

Advancements in Medical Textiles and the Integration of Herbal Extracts

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ABSTRACT

Medical textiles, also known as healthcare textiles, are a rapidly advancing segment of technical textiles with applications in wound care, infection control, tissue engineering, and medical devices. Current research focuses on developing multifunctional textiles that enhance safety, therapeutic performance, and environmental sustainability while minimizing cross-infection risks in healthcare settings. In this context, the incorporation of herbal bioactives has gained attention due to their inherent antimicrobial, anti-inflammatory, antioxidant, and wound-healing properties. Extracts derived from medicinal plants such as *Azadirachta indica* (neem), *Aloe vera*, *Curcuma longa* (turmeric), and *Ocimum sanctum* (tulsi) offer natural, biocompatible, and biodegradable alternatives to conventional synthetic finishes used in medical textiles. The intention of this review article is to critically examine recent developments in medical textiles, with a specific emphasis on the medical classification, requirements, and performance of healthcare textiles. It covers various techniques involved in the finishing of fabrics with herbal extracts, such as coating, grafting, microencapsulation, sol-gel processing, and nanotechnology-assisted delivery systems. This review presents future opportunities for herbal-functionalized medical textiles as sustainable and patient-centric solutions for next-generation healthcare applications.

Keywords: Antimicrobial material, Functional finishing, medical textiles, Herbal extracts, Sustainable healthcare

INTRODUCTION

Medical textiles constitute a specialized class of functional materials engineered for applications such as wound dressings, surgical apparel, sutures, implants, hygiene products, and tissue scaffolds. These materials are required to satisfy stringent criteria related to biocompatibility, sterility, mechanical integrity, comfort, and durability under clinical use (El-Ghazali & Sofia). The sector has expanded steadily, driven by increased demand for hygiene products, rising surgical interventions, and heightened infection-control requirements, with nonwoven textiles dominating due to their cost efficiency, disposability, and superior barrier performance (Precedence Research, 2025).

The global medical textiles market is growing at a robust rate, valued at USD 26.17 billion in 2025 and expected to reach USD 38.71 billion by 2034, with a compound annual growth rate of 4.45%. The major reason behind this major surge in the medical textiles market is the growing need for hygiene products, increased surgical procedures, awareness regarding infection control in medical institutions, along with the global ageing population demanding medical treatments (Precedence Research, 2025)..

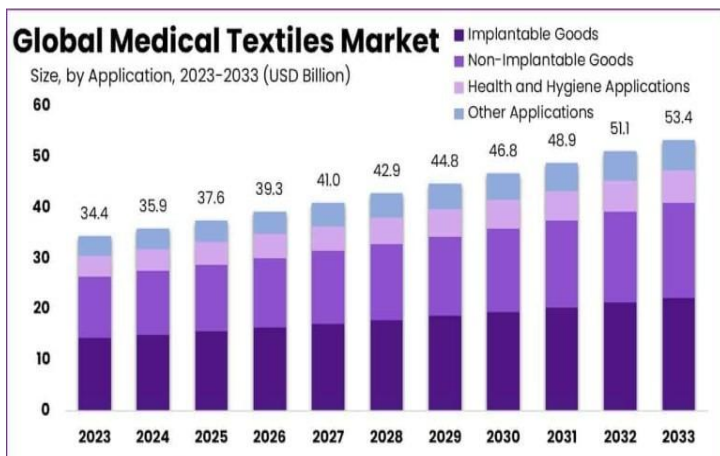


Figure 1 - Global Medical Textile Market

Functional performance in medical textiles has traditionally been achieved using synthetic antimicrobial agents, chemical treatments, and polymeric coatings (Simoncic & Tomsic, 2010). However, concerns regarding cytotoxicity, skin irritation, environmental persistence, and the potential contribution to antimicrobial resistance have stimulated interest in alternative material strategies (Walsh et al., 2023). In this context, plant-derived bioactive compounds, including polyphenols, terpenoids, and polysaccharides from medicinal plants such as *Azadirachta indica*, *Aloe vera*, *Curcuma longa*, and *Ocimum sanctum*, have emerged as candidates for imparting bioactivity to textile substrates (Ahmed et al., 2025; Anand et al., 2022; Popescu & Ungureanu, 2023).

