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Sustainable Natural Herbs for Antibacterial Activity on Cotton Fabric Using Bio-Mordants and Microencapsulation Techniques: A Comprehensive Review

K. P. Kalaivaanee[1], Dr S. Lakshmimanokari[2]

[1]Research Scholar, Department of Textile and Apparel Design, Periyar University, Salem
Email: *kalaivaanee[at]vcw.ac.in*

[2]Professor and Head, Department of Textile and Apparel Design, Periyar University, Salem
Email: *lakshmimanokari[at]yahoo.co.in*

Abstract: ***As global environmental concerns rise and demand for hygienic textiles grows, academic and industrial sectors urgently need sustainable alternatives to the traditional antimicrobial finishing agents used for cotton fabrics. Cotton fabrics are comfortable to wear and widely applied, but their hydrophilic nature makes them susceptible to microbial contamination. Traditional finishing agents carry key flaws: they are toxic, persist in the natural environment, and pollute wastewater, while natural herbal agents have prominent advantages. This review sorts out the latest progress in this field, with a focused analysis of bio-mordants and microencapsulation technology. This study focuses on medicinal herbs applicable to textile development, with its core research subjects being neem, turmeric, tulsi, aloe vera, and lemongrass. The research covers a range of topics including examination of fundamental properties such as antibacterial mechanisms, optimization technologies such as biological mordants, as well as discussions of performance and sustainability. The composite herbal textile finishing solution developed in this study, despite still facing challenges for industrial implementation, combines excellent antimicrobial durability and environmental friendliness, and is well-suited for the development of sustainable antimicrobial textiles.***

Keywords: antibacterial cotton, bio-mordants, herbal finishing, medicinal plants, microencapsulation, sustainable textiles

1. Introduction

The textile industry has long faced the dual pressure of reducing the environmental impact of the entire sector and maintaining the functional performance of its products. Within the textile post-finishing stage, antimicrobial finishing has grown increasingly critical, driven by rising demand from the medical, apparel, and protective sectors. Haji and Naebe (2020) note that the synthetic chemicals and metal compounds that conventional antimicrobial finishing relies on carry hidden hazards of pollution, toxicity, and ecological residue accumulation. Therefore, in the global field of sustainable textile research, attention to natural alternative solutions is continuously rising. According to a 2021 study by Hasan et al., herbal materials that naturally carry antimicrobial compounds and can be integrated into eco-friendly textile finishing systems are the most promising core approach for this research direction.

Cotton is the most widely used natural textile fiber globally. It has gained widespread popularity for its soft, breathable, and moisture-absorbent properties, yet it is susceptible to microbial growth in high-humidity environments. A 2021 study by Joseph et al. confirmed that this trait leads to numerous practical problems.

In recent years, multiple studies have confirmed that medicinal herbs can exert effective antibacterial effects when applied to cotton fabrics. However, this application faces core bottlenecks: insufficient durability and poor fiber affinity. The academic community has widely adopted the solution of combining biological mordants and embedding technology (Das & Samanta, 2021; Kumar et al., 2022).

This review will critically examine sustainable herbal raw materials for antibacterial cotton finishing, and assess the contributions of bio-mordants and microencapsulation technology to eco-friendly textile systems

2. Sustainable Natural Herbs for Antibacterial Cotton Finishing

Medicinal plants contain antibacterial active ingredients such as flavonoids, tannins, terpenes, alkaloids, and essential oils. As global attention to renewable functional materials keeps increasing, the scale of their application in cotton finishing has expanded significantly in recent years.

2.1 Neem (Azadirachta indica)

Neem, a natural raw material, has earned widespread recognition in academia for its antibacterial and medicinal properties. The azadirachtin and nimbidin contained in neem can interfere with bacterial growth processes and the stability of bacterial cell membranes. A 2020 textile-focused study by Patel et al. confirmed that applying neem to cotton fabrics achieves excellent antibacterial effects. However, untreated neem application systems suffer from reduced durability, as their active compounds gradually leach out during the washing process.

