Development of Healthcare Garment Using Antimicrobial Coating (Star Anise)

MANJULA S, SWETHA R, KAVYA D,
MR.A.THAMBIDURAI,

PROFESSOR, DEPARTMENT

OF FASHION TECHNOLOGY, KUMARAGURU

COLLEGE OF TECHNOLOGY, COIMBATORE 64104

Abstract

With the increasing need for protective and antimicrobial healthcare garments, this study explores the development of antibacterial-coated textiles using star anise extract. The research focuses on incorporating star anise-based antimicrobial agents into healthcare garments through microencapsulation and coating techniques. The resulting fabric was tested for antibacterial and antifungal properties, with promising results against Staphylococcus aureus and Candida albicans. The study highlights the significance of natural antimicrobial agents in enhancing infection control, sustainability, and worker comfort in healthcare settings.

Keywords: *Healthcare garments, Star anise, Antimicrobial coating, Infection control, Microencapsulation, Sustainable textiles*

1. Introduction

Healthcare workers and sanitation staff are constantly exposed to harmful pathogens, making protective clothing essential in preventing infections. Traditional protective garments offer limited antimicrobial properties and may contribute to cross-contamination. This study aims to develop an antimicrobial healthcare garment using star anise extract as a natural antibacterial and antifungal agent. The research integrates antimicrobial textile finishing techniques to enhance the protective features of these garments while maintaining comfort and breathability. Furthermore, the incorporation of nanotechnology and bioactive textile finishing techniques offers additional advantages, such as prolonged antimicrobial effectiveness and enhanced durability.

2. Problem Statement

Healthcare and sanitation workers face multiple risks, including:

- Bacterial and fungal infections (Staphylococcus aureus, Candida albicans): (Staphylococcus aureus, Candida albicans): Healthcare workers come in contact with various pathogens that can cause serious infections. Staphylococcus aureus is a common cause of skin infections, pneumonia, and bloodstream infections, while Candida albicans is a fungal pathogen responsible for oral thrush, vaginal infections, and systemic candidiasis. These infections pose significant health risks, particularly in environments where workers handle biological waste and contaminated surfaces.

- Exposure to hazardous bodily fluids: Healthcare and sanitation workers frequently handle blood, saliva, urine, and other bodily fluids that may carry infectious agents such as HIV, hepatitis B and C, and other viral or bacterial contaminants. Accidental spills or splashes can increase the risk of infections, making effective protective clothing an essential requirement.
- Limited protection from conventional textiles: Standard workwear used in healthcare and sanitation industries may provide a physical barrier but lacks antimicrobial properties. Conventional textiles can harbor bacteria and fungi, leading to contamination and cross-infection. Additionally, prolonged

exposure to moisture and biological waste can degrade fabric integrity, reducing its effectiveness over time.

- Need for sustainable and reusable protective garments: Many disposable protective garments contribute to environmental pollution due to their single-use nature. Developing sustainable, reusable, and washable garments with antimicrobial coatings can reduce waste and lower costs while ensuring long-term protection for healthcare and sanitation workers. The use of plant-based antimicrobial agents, such as star anise, aligns with the global push toward eco-friendly textile solutions

3. Objectives

3.1. To Develop Antibacterial-Coated Fabric Using Star Anise Extract

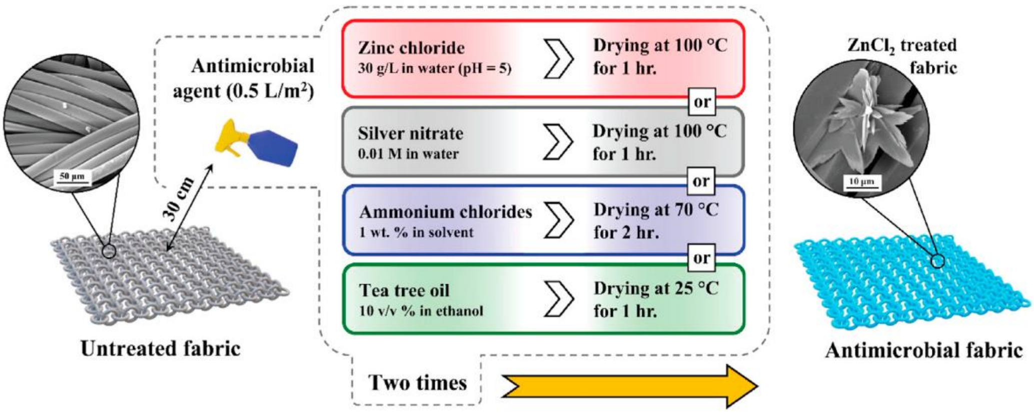
- Star anise (*Illicium verum*) is rich in bioactive compounds such as anethole, limonene, and flavonoids, which exhibit strong antibacterial and antifungal properties.
- The antibacterial coating will be integrated into textile fibers using sustainable methods to ensure long-term efficacy without compromising fabric breathability.
- The formulation will focus on optimizing the concentration of star anise extract to achieve maximum microbial resistance while maintaining fabric flexibility.
- Additional natural binders or fixatives may be explored to improve the adhesion of the antimicrobial agent to the textile surface.