Recent advances in textile processing—such as microencapsulation, electrospinning, sol–gel coating, and surface grafting—have enabled improved incorporation, stabilization, and controlled release of these bioactives (Sharma et al., 2021; Salehi et al., 2024). From a materials perspective, the performance of herbal-functionalized medical textiles is governed primarily by incorporation strategy, interfacial stability, and durability rather than intrinsic bioactivity alone. This review critically evaluates these material-level considerations, highlighting current limitations and research directions for the development of reliable and sustainable bioactive medical textile

Classification of Medical Textiles



Figure 2 – Examples of Medical Textiles

Medical textiles encompass a group of technical textiles with sophisticated features that cater to the demands of the healthcare and hygiene sectors. Medical textiles have been designed to perform strictly in terms of their compatibility, sterility, strength, comfort, and efficacy as per the demands of their end-use product and

interaction with the human body. Medical textiles can be categorized into non-implantable, implantable, extracorporeal, and healthcare & hygiene textiles, depending on their end-use product and interaction with the human body (Anandjiwala, 2006).

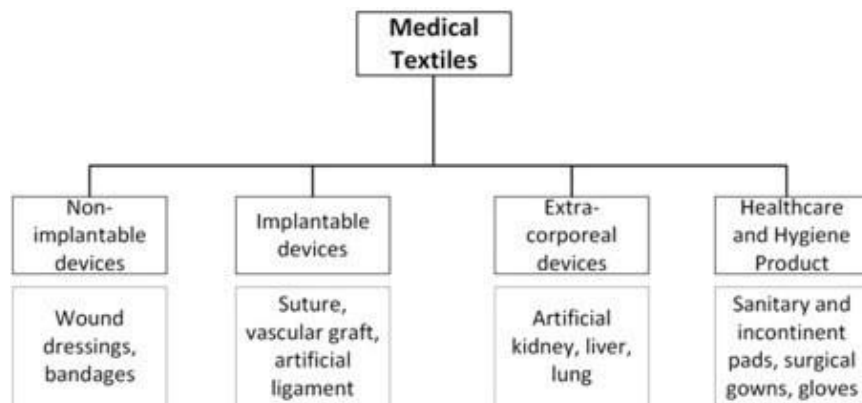


Figure 3- Types of Medical Textile Non-implantable devices

Non-implantable medical textiles are designed for external use and may come into temporary contact with intact or wounded skin. Typical examples include wound dressings, bandages, medical gauze, compression textiles, sanitary napkins, and baby diapers. These materials must exhibit high absorbency, breathability, antimicrobial performance, and skin compatibility, particularly in wound-contact applications (Saha et al., 2022).

The incorporation of herbal bioactive into non-implantable medical textiles has been investigated as a strategy to enhance functional performance while maintaining biocompatibility. Plant-derived compounds can impart antimicrobial, anti-inflammatory, antioxidant, and wound-healing effects, thereby supporting localized therapeutic action at the skin-textile interface. Commonly studied botanicals include *Azadirachta indica* (neem), *Aloe vera*, *Curcuma longa* (turmeric), *Matricaria chamomilla* (chamomile), and *Camellia sinensis* (green tea), selected based on application-specific functional requirements.

From an application perspective, non-implantable medical textiles may be broadly categorized as wound dressings, surgical gowns and masks, and protective textiles such as gloves. Wound dressings typically employ hydrogel coatings, fibre embedding, or encapsulation techniques to achieve sustained release of herbal bioactives, with aloe vera and turmeric frequently used to support wound healing and antimicrobial protection (Chelu et al., 2023; Salehi et al., 2024). Surgical gowns and face masks require surface antimicrobial functionality without compromising breathability or mechanical integrity; accordingly, chemical grafting or surface coating with neem, turmeric, or green tea extracts has been explored (Wylie & Merrell, 2022; Schneider et al., 2023). Protective textiles such as gloves generally incorporate herbal agents through grafting or encapsulation to maintain flexibility and user comfort.

The successful integration of herbal bioactives into non-implantable medical textiles depends on several material-level considerations. These include extraction efficiency and stability of bioactive compounds, selection of appropriate incorporation techniques, controlled release behavior, safety and biocompatibility, antimicrobial effectiveness, preservation of mechanical and physical properties, and compliance with applicable medical device regulations. Encapsulation approaches, particularly micro- and nano-encapsulation, are widely employed to protect labile compounds, regulate release kinetics, and improve durability during processing and use (Sharma et al., 2021).

