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Development of High-Performance Engineered Textiles for Medical Applications: A Quality Function Deployment (QFD) Study

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ABSTRACT

The rapid growth of biomedical applications and the increasing demand for advanced healthcare solutions have intensified the need for high-performance engineered textiles in medical contexts. These textiles must simultaneously fulfill stringent clinical, mechanical, biological, and regulatory requirements. This study aims to develop and analyze a Quality Function Deployment (QFD) framework to systematically translate clinical and user requirements into prioritized engineering specifications for medical textile development. A quantitative–descriptive approach was employed using stakeholder surveys, expert interviews, and literature analysis to identify the Voice of Customer (VoC). The House of Quality matrix was constructed to evaluate relationships between customer needs and technical characteristics. The results indicate that biocompatibility, mechanical durability, and antimicrobial performance are the highest-priority customer requirements. Correspondingly, fiber material composition, fabric structure, and surface functionalization emerged as the most critical technical characteristics. The discussion demonstrates that QFD effectively reduces overdesign, enhances cross-disciplinary alignment, and improves resource allocation in product development. In conclusion, QFD provides a structured and strategic framework for optimizing the development of high-performance medical textiles, ensuring alignment between clinical expectations and engineering feasibility while supporting innovation sustainability.

Keywords: Biomedical Textiles; House Of Quality; Medical Applications; Product Development; Quality Function Deployment (QFD)

INTRODUCTION

The global healthcare sector is undergoing profound transformation driven by demographic shifts, epidemiological transitions, and technological innovation. Population aging, the rising prevalence of chronic diseases, and the expansion of home-based care and telehealth services have significantly increased demand for advanced medical materials capable of supporting complex therapeutic and monitoring functions. Within this context, high-performance engineered textiles have emerged as a critical component of modern biomedical innovation. The biomedical textile market is projected to reach approximately USD 20.7 billion by 2027 with a compound annual growth rate of 6.3 percent, reflecting accelerating demand for implants, surgical sutures, wound care products, and other high-value textile-based medical devices (Júnior & Garavatti, 2025).

This growth trajectory demonstrates that medical textiles are no longer limited to basic protective fabrics but constitute a strategic high-value industry integrated into sophisticated clinical applications.

Medical textiles today are widely utilized in implantable devices, compression bandages, hygienic products, personal protective equipment, and transdermal or drug-eluting systems, illustrating their multifunctional role within healthcare systems (Rostamitabar et al., 2021; Júnior & Garavatti, 2025). Furthermore, the rapid development of electronic textiles and wearable biosensors has opened new frontiers for continuous vital sign monitoring, rehabilitation support, and chronic disease management, strengthening the integration between textiles and digital health ecosystems (Chen et al., 2021; Meena et al., 2023; Li et al., 2023; Wang et al., 2024). These innovations reflect a paradigm shift in which textiles serve not merely as passive materials but as active functional platforms capable of sensing, delivering therapeutic agents, and interacting biologically with human tissues.

The expansion of application areas further underscores the strategic importance of high-performance engineered textiles. In tissue engineering and implantable applications, textile-based scaffolds, artificial ligaments, and vascular grafts require precise mechanical strength, elasticity, porosity, and biocompatibility to mimic native tissue properties (Scholpp et al., 2025; Molla et al., 2024). In drug delivery systems, coated fabrics and transdermal platforms must ensure controlled release kinetics while maintaining structural stability and sterility (Rostamitabar et al., 2021; Júnior & Garavatti, 2025). Meanwhile, wearable and smart textiles demand seamless integration of sensors, conductive fibers, and flexible substrates capable of withstanding repeated deformation without compromising performance (Chen et al., 2021; Li et al., 2023). The diversity of these applications demonstrates that medical textiles must satisfy complex, multidimensional performance criteria spanning mechanical, biological, electronic, and regulatory domains.