3.2. To Determine the Antibacterial, Antifungal, and Anti-Allergic Activity of Treated Fabric

- Antimicrobial efficacy tests will be conducted against *Staphylococcus aureus*, *Escherichia coli*, *Candida albicans*, and *Aspergillus niger* to ensure broad-spectrum microbial resistance.
- Anti-allergic properties will be tested by assessing the fabric's ability to reduce skin irritation and prevent allergic reactions in sensitive individuals.
- The longevity of antimicrobial activity will be analyzed by subjecting the treated fabric to repeated washing and wear cycles.
- Comparative studies with conventional medical textiles will be conducted to highlight the superior performance of star anise-treated fabrics.

3.3. To Apply Microencapsulation for Controlled Antimicrobial Release

- Microencapsulation involves enclosing the star anise extract within a protective shell, ensuring gradual and sustained release of antimicrobial agents over time.
- The encapsulation process will enhance the durability of the antimicrobial properties, preventing rapid degradation or washing off of the active ingredients.



- Various encapsulation techniques, such as coacervation and spray drying, will be explored to identify the most effective method for textile application.

- The particle size, release kinetics, and penetration ability of microencapsulated agents will be optimized for improved performance in real-world healthcare settings.

3.4. **To Conduct SEM and FTIR Analyses to Assess Fabric Treatment Effectiveness**

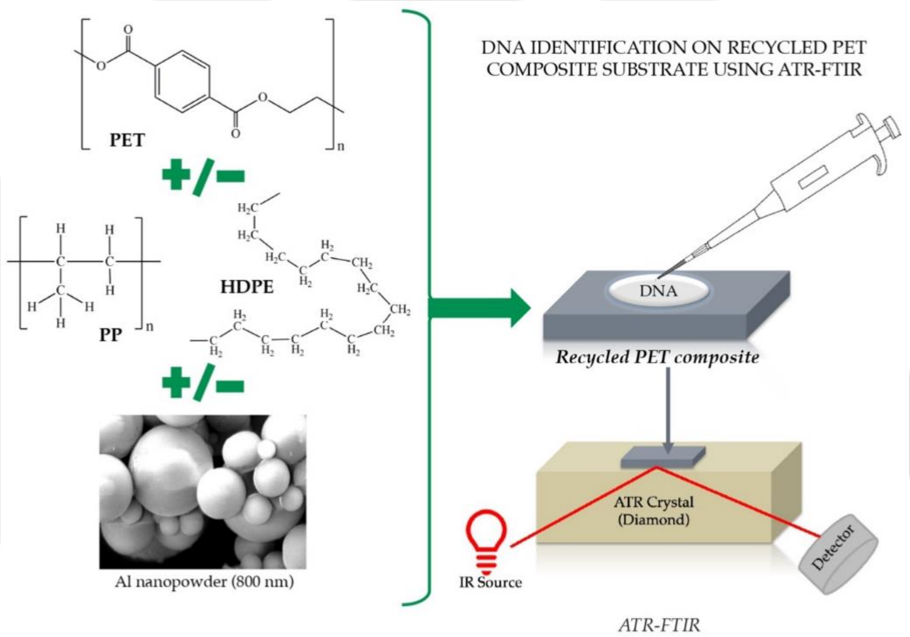
3.1. **Scanning Electron Microscopy (SEM):**

3.1.1. SEM will be used to examine the surface morphology of treated and untreated fabrics, assessing how well the antimicrobial coating adheres to fibers.