A range of herbal extracts has been studied in this context. *Aloe vera* gel extracts provide moisture retention and soothing effects in wound dressings (Chelu et al., 2023). Neem leaf extracts and oils exhibit broad-spectrum antimicrobial activity and are commonly applied as coatings on bandages and dressings (Wylie & Merrell, 2022). Curcumin from *Curcuma longa*, incorporated either directly or via nano-encapsulation, offers antioxidant and anti-inflammatory activity with demonstrated wound-healing potential (Salehi et al., 2024). Chamomile extracts are used for their mild antimicrobial and soothing properties in sensitive skin applications (El Mihyaoui et al., 2022), while green tea polyphenols contribute antioxidant and antimicrobial effects in

hygiene textiles (Schneider et al., 2023). Other botanicals, including pomegranate peel extracts, *Moringa oleifera*, and tea tree oil, have also been explored for antimicrobial functionality using coating, encapsulation, and composite approaches (Paczkowska-Walendowska et al., 2024; Gheorghita et al., 2023; Zhou et al., 2024).



Figure 4 – Antibacterial nonwoven materials in medicine and healthcare

Critical Considerations in the Development of Herbal-Based Medical Textiles

When integrating herbal bioactives into non-implantable medical textiles, several key material and performance considerations must be addressed. Bioactive extraction methods should preserve compound efficacy and ensure stability during textile processing and storage. The selected incorporation approach must enable controlled and sustained release to maintain therapeutic functionality over the intended use period. Safety and biocompatibility are critical, requiring that both the bioactives and their delivery do not induce toxicity or adverse skin reactions. Herbal treatments should provide sufficient antimicrobial effectiveness against relevant pathogens without compromising essential textile properties such as strength, flexibility, and breathability. Finally, all herbal functionalized non-implantable medical textiles must comply with applicable medical device regulations and performance standards.

IMPLANTABLE MEDICAL TEXTILES

Implantable medical textiles constitute a specialized class of biomedical materials designed for temporary or permanent implantation, including vascular grafts, hernia meshes, sutures, and tissue-engineering scaffolds fabricated from biodegradable or bioresorbable polymers (Liu et al., 2023). Owing to continuous exposure to physiological environments, these materials must satisfy stringent requirements related to sterility, cytotoxicity, hemocompatibility, inflammatory response, and long-term stability (Zhou et al., 2024).

Growing interest has emerged in the use of herbal and plant-derived bioactive compounds in implantable textile systems to impart multifunctionality. Phytochemicals such as curcumin, polyphenols, and natural resins exhibit antibacterial, antioxidant, and anti-inflammatory activity and have been investigated for reducing implant-associated infections and modulating host responses (Zhou et al., 2024). Compared with conventional antibiotics, these bioactives demonstrate broad-spectrum antimicrobial effects and are suggested to present a lower propensity for resistance development, although supporting clinical evidence remains limited (Sun et al., 2025).

Among these compounds, curcumin from *Curcuma longa* has been most extensively studied. Curcumin-functionalized implants and textile-based scaffolds have demonstrated enhanced antibacterial performance with acceptable cytocompatibility, as well as sustained antimicrobial activity while supporting cell viability in tissue engineering models (Wang et al., 2024; Sun et al., 2025). Propolis-based systems have similarly shown improved cell attachment, osteogenic differentiation, and bacterial inhibition in implant-related studies, highlighting their potential for orthopedic and dental applications (Askari et al., 2024). Other herbal bioactives, including green tea polyphenols (EGCG) and *Centella asiatica* extracts, have also been explored for localized and controlled bioactivity at the implant–tissue interface (Xu et al., 2021; Chen et al., 2024).

Despite promising laboratory-scale results, the clinical translation of herbal-functionalized implantable medical textiles remains challenging. Stringent regulatory requirements, long-term biocompatibility assessment, sterilization stability, and reproducibility continue to limit advancement beyond proof-of-concept studies (Zhou et al., 2024). Nevertheless, existing evidence suggests that, when carefully integrated into implantable textile systems, herbal bioactives may contribute to next-generation implants with improved resistance to infection and support for tissue regeneration.

Silk sutures functionalized with herbal coatings

Silk is widely used as a natural biomaterial for surgical sutures due to its high tensile strength, elasticity, knot security, and favorable handling characteristics. Silk fibroin also supports cell adhesion and proliferation, making silk sutures suitable for wound closure applications requiring tissue integration (Altman et al., 2003). However, unmodified silk sutures are prone to microbial adhesion and biofilm formation, which can increase the risk of post-surgical infections.