2.2 Turmeric (Curcuma longa)

Curcumin, a polyphenolic compound found in turmeric, has antibacterial and antioxidant activities, and textile finishing agents produced from curcumin meet all necessary performance requirements (Mehta et al., 2021). Natural curcumin is prone to degradation, so controlled-release technology must be adopted to effectively extend the duration of its functionality.

2.3 Tulsi (Ocimum sanctum)

Holy basil contains eugenol and related phytochemicals, and has broad-spectrum antibacterial properties. Cotton fabrics treated with its extracts exhibit bacteria-inhibiting effects and are compatible with eco-friendly fabric finishing systems, as cited in a 2021 study by Arora et al.

2.4 Aloe Vera (Aloe barbadensis)

According to a 2021 study by Ouadil et al., aloe vera can endow textiles with antibacterial properties and excellent comfort, making it suitable for health and medical textile products.

2.5 Lemongrass (Cymbopogon citratus)

Lemongrass essential oil (essential oils) is rich in citral (citral) and can disrupt bacterial cell membranes (bacterial cell membranes). In 2022, Gogoi et al. confirmed that encapsulation (encapsulation) can enhance antibacterial persistence (antibacterial persistence) and reduce volatility (volatility).

In conclusion, all the aforementioned types of herbaceous plants can underpin sustainable textile antimicrobial finishing by leveraging the technology for compounding and toughening plant-derived compounds.

3. Mechanisms of Herbal Antibacterial Activity

The performance of herbal antimicrobial materials for textiles is determined by the interaction of three core categories of factors.According to the research by Ali et al. (2022), plant-derived compounds such as essential oils and hydrophobic bioactive molecules can alter the permeability of bacterial cell membranes, penetrate these membranes to trigger cellular leakage, and produce bacteriostatic effects. Other phytochemicals interfere with the enzymatic metabolism of bacteria, inhibiting their growth and reproduction. Herbal antimicrobial materials, a class of natural compounds, possess strong antimicrobial potential. However, when applied directly, they generally suffer from the core problem of insufficient durability, caused by their extremely weak interaction force with cotton cellulose.

The fiber-complex interaction can be optimized by employing two types of systems: immobilization systems and controlled-release systems.

4. Role of Bio-Mordants in Cotton Functionalization

Currently, biological mordants are growing increasingly important in the field of sustainable textile finishing, as they can effectively enhance the adhesion between herbal compounds and cotton fibers. In the textile field, the metal salts that traditional mordants rely on cause wastewater pollution. By contrast, plant-derived biological mordants are environmentally friendly and deliver improved performance, an advantage corroborated by a 2023 study by Singh et al. Polyphenolic compounds can effectively promote the formation of hydrogen bonds and improve the adsorption effect between herbal compounds and cellulose. According to a 2022 study by Rani et al., optimizing immobilization can enhance antibacterial durability and reduce washing loss. Green chemical products feature low environmental load, low toxicity, rapid degradation, and strong compatibility. The integration of herbal compounds and bio-mordants is a critical core underpinning for the green transition of the textile finishing industry.

Table 1: Sustainable Herbs and Their Antibacterial Functions

Herb	Active Compound	Major Antibacterial Action
Neem	Azadirachtin	Membrane disruption
Turmeric	Curcumin	Enzyme inhibition
Tulsi	Eugenol	Membrane alteration
Aloe vera	Aloin	Metabolic suppression
Lemongrass	Citral	Cellular leakage

5. Microencapsulation Techniques

Microencapsulation technology is increasingly being applied to enhance the durability and functional efficiency of herbal antibacterial finishing agents. In the textile field, natural bioactive compounds are prone to oxidation, volatilization, and elution, and encapsulation technology can protect their efficacy while enabling sustained release.

5.1 Spray drying

Spray drying can convert herbal solutions into stable microcapsules, and is suitable for mass production. The improvements in its storage performance and antibacterial properties are supported by the 2022 study by Kumar et al.

5.2 Coacervation

Coacervation technology can encapsulate active compounds to form a polymeric shell that enables controlled release, and it is particularly suitable for essential oils and volatile herbal compounds (Jain & Vigneshwaran, 2022).