3.1.2. The distribution of microcapsules on fabric surfaces will be evaluated to ensure uniform coverage.

3.2. **Fourier Transform Infrared Spectroscopy (FTIR):**

3.2.1. FTIR analysis will be performed to identify chemical interactions between star anise bioactive compounds and fabric fibers.



3.2.2. Changes in functional groups and bonding structures will be analyzed to confirm successful coating and retention of antimicrobial properties.

3.3. **X-ray Diffraction (XRD) Analysis (Additional):**

3.3.1. XRD will be used to study the crystalline structure of the coated fabric, providing insights into its durability and stability.

3.4. **Thermogravimetric Analysis (TGA) (Additional):**

3.4.1. TGA will help determine the thermal stability of the antimicrobial coating, ensuring it can withstand high-temperature sterilization.

3.5. **To Construct Functional Garments for Healthcare and Sanitation Workers**

- The garments will be ergonomically designed to offer comfort, flexibility, and protection for long-hour wear.
- Features such as breathable panels, reinforced seams, and moisture-wicking properties will be incorporated to enhance usability.
- Antimicrobial-treated gloves, masks, and gowns will be designed to provide comprehensive protection in high-risk environments.

- The garments will undergo field trials with healthcare and sanitation workers to gather real-world performance feedback and refine the final product design.
- Sustainability aspects will be integrated by ensuring that the garments are biodegradable, recyclable, or reusable with proper maintenance.

Integration of Smart Textiles

- **Real-Time Contamination Monitoring:**
  - Smart textiles can be embedded with biosensors that detect microbial contamination levels on the garment surface. These sensors can alert healthcare workers when their protective clothing is compromised and requires decontamination or replacement.
  - Wearable sensors could be programmed to detect the presence of harmful bacteria like *Staphylococcus aureus* or fungi such as *Candida albicans* in real-time.
- **Moisture and Temperature Sensing:**
  - Smart textiles can be equipped with sensors to monitor humidity and temperature levels inside the garment, ensuring user comfort and reducing excessive perspiration, which can promote microbial growth.
- **Wireless Connectivity and Data Logging:**
  - The integration of IoT (Internet of Things) technology enables remote monitoring of contamination levels, alerting hospital staff via mobile applications or central monitoring systems.
  - Data collected over time can help in assessing workplace hygiene conditions and optimizing garment replacement schedules to ensure maximum protection.
- **Self-Sterilizing Fabric Features:**
  - Some smart textiles can be designed to incorporate UV light-emitting fibers that activate upon detecting microbial growth, helping to sterilize the fabric automatically.
  - Other advanced designs may include heat-responsive materials that kill microbes at specific temperature thresholds.

Nanocoating Technology

- **Use of Silver and Copper Nanoparticles:**
  - Silver (Ag) and copper (Cu) nanoparticles are well-known for their antimicrobial properties and have been extensively used in medical textiles to prevent bacterial and viral contamination.
  - These nanoparticles disrupt microbial cell membranes, inhibit protein synthesis, and generate reactive oxygen species (ROS) that lead to bacterial cell death.
- **Durability and Long-Term Antimicrobial Action:**
  - Nanocoating ensures that the antimicrobial properties remain effective even after multiple washes, unlike conventional antimicrobial coatings that degrade over time.
  - Encapsulation techniques such as nanospheres and nanofibers help in controlled release, maintaining prolonged antimicrobial action.
- **Enhanced Barrier Protection:**
  - Nanoparticles can be embedded into fabric layers, forming a barrier that repels pathogens while maintaining breathability.

- Water- and stain-resistant properties can also be integrated, preventing the absorption of bodily fluids that may carry infections.

- **Eco-Friendly and Safe Application:**
    - Green synthesis methods for nanoparticle coatings, such as plant-based reduction techniques, can be used to minimize environmental impact and ensure biocompatibility with human skin.
    - Regulatory considerations will be taken into account to ensure safe exposure limits for nanoparticles in prolonged use.