To address this limitation, recent studies have focused on functionalizing silk sutures with herbal bioactives to impart antimicrobial and tissue-supportive properties. Plant-derived compounds such as neem (*Azadirachta indica*), turmeric (*Curcuma longa*), aloe vera, tulsi (*Ocimum sanctum*), and *Cynodon dactylon* have been investigated for this purpose due to their demonstrated antibacterial activity (Raina, 2008). These bioactives are typically applied as surface coatings or immobilized using biopolymer matrices, forming protective interfaces that inhibit microbial colonization without compromising the mechanical integrity or biocompatibility of the sutures.

Biodegradable polymers, particularly chitosan and alginate, are commonly employed as binder matrices for herbal coatings. Chitosan provides intrinsic antimicrobial activity, improves coating adhesion, and enables controlled release of herbal constituents at the wound site. Chitosan–herbal composite coatings on silk sutures have been reported to reduce bacterial load, enhance wound healing, and elicit minimal inflammatory responses compared with uncoated or conventionally treated sutures (Tummalapalli et al., 2016). Overall, herbfuntionalized silk sutures represent a promising approach toward developing multifunctional and potentially more sustainable surgical sutures, although further evaluation of long-term performance and clinical translation remains necessary.

EXTRACORPOREAL MEDICAL DEVICES

Extracorporeal medical devices operate outside the body while directly contacting blood, body fluids, or tissues, and include hemodialysis membranes, blood oxygenators, extracorporeal membrane oxygenation (ECMO) systems, plasmapheresis filters, wound drainage devices, and blood-contact tubing. These devices are typically fabricated from polymeric membranes, fibres, and textile-based constructions and must meet stringent requirements for hemocompatibility, anti-thrombogenicity, antimicrobial performance, and minimal inflammatory response (Ratner, 2013). Biofouling—encompassing protein adsorption, platelet activation, microbial adhesion, and biofilm formation—remains a major challenge limiting device performance and longevity.

To mitigate biofouling, surface modification and functional coatings are widely employed. In recent years, herbal and plant-derived bioactives have been investigated as alternative surface modifiers due to their favorable biocompatibility profiles compared with conventional synthetic agents (Olmo et al., 2020). Phytochemicals such as curcumin, green tea polyphenols (EGCG), neem (*Azadirachta indica*), aloe vera, and plant-derived flavonoids have attracted interest for extracorporeal applications owing to their antimicrobial, antioxidant, and antiinflammatory properties. When incorporated onto polymeric or textile surfaces, these compounds have been reported to reduce microbial adhesion and oxidative stress without inducing cytotoxic effects in blood-contacting environments (Ebenezer et al., 2025).

In addition to antimicrobial activity, several herbal bioactives exhibit anti-thrombogenic and anti-inflammatory effects, which are particularly relevant for blood-contacting extracorporeal devices. Polyphenolic compounds from green tea extracts have demonstrated inhibition of platelet activation and protein fouling, contributing to prolonged device functionality by limiting biofouling-related complications (Zhou et al., 2024). The

multicomponent nature of herbal extracts may further reduce reliance on single-agent antimicrobials, potentially lowering the risk of resistance development.

Despite promising laboratory-scale findings, the clinical translation of herbal-functionalized extracorporeal devices remains limited. Challenges related to long-term stability under continuous flow, compatibility with sterilization processes, and reproducibility of herbal extracts continue to hinder widespread adoption.

Nevertheless, emerging evidence suggests that herbal surface functionalization represents a viable and biocompatible strategy for improving the safety and performance of next-generation extracorporeal medical devices (Sun et al., 2025).



Figure 5 - Healthcare and Hygiene Textiles

Classification	Examples	Key Functions	Herbal Application Potential
Non-implantable	Dressings, pads, diapers	Absorbency, healing	High
Implantable	Sutures, meshes	Strength, biocompatibility	Emerging
Extracorporeal	Dialysis membranes	Filtration	Limited
Healthcare & hygiene	Gowns, masks	Barrier protection	High

Table 1- Summary of Medical Textile and Herbal Application Potential

Critical Considerations in the Development of Herbal-Based Medical Textiles

When integrating herbal bioactive into non-implantable medical textiles, several key material and performance considerations must be addressed. Bioactive extraction methods should preserve compound efficacy and ensure stability during textile processing and storage. The selected incorporation approach must enable controlled and sustained release to maintain therapeutic functionality over the intended use period. Safety and biocompatibility are critical, requiring that both the bioactive and their delivery do not induce toxicity or adverse skin reactions. Herbal treatments should provide sufficient antimicrobial effectiveness against relevant pathogens without compromising essential textile properties such as strength, flexibility, and breathability. Finally, all herbfuntionalized non-implantable medical textiles must comply with applicable medical device regulations and performance standards