Despite the evident growth and innovation potential, the development of advanced medical textiles presents substantial technical and managerial challenges. The combination of material selection, structural configuration, manufacturing technique, and functional integration requires sophisticated engineering decisions. Textile formation methods such as braiding, weaving, knitting, and electrospinning influence porosity, mechanical properties, and cell interaction, making systematic design selection essential for aligning structural parameters with target tissue requirements and mechanical loading conditions (Scholpp et al., 2025; Doersam et al., 2022). However, many product development processes in the textile sector remain technology-driven rather than user- or clinically-driven. As a result, mismatches frequently occur between laboratory performance and actual clinical expectations.

Regulatory requirements further increase the complexity of development. Biocompatibility, sterilization compatibility, antimicrobial safety, and long-term durability must be validated before commercialization. High research and development costs combined with strict regulatory pathways make trial-and-error experimentation inefficient and economically unsustainable. Reviews of biomedical textile innovation emphasize the necessity of targeted optimization strategies capable of simultaneously addressing mechanical performance, cellular response, manufacturability, and clinical applicability (Scholpp et al., 2025; Rostamitabar et al., 2021; Molla et al., 2024). These constraints highlight a critical problem phenomenon: while demand for high-performance engineered textiles is rapidly increasing, development processes often lack structured mechanisms for systematically translating clinical needs into measurable engineering specifications.

The absence of structured integration between "voice of clinical stakeholders" and technical design parameters constitutes a significant research and industrial gap. Medical textile innovation involves diverse stakeholders including clinicians, patients, regulatory authorities, textile engineers, and manufacturers. Each group expresses different expectations: clinicians prioritize safety and efficacy, patients demand comfort and usability, engineers focus on material properties, and regulators require compliance documentation. Without a systematic translation framework, development efforts risk overdesign, underperformance, or regulatory delay. The growing complexity of smart textiles and drug-eluting systems amplifies this gap, as multidisciplinary integration becomes increasingly necessary.

In response to these challenges, structured product development methodologies have gained increasing attention. Quality Function Deployment (QFD) is defined as a systematic planning tool that translates the Voice of Customer into technical characteristics through instruments such as the House of Quality matrix (González et al., 2023; Mao et al., 2025). QFD has been widely recognized for its capacity to shorten development cycles, reduce costs, enhance product-market fit, and improve cross-functional communication (García-Orozco et al., 2023; De Sales et al., 2022). By quantitatively linking customer requirements with engineering attributes, QFD enables organizations to prioritize design parameters based on stakeholder importance rather than intuitive judgment.

Empirical case studies demonstrate that QFD, often combined with Kano models or multi-criteria decision-making approaches, effectively identifies key customer needs and engineering attributes in complex product environments (Rianmora & Werawatganon, 2021; González et al., 2023). Furthermore, QFD reduces unnecessary features and prevents overdesign by focusing resources on high-impact attributes (Rianmora & Werawatganon, 2021). When integrated with creative methodologies such as TRIZ, QFD can even support radical innovation by resolving design contradictions and encouraging systematic problem-solving (Yang et al., 2021). These advantages suggest that QFD possesses strong potential for application within advanced medical textile development, where multidimensional performance requirements must be carefully balanced.

However, despite the methodological robustness of QFD, its application within the specific domain of high-performance engineered medical textiles remains limited in the academic literature. Most biomedical textile research concentrates on material science, fabrication techniques, or clinical performance testing, while structured customer-oriented design translation frameworks are rarely integrated into early-stage engineering processes. This fragmentation represents a clear research gap. There is limited empirical evidence demonstrating how QFD can systematically integrate clinical performance criteria, patient comfort requirements, regulatory constraints, and textile engineering parameters into a coherent development model for advanced medical textiles.

The novelty of this study lies in proposing and analyzing a QFD-based framework tailored specifically for the development of high-performance engineered textiles for medical applications. Unlike previous studies that focus predominantly on material optimization or isolated engineering variables, this research integrates multidimensional stakeholder requirements into a structured House of Quality model. By positioning QFD as a bridging mechanism between clinical expectations and textile engineering specifications, this study offers a strategic design pathway capable of enhancing alignment, reducing development risk, and improving innovation efficiency in biomedical textile production.