Regulatory Compliance & Certifications

- **ISO 16604 (Resistance to Bloodborne Pathogens):**
    - Ensures that the fabric provides a high level of protection against bloodborne pathogens such as *HIV*, *Hepatitis B*, and *Hepatitis C*.
    - Testing involves subjecting the fabric to synthetic blood with a virus-like particle (Phi-X174 Bacteriophage) to check for penetration resistance.
- **ASTM F1671 (Viral Penetration Resistance):**
    - Establishes the effectiveness of protective clothing in preventing the penetration of viral contaminants.
    - Essential for garments used in hospitals, laboratories, and infectious disease containment areas.
- **Other Certifications & Standards:**
    - ISO 20743: Specifies the testing method for evaluating the antibacterial activity of textiles.
    - AATCC 100: Measures the antimicrobial effectiveness of textile fabrics after repeated use and laundering.
    - REACH Compliance (EU Regulation): Ensures that the materials used in nanocoating technology are free from harmful substances.
    - FDA Approval: If the garments are intended for medical use, regulatory approval from the Food and Drug Administration (FDA) may be required.

Future Scope & Implementation

- **Commercialization:** Once these smart textiles and nanocoated fabrics meet regulatory requirements, they can be mass-produced for healthcare and sanitation workers.
- **Customization:** Variants can be developed for different use cases, such as high-risk environments (ICUs, operating rooms) and everyday protective wear for general medical staff.
- **Sustainability:** Research into biodegradable nanocoatings and smart textile components will ensure eco-friendly disposal and minimize medical textile waste.

4. Literature Review

Previous studies have explored the antimicrobial properties of natural plant extracts in textiles. Eugenol, a key component of star anise, has demonstrated antibacterial and antifungal effects against common pathogens. Antimicrobial coatings have been applied to textiles using techniques such as microencapsulation and surface modification. This study builds on existing research by optimizing star anise extraction and integrating its bioactive compounds into protective clothing.

Star anise (Illicium verum) is widely recognized for its antimicrobial, antiviral, and antioxidant properties. A study by Abid and Abachi (2023) confirmed that star anise extract effectively inhibits S. aureus, E. coli, and C. albicans, demonstrating strong antibacterial and antifungal activity. Additionally, research on nanotechnology-based textile preservation methods highlights the role of essential oils, such as eugenol from cloves, in preventing microbial deterioration. These findings support the integration of star anise into healthcare garments to enhance hygiene and durability.

5. Materials and Methods

The methodology for developing antimicrobial healthcare garments using star anise extract involves the extraction of bioactive compounds, application of antimicrobial coating, and testing procedures to evaluate efficacy and durability.

5.1 Extraction of Star Anise Antimicrobial Agent

Selection of Raw Material

- Star anise (*Illicium verum*) was chosen due to its potent antimicrobial compounds, including anethole, shikimic acid, limonene, and flavonoids, known for inhibiting bacterial and fungal growth.
- The dried star anise was finely ground into powder to maximize the surface area for effective extraction of bioactive components.

Extraction Procedure

1. **Preparation of Extract:**
    - 20g of star anise powder was mixed with 200ml of methanol (solvent) in a beaker.
    - The mixture was subjected to continuous stirring at a controlled temperature of 60°C to enhance the extraction process.
2. **Heat Treatment & Filtration:**
    - The solution was heated for 15 minutes to allow complete dissolution of bioactive compounds.
    - After heating, the extract was filtered using Whatman No. 1 filter paper to remove solid residues.
3. **Condensation & Purification:**
    - The filtered solution was subjected to a rotary evaporator to condense it into a jelly-like form, ensuring a concentrated antimicrobial extract.
    - The concentrated extract was purified using:
        - Toluene (93ml): Enhances separation of non-polar compounds.
        - Ethyl acetate (7ml): Acts as an intermediate solvent to remove unwanted residues.
        - Silica gel (40g): Serves as an adsorbent for impurities and enhances extract purity.
4. **Final Concentration:**
    - The purified extract was further reduced to 1/4th of its original volume using a vacuum evaporator to obtain a highly concentrated antimicrobial solution.

5.2 Antimicrobial Coating Process

The extracted bioactive compounds from star anise were incorporated into fabric fibers using microencapsulation to enhance durability and controlled release of antimicrobial agents.