Natural herbs provide a promising approach for the sustainable antibacterial finishing of cotton textiles. Five medicinal plants including neem and turmeric can exert antibacterial effects through phytochemical mechanisms.

However, the direct application of herbal compounds to cotton fabrics faces two core bottlenecks: insufficient stability and substandard environmental performance. The two technologies of biological mordants and microencapsulation can resolve these respective application drawbacks.In summary, the various R&D technologies for antimicrobial textiles discussed above can produce compliant products that combine environmental responsibility, upgraded functionality, and practical potential. These technologies are expected to, by achieving breakthroughs in fixation technologies, biodegradable encapsulation materials, and sustainable manufacturing practices, advance the industrial implementation of herbal antimicrobial textiles and expand their application boundaries.

5.3 Ionic Gelation

The ionogel method with specified processing conditions can be used to prepare high-performance chitosan and alginate systems, and this capability has been verified in existing literature.

6. Role of Bio-Mordants in Cotton Functionalization

Biopolymer-assisted systems can improve the surface adhesion between capsules and textiles, and the application prospects of chitosan-based technologies featuring antimicrobial encapsulation properties are supported by Wang et al.'s 2021 study. The selection of encapsulation options for herbal medicines must balance cost, medicinal properties, and drug-release requirements.

The following table lists the names, core advantages and application limitations of four microcapsule processing technologies.

Table 2: Comparison of Microencapsulation Techniques

Technique	Advantage	Limitation
Spray Drying	Scalable	Thermal sensitivity
Coacervation	Controlled release	Process complexity
Ionic Gelation	Mild processing	Moderate durability
Polymer Encapsulation	Better fixation	Cost

7. Functional Performance and Sustainability

Antibacterial cotton must maintain stable antibacterial performance while not compromising its original textile quality. According to the 2021 study by Hasan et al., this herbal finishing system exhibits bacteriostatic effects against the two tested microorganisms.

Functional textiles often suffer from insufficient wash resistance, which stems from their active ingredients detaching during laundering. This problem can be improved by encapsulation and mordant fixation technologies, a conclusion confirmed by Verma et al.'s 2023 study.

This paper proposes that functional modification of textiles must retain their inherent comfort properties, as excessive surface deposition will undermine air permeability and softness. A 2021 study by Ouadil et al. confirms that relevant systems can maintain wear comfort.

The textile characteristics collated in this study align with the principles of circular textiles and green chemistry (Karthik et al., 2022). Although significant progress has been made in this field, limitations still remain. The volatility of the natural components in herbal medicines hinders the stable replication of their textile performance, and three categories of shortcomings in supporting capacity must be overcome to enable large-scale industrial application.

The five core research directions in the advanced textiles field are: multifunctional textile systems, advanced biodegradable encapsulation, long-term durability assessment, industrialization verification, and full lifecycle sustainability assessment. The integration of natural antimicrobial agents and intelligent textile technology can expand the future application boundaries of both fields.

8. Future Directions

Although significant progress has been achieved, several limitations remain. Variability in herbal composition creates challenges in achieving reproducible textile performance. Industrial adoption also requires scalable extraction methods, cost-effective encapsulation technologies, and standardized evaluation protocols.

Future studies should prioritize:
- Multifunctional textile
- Systems Advanced
- Biodegradable encapsulation Long-term
- Durability evaluation
- Industrial-scale validation Life-cycle sustainability assessment
- Integration of natural antibacterial agents with smart textile technologies may further expand future applications.

9. Conclusion

Natural herbs provide a promising pathway for sustainable antibacterial finishing of cotton textiles. Medicinal plants, including neem, turmeric, tulsi, aloe vera, and lemongrass, demonstrate effective antibacterial activity through diverse phytochemical mechanisms. However, durability remains a major limitation when herbal compounds are directly applied to cotton. Bio-mordants improve fixation and reduce environmental burden, while microencapsulation enhances protection and controlled release of active compounds. Together, these approaches support the development of environmentally responsible antibacterial textiles with improved functionality and practical potential. Continued advances in fixation technologies, biodegradable encapsulation materials, and sustainable manufacturing practices are expected to strengthen industrial implementation and expand the role of herbal antibacterial textiles in future textile systems.

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