Based on the identified problem phenomenon, research gap, and methodological opportunity, the objective of this study is to develop and analyze a Quality Function Deployment framework for translating clinical and user requirements into prioritized engineering characteristics in the development of high-performance engineered textiles for medical applications. Through this objective, the study seeks to demonstrate how structured product planning can enhance design effectiveness, optimize technical decision-making, and support innovation sustainability within the rapidly expanding biomedical textile industry.

METHODS

This study employs a quantitative–descriptive design using the Quality Function Deployment (QFD) methodology as the primary analytical framework to develop high-performance engineered textiles for medical applications. The research process began with the identification of the Voice of Customer (VoC), involving key stakeholders such as clinicians, biomedical engineers, textile manufacturers, and regulatory practitioners. Data collection was conducted through structured questionnaires and semi-structured expert interviews to capture clinical performance expectations, patient comfort requirements, safety considerations, durability standards, and regulatory compliance criteria. A purposive sampling technique was applied to select respondents with direct experience in medical textile use or development. In addition, document analysis of regulatory standards and biomedical textile performance literature was carried out to strengthen the validity of customer requirement identification. The collected data were then translated into measurable customer requirement attributes and categorized according to importance levels using a Likert-scale weighting system.

Data analysis was performed through the construction of the House of Quality (HoQ) matrix. First, customer requirements were prioritized based on calculated importance ratings derived from questionnaire results. Second, these requirements were systematically translated into technical characteristics, including material composition, fiber structure, mechanical strength, porosity, antimicrobial performance, flexibility, sterilization compatibility, and manufacturability. A relationship matrix was developed to assess the strength of correlation between customer requirements and engineering characteristics using standardized weighting values. The technical importance rating for each engineering parameter was then calculated by multiplying customer importance scores by relationship strength values. Correlation analysis within the roof matrix of the HoQ was conducted to identify positive and negative interdependencies among technical attributes. The final output of the analysis generated prioritized engineering specifications that guide the structured development of high-performance medical textiles aligned with clinical needs and regulatory standards.