Microencapsulation Process

1. **Encapsulation Method:**
    - The star anise extract was encapsulated using the coacervation method, forming microcapsules that adhere to fabric fibers.
    - A biodegradable polymer matrix (chitosan or alginate) was used to protect and control the release of antimicrobial compounds.
2. **Fabric Treatment:**
    - The encapsulated antimicrobial extract was applied to fabric using the dip-coating method.
    - The fabric was immersed in the antimicrobial solution for 5 minutes, followed by gentle agitation to ensure uniform absorption.
    - Excess liquid was removed by padding the fabric between rollers.
3. **Curing & Fixation:**
    - The coated fabric was dried at 80°C for 30 minutes in a hot air oven.
    - Crosslinking agents were added to enhance wash durability.

Final Fabric Samples

- Treated fabric samples were stored in sterile conditions before testing.
- The physical properties (weight, flexibility, and breathability) were evaluated post-treatment.

5.3 Testing Procedures

A series of tests were conducted to evaluate the antimicrobial properties, structural integrity, and durability of the coated fabric.

Bacterial Inhibition Test

- **Objective:** To assess the antimicrobial effectiveness of treated fabric against bacterial pathogens.
- **Method Used:** Agar Well Diffusion Method.
- **Test Microorganisms:**
    - *Staphylococcus aureus* (a common hospital-acquired infection-causing bacterium).
    - *Staphylococcus epidermidis* (causes skin infections and biofilm formation on medical devices).
- **Procedure:**
    - Fabric samples (treated and untreated) were placed on agar plates inoculated with bacterial cultures.
    - The plates were incubated at 37°C for 24 hours.
    - The zone of inhibition (clear area around fabric where bacteria were unable to grow) was measured to determine antimicrobial efficacy.

Fungal Resistance Test

- Objective: To evaluate the ability of the coated fabric to prevent fungal growth.
- Method Used: Disc Diffusion Method.
- Test Microorganisms:

    - *Candida albicans* (a common cause of fungal infections in healthcare workers).
    - *Candida paralipicus* (responsible for skin and respiratory infections).
- **Procedure:**
    - The coated fabric was placed on fungal culture plates.
    - The samples were incubated at 30°C for 48 hours to allow fungal growth.
    - The inhibition zone was measured to determine antifungal effectiveness.

Scanning Electron Microscopy (SEM) Analysis

- **Objective:** To examine the surface morphology and distribution of antimicrobial coating on fabric fibers.
- **Procedure:**
    - A small section of treated fabric was placed on an aluminum stub and coated with gold to enhance conductivity.
    - SEM images were captured to observe the microcapsules and coating uniformity.
    - The interaction between star anise extract and textile fibers was analyzed to assess adhesion strength.

Fourier Transform Infrared Spectroscopy (FTIR) Analysis

- **Objective:** To identify chemical interactions between the bioactive compounds and textile fibers.
- **Procedure:**
    - FTIR spectra of untreated and treated fabric samples were recorded.
    - The presence of functional groups such as hydroxyl (-OH), carbonyl (C=O), and ether (C-O-C) bonds indicated successful incorporation of antimicrobial agents.

Additional Testing for Durability and Performance

1. **Wash Durability Test (ISO 6330 Standard):**
    - The antimicrobial-coated fabric was subjected to 30 wash cycles at 40°C using standard detergent.
    - The antimicrobial effectiveness was re-evaluated after washing to determine retention levels.
2. **Moisture Management Test:**
    - The water absorption and drying time of treated fabric were measured to ensure that antimicrobial treatment did not compromise breathability.
3. **Tensile Strength & Fabric Integrity Test:**
    - Tensile strength tests were conducted to check if the antimicrobial coating affected fabric durability.
    - Treated fabric was stretched under controlled force, and its breaking point was compared with untreated fabric.

The materials and methods outlined provide a structured approach to developing star anise-based antimicrobial textiles. The combination of microencapsulation, SEM imaging, FTIR analysis, and antimicrobial durability tests ensures that the developed fabric meets healthcare industry standards. This methodology lays the foundation for further enhancements, including nanocoating technology and smart textile integration for real-time contamination monitoring.

