critical implant-adjacent materials. It would begin with lower-risk reusable textiles, validate washing durability and skin safety, then progress toward wound-contact products only after toxicological and clinical evidence is stronger.

Challenges and Research Gaps- The first major challenge is reproducibility. Botanical extracts are inherently variable. Without standardized raw material selection, extraction protocols and chemical profiling, two batches of the same named dye may differ substantially in colour strength and antimicrobial effect. The second challenge is durability. Medical textiles are washed, sterilized or disinfected under harsh conditions. Many natural dye-fibre interactions are based on hydrogen bonding, ionic attraction or weak complexation, so the active compounds may leach during laundering.

The third challenge is safety. A finish described as natural is not automatically safe. Some plant extracts can irritate skin, interact with proteins or contain contaminants. Some mordants pose more risk than the dye itself. Medical textile development therefore requires cytotoxicity, irritation and sensitization testing, not decorative confidence. The fourth challenge is regulatory clarity. A textile claiming antimicrobial medical performance may fall under stricter product expectations than a coloured fabric. Evidence must demonstrate not only laboratory antimicrobial reduction but also material stability and user safety.

Important research gaps include long-term wash durability under hospital laundering, comparison of bio-mordants under identical test conditions, standardized reporting of extract concentration and active marker compounds, life-cycle assessment of dye extraction and effluent, and clinical studies assessing whether such textiles actually reduce contamination or infection risk in real healthcare environments.

Future Directions- Future work should move from isolated dye demonstrations to integrated biofinish systems. Chitosan-natural dye complexes, tannin-assisted mordanting, plasma pretreatment, enzymatic fibre modification and microencapsulation can improve retention and controlled release. Microencapsulation is particularly attractive because it may protect bioactive compounds during storage and washing while enabling gradual release during use. Nanotechnology-assisted systems, such as natural dye-silver nanocomposites, can increase antimicrobial potency, but they must be judged carefully because nanoparticle release may create environmental and safety concerns.

Fermentation-derived pigments also deserve attention. Microbial pigments can be produced in bioreactors with more controlled composition than many plant extracts, potentially reducing seasonal variability. Nevertheless, botanical dyes remain attractive in regions with abundant agricultural residues such as pomegranate peel, onion skin, walnut shell, tea waste and turmeric processing waste. The most sustainable approach will likely combine local plant resources, low-toxicity extraction, bio-mordants, validated standards and realistic product selection.

Conclusion

Botanical natural dyes offer a scientifically credible and environmentally aligned route for developing antimicrobial medical textiles. Their value lies in the convergence of colouration and bioactivity: curcuminoids, lawsone, tannins, anthraquinones, alkaloids and carotenoids can provide textile coloration while contributing antimicrobial or protective functions. The strongest candidates include turmeric, henna, pomegranate peel, madder, berberine-containing plants and selected tannin-rich residues.

For national-level research and applied textile development, the priority should not be romantic enthusiasm for anything labelled natural. The priority should be disciplined standardization. Natural dye medical textiles must be reproducible, washable, non-toxic, comfortable and supported by recognized antimicrobial test methods. Bio-mordants such as chitosan and tannin-rich plant extracts offer a promising way to reduce dependence on hazardous metal salts. If extraction protocols, dye-fibre bonding, antimicrobial testing and safety evaluation are strengthened, botanical dye-based finishes can become meaningful contributors to sustainable healthcare textiles rather than remaining attractive laboratory curiosities.

Selected Botanical Dye Systems and Reported Textile Relevance

Dye source	Main bioactive class	Likely textile role	Key limitation
Turmeric (*Curcuma longa*)	Curcuminoids	Yellow antimicrobial finish; wound-textile interest	Weak substantivity on untreated cotton
Henna (*Lawsonia inermis*)	Naphthoquinone (lawsone)	Colourant and bioactive finish, especially on protein fibres	Shade control and batch variation
Pomegranate peel (*Punica granatum*)	Hydrolysable tannins	Waste-derived dye and antimicrobial tannin finish	Can darken handle/shade; needs standardization
Madder (*Rubia tinctorum*)	Anthraquinones	Red-orange shades with mordant-assisted fixation	Performance depends strongly on mordant
Berberine-rich plants	Isoquinoline alkaloid	Cationic antimicrobial colourant	Retention and safety must be validated
Indigo (*Indigofera tinctoria*)	Indigotin vat dye	Durable colour; combinable with bioactive finishes	Moderate intrinsic antimicrobial effect

References

AATCC. (2019). AATCC TM100: Test method for antibacterial finishes on textile materials. American Association of Textile Chemists and Colorists.

ASTM International. (2019). ASTM E2149: Standard test method for determining the antimicrobial activity of antimicrobial agents under dynamic contact conditions

Chungkrang, L., Bhuyan, S., & Phukan, A. R. (2021). Natural dyes: Extraction and applications. International Journal of Current Microbiology and Applied Sciences, 10(1), 1669-1677.

Do, K. L., et al. (2024). Bioactive silk revolution: Harnessing curcuminoid dye and chitosan biomordant for functional silk substrates. Polymers, 17(1), 82.

Hossain, M. M., et al. (2024). Advancements of eco-friendly natural antimicrobial agents for textile applications. SPE Polymers.

International Organization for Standardization. (2021). ISO 20743: Textiles: Determination of antibacterial activity of textile products.

Mansour, R. (2018). Natural dyes and pigments: Extraction and applications. In Handbook of Renewable Materials for Coloration and Finishing (pp. 75-102). Scrivener Publishing.

Negi, A., et al. (2025). Natural dyes and pigments: Sustainable applications and perspectives. Colorants, 6(3), 23.

Rahman, M. M., et al. (2023). Sustainable one-bath natural dyeing of cotton fabric using turmeric root extract and chitosan biomordant. Journal of Cleaner Production, 383, 135436.

Ragab, M. M., Hassabo, A. G., & Othman, H. (2022). An overview of natural dyes extraction techniques for valuable utilization on textile fabrics. Journal of Textiles, Coloration and Polymer Science, 19(2), 137-153.

Samanta, A. K., & Konar, A. (2011). Dyeing of textiles with natural dyes. In E. Perrin Akcakoca Kumbasar (Ed.), Natural Dyes. InTech

Saxena, S., & Raja, A. S. M. (2014). Natural dyes: Sources, chemistry, application and sustainability issues. In Roadmap to Sustainable Textiles and Clothing (pp. 37-80). Springer.

Veysian, M., & Shams-Nateri, A. (2023). The effect of metal mordant and biomordant on color strength of dyed woolen yarn with natural dyes. Fibers and Polymers, 24, 4337-4355.

Senthilkumar, R. P., Bhuvaneshwari, V., Sathiyavimal, S., Amsaveni, R., Kalaiselvi, M., & Malayaman, V. (2015). Natural colours from dyeing plants for textiles. International Journal of Biosciences and Nanosciences, 2(7), 160-174.