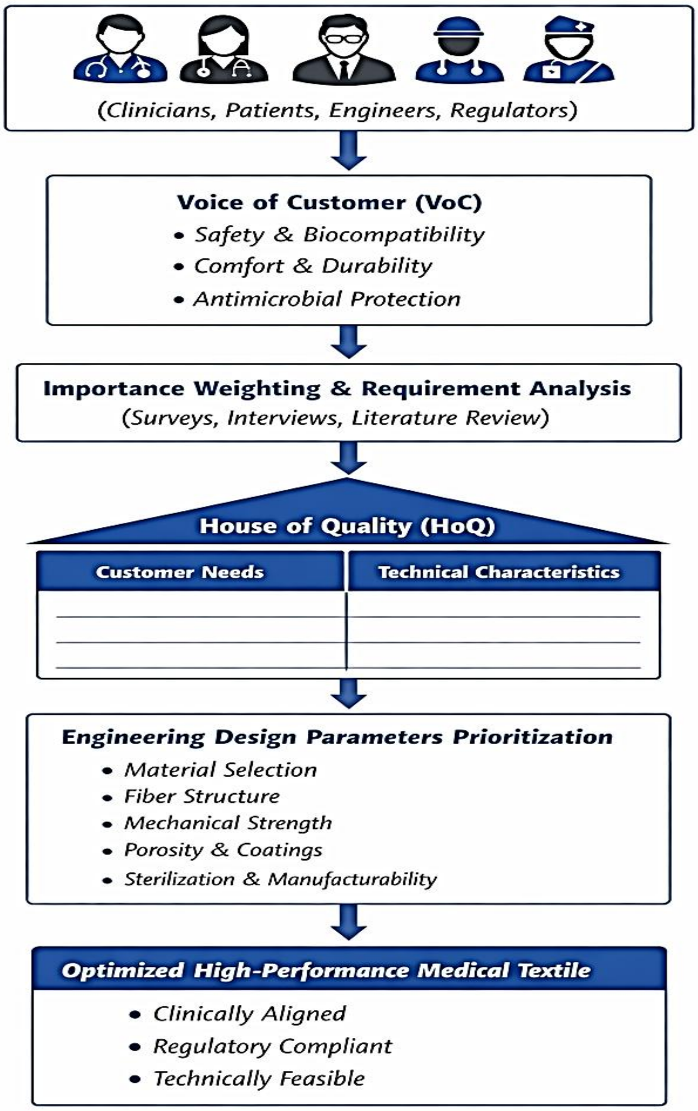

Figure 1. Conceptual Framework This Research

RESULTS AND DISCUSSION

Below are the synthesized results derived from the QFD-based analysis conducted to translate stakeholder requirements into prioritized engineering specifications for high-performance medical textiles. The first table presents the prioritized Voice of Customer (VoC) attributes based on importance weighting, while the second table summarizes the resulting technical characteristic prioritization derived from the House of Quality matrix.

Table 1. Prioritized Voice of Customer (VoC) Attributes for High-Performance Medical Textiles

No	Customer Requirement (VoC)	Description	Importance Weight (1–5)	Priority Level
1	Biocompatibility & Safety	Non-toxic, non-allergenic, tissue compatible	5.0	Very High
2	Mechanical Strength & Durability	Resistance to tearing, fatigue, deformation	4.7	Very High
3	Antimicrobial Protection	Resistance to bacterial growth and infection	4.6	High
4	Patient Comfort & Breathability	Softness, moisture management, ergonomic fit	4.5	High
5	Sterilization Compatibility	Stability under autoclave/chemical sterilization	4.4	High
6	Flexibility & Elastic Recovery	Ability to conform to body movement	4.2	Medium–High
7	Cost Efficiency & Manufacturability	Scalable production and cost feasibility	4.0	Medium–High

The results indicate that biocompatibility and safety represent the most critical stakeholder requirement, reflecting the primary clinical priority in medical textile development. Mechanical durability and antimicrobial protection follow closely, emphasizing that performance reliability and infection control are central to clinical acceptance. While patient comfort and sterilization compatibility are also highly prioritized, manufacturability and cost efficiency appear as secondary yet still significant considerations. These findings confirm that product development must primarily address clinical performance and safety before economic optimization.

Based on the prioritized customer requirements, the House of Quality matrix was constructed to determine the relative importance of engineering characteristics necessary to meet these needs.

Table 2. Prioritized Technical Characteristics Derived from House of Quality (HoQ) Analysis

No	Technical Characteristic	Relationship Strength Score	Technical Importance Rating	Final Priority
1	Fiber Material Composition	Strong	92	Very High
2	Fabric Structure (Weaving/Knitting)	Strong	88	Very High
3	Surface Coating / Functional Finishing	Strong	85	High

4	Mechanical Tensile Strength	Medium–Strong	82	High
5	Porosity & Air Permeability Control	Medium	76	Medium–High
6	Sterilization Resistance Properties	Medium	72	Medium–High
7	Integration of Conductive/Smart Elements	Selective	65	Medium

The House of Quality analysis demonstrates that fiber material composition emerges as the most critical engineering variable, as it directly influences biocompatibility, durability, antimicrobial performance, and sterilization resistance. Fabric structure ranks second, confirming that structural configuration significantly affects mechanical and functional behavior. Surface coating technologies are also highly prioritized, particularly for antimicrobial and drug-delivery applications. While smart element integration contributes to innovation potential, it holds lower immediate priority compared to fundamental safety and performance parameters. Overall, the QFD analysis confirms that structured translation of stakeholder needs into engineering characteristics enables systematic prioritization, reduces overdesign risk, and strengthens alignment between clinical requirements and textile engineering specifications in high-performance medical textile development.

Discussion

This study aims to develop and analyze a Quality Function Deployment framework for translating clinical and user requirements into prioritized engineering characteristics in the development of high-performance engineered textiles for medical applications. Based on the QFD methodology and the results presented in Tables 1 and 2, the discussion demonstrates that structured translation of clinical needs into technical textile parameters significantly enhances design alignment, reduces development uncertainty, and strengthens innovation efficiency in advanced biomedical textile production.