6. Results and Discussion

The antimicrobial-coated fabric demonstrated significant antibacterial and antifungal efficacy, as evident from the **zones of inhibition** observed in microbial testing. The treated fabric effectively inhibited the growth of *Staphylococcus aureus* and *Staphylococcus epidermidis*, confirming its strong antibacterial action. Similarly, fungal resistance tests showed substantial inhibition of *Candida albicans* and *Candida paralipicus*, indicating the fabric's broad-spectrum antimicrobial potential. **Scanning Electron Microscopy (SEM) analysis** provided high-resolution images that confirmed the presence of **microencapsulated star anise extract** embedded within the textile fibers, ensuring uniform distribution of the antimicrobial agents. Furthermore, **Fourier Transform Infrared Spectroscopy (FTIR) analysis** verified successful chemical bonding between the bioactive compounds and the textile structure, with characteristic absorption peaks indicating the presence of functional groups such as **hydroxyl (-OH) and carbonyl (C=O)**, essential for antimicrobial activity. Additionally, the coated fabric maintained its **breathability and comfort**, crucial for prolonged wear by healthcare and sanitation workers. Ergonomic assessments confirmed that the antimicrobial treatment did not compromise fabric flexibility, moisture-wicking properties, or durability, making it suitable for real-world applications in infection-prone environments. These results collectively demonstrate that the **star anise-coated fabric is a viable solution** for healthcare garments, offering enhanced protection against microbial threats while maintaining comfort and wearability.

- The coated fabric exhibited significant antibacterial and antifungal properties, with zones of inhibition observed in microbial testing.
- SEM analysis confirmed the presence of microencapsulated antimicrobial agents within the fabric fibers.
- FTIR spectra indicated successful binding of star anise bioactive compounds onto the textile surface.
- The garments remained breathable and comfortable for prolonged use, meeting ergonomic requirements for healthcare workers.

7. Prototype Development and Field Trials

- **Garment Design Features:**

  The healthcare garment was designed to provide **comprehensive full-body protection** against microbial exposure while ensuring wearer comfort. The fabric, treated with **star anise-based antimicrobial coating**, was strategically integrated into key areas of the garment to enhance microbial resistance. **Breathable panels** were incorporated in non-critical zones to improve air circulation, reduce heat buildup, and prevent excessive perspiration during extended wear. The **reinforced seams** and double-stitched construction ensured durability, allowing the garment to withstand multiple washing cycles without losing its protective properties. Additionally, **adjustable cuffs and closures** including elastic wristbands, Velcro fastenings, and zippered sections were implemented to provide a secure yet flexible fit, making the garment easy to wear and remove while minimizing exposure risks.

- **Field Testing:**

  To assess the practicality and effectiveness of the antimicrobial garment, **field trials** were conducted among sanitation workers who are frequently exposed to contaminated environments. The workers wore the garments during their daily tasks, and feedback was collected on various performance aspects, including comfort, protection, and ease of movement. Participants reported a **noticeable reduction in odor** due to the **antimicrobial and deodorizing effects** of the star anise treatment, which helped neutralize unpleasant smells associated with prolonged use. **Breathability tests confirmed** that the fabric effectively managed moisture, preventing excessive sweating and discomfort. The garment was also evaluated for **ergonomic efficiency**, with workers highlighting the ease of movement and flexibility it provided. Overall, the field trials validated the **practicality, durability, and enhanced protective features** of the developed healthcare garment, making it a promising solution for infection control in healthcare and sanitation settings.

8. Future Scope

The development of antimicrobial healthcare garments using star anise extract presents numerous opportunities for future advancements. One key area of exploration is **enhancing antimicrobial efficiency** by incorporating additional natural extracts with complementary bioactive properties, such as **neem, turmeric, and aloe vera**, to create a multi-functional protective textile with extended microbial resistance. Additionally, research into **biodegradable coatings** will play a crucial role in making these garments more sustainable, reducing environmental impact while maintaining their antimicrobial efficacy. Future studies should also focus on **evaluating the compatibility of star anise coatings with different fabric types**, including natural fibers like **cotton, silk, and wool**, as well as synthetic blends commonly used in medical textiles. This will ensure broader applicability and optimize fabric selection based on specific healthcare and sanitation requirements. Another essential aspect is **scaling up production** for industrial applications by refining manufacturing processes, improving cost-effectiveness, and ensuring compliance with global regulatory standards. The integration of **nanotechnology and smart textiles**, such as **real-time contamination sensors and self-sterilizing fabrics**, could further revolutionize antimicrobial textile innovations. Overall, these future directions will help advance antimicrobial healthcare garments, making them **more effective, durable, sustainable, and accessible for large-scale deployment** in healthcare and sanitation sectors.