Overview of Herbal Bioactive Incorporation Mechanisms

Several incorporation strategies have been employed to functionalize medical textiles with herbal bioactives, each offering distinct advantages and limitations. Conventional pad-dry-cure or dip-dry-cure processes remain widely used for cotton and nonwoven substrates due to their simplicity and scalability; however, these methods often provide limited durability despite immediate bioactivity (H. Mondal, 2023).

Microencapsulation is widely applied to protect sensitive or volatile compounds, enabling controlled and sustained release while enhancing stability during textile processing and storage. This approach is particularly effective for essential oils such as tea tree oil and neem oil when microcapsules are integrated into nonwoven or surface-bound textile systems (Sharma et al., 2021).

Electrospinning enables direct incorporation of herbal bioactives during fiber formation, producing nanofibrous structures with high surface area and tunable release characteristics. Owing to its extracellular matrix-like morphology, electrospinning is frequently employed in the development of bioactive wound dressings incorporating compounds such as curcumin, pomegranate extracts, EGCG, and propolis (Salehi et al., 2024).

Plasma treatment and surface grafting are used to activate textile surfaces and improve the adhesion of herbal finishes. These approaches enhance finish durability through chemical binding and are particularly relevant for reusable medical textiles subjected to repeated sterilization cycles (Ivanovska et al., 2023).

Key Unresolved Challenges in Herbal-Functionalized Medical Textiles

Despite substantial research activity, several unresolved challenges continue to limit the translation of herbal-functionalized medical textiles across different incorporation techniques and application domains. A major concern is the lack of standardization of herbal extracts, as variability in plant source, chemotype, and extraction protocol leads to inconsistent bioactive content and poor reproducibility of textile performance (Sharma et al., 2021; Popescu & Ungureanu, 2023). In addition, durability assessment remains non-uniform, with inconsistent reporting of wash resistance, release kinetics, and post-sterilization activity, making it difficult to compare results across finishing, encapsulation, and nanofiber-based systems (H. Mondal, 2023; Salehi et al., 2024). Sterilization compatibility presents a further challenge, as many phytochemicals are sensitive to autoclave, ethylene oxide, or gamma irradiation, resulting in degradation or uncontrolled leaching, particularly in implantable and extracorporeal applications (Zhou et al., 2024). From an industrial perspective, scale-up and cost feasibility remain uncertain for advanced incorporation routes such as microencapsulation and electrospinning, where limited techno-economic data hinder assessment of manufacturing viability (Salehi et al., 2024). Finally, regulatory ambiguity continues to impede clinical translation, as herbal-functionalized textiles may be classified as cosmetics, medical devices, or combination products depending on jurisdiction, with limited regulatory guidance specific to plant-based bioactive finishes (Bibi et al., 2024; Sun et al., 2025). Addressing these challenges through standardized testing, durability benchmarks, sterilization studies, and clearer regulatory frameworks is essential for advancing herbal-based medical textiles beyond laboratory-scale demonstrations.

SUMMARY

One of the most important trends in current medical textile technology is that herbal alternatives are being considered in place of synthetic antimicrobial compounds, due to safety concerns associated with cytotoxicity, skin sensitization, persistence, and microbial resistance. By nature, herbal extracts are biocompatible, nonspecific, multi-action, and act by synergistic principles, suitable for long-term skin contact applications such as wound care, toilet articles, and medical fabrics. Besides infection control, these phyto-bioactives exhibit ancillary therapeutic properties, including anti-inflammatory, antioxidant, and wound-healing activities, enabling the formulation of multifunctional "active" medical textiles that promote tissue repair and patient comfort. Another critical factor is that natural herbal remedies are renewable and biodegradable, holding great promise for meeting the requirements of sustainability and green chemistry principles in the medical industry, thereby enabling reduced environmental impact and facilitating end-of-life management of medical textile products. Encouraged by tightening regulatory frameworks and growing demand for safer, eco-friendly healthcare materials, herbal-functionalized medical textiles may offer a promising pathway to next-generation, patient-centred, sustainable solutions in healthcare.

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