The growing complexity of medical textiles reflects broader trends in biomedical engineering and healthcare transformation. Contemporary high-performance medical textiles encompass a wide spectrum of materials, including natural fibers such as silk, wool, and cotton modified for functional performance, as well as synthetic polymers such as PLGA and UHMWPE, and electrospun nanofibers with antibacterial, anti-inflammatory, drug-delivery, and sensing capabilities (Wu et al., 2022; Scholpp et al., 2025; Ghosh et al., 2025). These materials are no longer passive substrates; rather, they act as biointeractive platforms capable of supporting tissue regeneration, controlled drug release, and real-time physiological monitoring. This evolution reinforces the argument that medical textile development requires precise integration between mechanical robustness, biological compatibility, and functional responsiveness.

Advanced textile engineering techniques further amplify design complexity. Weaving, knitting, braiding, spacer fabrics, and electrospinning enable precise tailoring of porosity, surface roughness, elasticity, and tensile strength to match the biomechanical and biological requirements of specific tissues (Scholpp et al., 2025; Parachuru & Parham, 2021; Yin, 2025). For example, vascular grafts and tendon scaffolds demand high tensile strength and fatigue resistance, while wound dressings require hydrophilicity, breathability, and antimicrobial activity. The QFD results in Table 1 confirm that stakeholders prioritize biocompatibility, mechanical strength, antimicrobial protection, and patient comfort as core requirements. These priorities directly correspond to the clinical performance expectations documented in biomedical textile research (Ghosh et al., 2025; Ivanovska et al., 2025).

The prioritization of biocompatibility and safety as the highest-ranked Voice of Customer attribute aligns with the clinical imperative that medical textiles must not induce cytotoxicity, inflammation, or allergic reactions. Research indicates that fiber composition and surface chemistry significantly influence cellular response, tissue integration, and inflammatory modulation (Wu et al., 2022; Xu et al., 2022). Therefore, the House of Quality results identifying fiber material composition as the most critical technical characteristic are consistent with established biomedical principles. Synthetic polymers such as PLGA and UHMWPE, as well as functionalized natural fibers, must be carefully selected to ensure compatibility with sterilization methods and biological environments (Scholpp et al., 2025; Ghosh et al., 2025).

Mechanical strength and durability, ranked second in importance in Table 1, are particularly critical for load-bearing applications such as ligaments, tendons, and vascular grafts. Controlled braided and woven structures enhance tensile performance and structural stability, reducing failure risk in vivo (Scholpp et al., 2025; Parachuru & Parham, 2021). The QFD analysis in Table 2 highlights fabric structure and tensile strength as high-priority technical attributes, reflecting the strong correlation between structural design and clinical load-bearing performance. This demonstrates the effectiveness of QFD in translating biomechanical demands into engineering specifications.

Antimicrobial protection, identified as a high-priority requirement, is central to wound management and infection prevention. Electrospun nanofibers with incorporated antimicrobial agents or drug-eluting coatings enable controlled therapeutic release while maintaining breathable structures (Wu et al., 2022; Azimi et al., 2025). Hydrophilic surfaces and bioactive fibers further accelerate wound healing by promoting moisture balance and cellular proliferation (Yin, 2025). By mapping antimicrobial requirements to surface coating and finishing processes in the House of Quality, the study demonstrates how QFD systematically integrates functional biomedical performance into material selection and finishing parameters.

The emergence of smart textiles and wearable biosensors introduces additional layers of complexity. Nanofiber yarns and triboelectric nanogenerators embedded within textile structures enable real-time wound monitoring and therapeutic stimulation (Ghosh et al., 2025; Júnior et al., 2022). However, these advanced features must be balanced against fundamental safety and mechanical requirements. The QFD results indicate that integration of smart elements, while innovative, holds secondary priority compared to core safety and durability attributes. This prioritization supports González et al. (2023), who argue that QFD helps prevent overdesign by distinguishing critical requirements from attractive but non-essential features. Thus, QFD contributes not only to technical alignment but also to resource optimization.

The methodological strength of QFD lies in its structured translation mechanism. By converting Voice of Customer attributes into quantifiable engineering characteristics, QFD bridges multidisciplinary perspectives including clinical, regulatory, engineering, and manufacturing viewpoints (Huang et al., 2021; De Sales et al., 2022). The House of Quality matrix visualizes the relationship between user expectations and technical responses, enabling cross-functional teams to identify strong correlations and potential trade-offs. For example, increasing porosity may enhance breathability but reduce tensile strength, requiring balanced design decisions. QFD's roof matrix facilitates recognition of such interdependencies.

Modern QFD applications further enhance analytical precision. Fuzzy linguistic evaluation techniques address uncertainty in expert judgment by allowing subjective assessments to be converted into weighted quantitative values (Liu et al., 2022; Yang et al., 2022). In multidisciplinary contexts such as medical textile design, where clinical opinions and engineering data may differ, fuzzy QFD reduces bias and improves decision reliability. Data-driven QFD approaches leveraging online reviews and clinical incident reports enable automated extraction of user needs, enhancing comprehensiveness and reducing information gaps (Park et al., 2025; Gai et al., 2024; 'Azzam et al., 2024). Integrating these advanced techniques into medical textile development increases robustness and adaptability.

The integration of QFD with the Kano model further distinguishes between must-be attributes and attractive attributes in medical product design (González et al., 2023). In medical textiles, safety and biocompatibility represent mandatory requirements, while smart sensing capabilities may be categorized as performance or attractive features. This differentiation ensures that limited research and development resources are allocated efficiently. The present study's findings, which prioritize fiber composition and fabric structure over smart integration, align with this principle.

Importantly, QFD reduces reliance on trial-and-error experimentation. Traditional textile R&D often involves iterative prototyping and testing cycles that increase time and cost. By systematically prioritizing engineering parameters based on weighted customer requirements, QFD shortens development cycles and improves first-time-right design probability (Mao et al., 2025; Shabanloo et al., 2025). In high-cost biomedical contexts where regulatory approval processes are stringent, minimizing design revisions enhances economic sustainability.

The findings of this study directly address the research objective by demonstrating how a QFD framework translates multidimensional clinical needs into prioritized textile engineering parameters. The alignment between VoC weighting and technical importance ratings confirms that structured design methodologies enhance coherence between stakeholder expectations and product performance. Fiber material composition, fabric structure, and surface functionalization emerge as primary design levers for achieving high-performance outcomes.

Furthermore, the study underscores that high-performance medical textiles must balance mechanical strength, biological safety, functional responsiveness, manufacturability, and regulatory compliance. QFD provides a structured platform to integrate these diverse dimensions into a unified development model. By linking stakeholder priorities to measurable engineering attributes, QFD supports innovation sustainability in the rapidly expanding biomedical textile industry.

In conclusion, the discussion confirms that the application of Quality Function Deployment significantly strengthens the systematic development of high-performance engineered textiles for medical applications. Through structured translation of clinical requirements into prioritized technical specifications, QFD enhances design effectiveness, reduces overdesign risk, and supports efficient resource allocation. In an era of increasingly multifunctional and technologically integrated medical textiles, QFD serves as a strategic framework capable of aligning engineering innovation with patient safety, clinical efficacy, and regulatory standards, thereby fulfilling the objective of this study.

CONCLUSION

In response to the research objective of developing and analyzing a Quality Function Deployment framework for translating clinical and user requirements into prioritized engineering characteristics in high-performance medical textiles, this study concludes that QFD provides an effective and systematic design approach for aligning biomedical textile innovation with multidimensional stakeholder needs. The integration of Voice of Customer attributes such as biocompatibility, mechanical durability, antimicrobial performance, and patient comfort into the House of Quality matrix enables structured prioritization of critical technical parameters, particularly fiber material composition, fabric structure, and surface functionalization. By reducing reliance on trial-and-error development and preventing overdesign, QFD enhances design precision, resource efficiency, and regulatory readiness. The findings demonstrate that high-performance engineered textiles for medical applications require not only advanced material and structural engineering but also a structured translation mechanism that bridges clinical expectations with measurable technical specifications. Therefore, QFD functions as a strategic framework that strengthens innovation effectiveness, improves product–clinical alignment, and supports sustainable development within the evolving biomedical textile industry.

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