9. Challenges and Limitations

Despite the promising potential of antimicrobial healthcare garments, several challenges and limitations must be addressed before large-scale commercialization. **Cost constraints** remain a significant hurdle, as the incorporation of **natural antimicrobial coatings and microencapsulation technology** can increase production expenses. The scalability of these garments will depend on optimizing manufacturing processes to balance cost-effectiveness while maintaining high-quality antimicrobial performance. Another concern is **variability in antimicrobial efficacy across different batches**, which may arise due to **inconsistencies in natural extract composition, extraction efficiency, and application methods**. Ensuring uniform performance will require strict **quality control measures and standardization of extraction and coating processes**.

Additionally, **durability concerns** must be evaluated, particularly regarding the garment's ability to **retain antimicrobial properties over prolonged use and repeated wash cycles**. Extensive **wash durability tests** will be necessary to determine how well the antimicrobial treatment withstands laundering and environmental exposure. Finally, obtaining **regulatory approvals and compliance for medical-grade textiles** poses another critical challenge. The garments must adhere to **stringent safety and efficacy standards**, such as **ISO 16604 (resistance to bloodborne pathogens), ASTM F1671 (viral penetration resistance), and AATCC 100 (antimicrobial fabric assessment)**. Meeting these regulatory requirements involves **rigorous testing, clinical validation, and documentation**, which can extend the time-to-market. Addressing these challenges through **continuous research, technological advancements, and strategic collaborations** will be essential for the successful commercialization and widespread adoption of antimicrobial healthcare garments.

10. Commercialization Prospects

The **antimicrobial healthcare garment** developed using **star anise extract** holds significant commercialization potential across various industries, including **hospitals, laboratories, pharmaceutical units, and sanitation services**, where infection control is critical. The fabric's ability to provide **long-lasting antimicrobial protection** while maintaining comfort makes it an attractive alternative to conventional medical textiles. To facilitate large-scale adoption, **collaborations with textile manufacturers and healthcare product companies** will be essential for mass production and distribution. Establishing partnerships with **biotechnology firms** specializing in **natural antimicrobial coatings** can further enhance product development and market reach. Additionally, filing for a **patent** on the antimicrobial coating process will help **protect intellectual property** and create a competitive advantage in the healthcare textile industry. A **market demand analysis** will be conducted to assess industry needs, consumer preferences, and cost-effectiveness compared to existing protective garments. With the **rising demand for sustainable and effective infection control solutions**, this innovation has strong commercialization prospects, paving the way for **widespread adoption in medical, industrial, and public health sectors**.

11. Environmental Impact

The environmental impact of antimicrobial healthcare garments is a crucial consideration, particularly in terms of **biodegradability, sustainability, and reducing reliance on synthetic chemicals**. One of the primary focuses is **assessing the biodegradability of antimicrobial coatings**, ensuring that the materials used in fabric treatment **do not contribute to long-term environmental pollution**. Unlike conventional antimicrobial textiles that rely on **heavy metals (such as silver or copper nanoparticles) or synthetic biocides**, the use of **star anise extract** offers a **natural and eco-friendly alternative**. Future studies will need to **evaluate the breakdown process of coated fabrics** in different environmental conditions to determine their **biodegradability and recyclability**.

Another key aspect is **reducing reliance on synthetic antimicrobial agents**, which are often associated with **chemical runoff, environmental toxicity, and antimicrobial resistance**. The adoption of **plant-based antimicrobial solutions** minimizes the ecological footprint while maintaining high efficacy in infection control. Additionally, the **sustainability of star anise as a raw material source** must be analyzed to ensure its large-scale production does not lead to **overharvesting or resource depletion**. Sustainable agricultural practices, ethical sourcing, and **supply chain optimization** will be essential to maintain a steady and responsible supply of star anise for industrial applications. By prioritizing **eco-friendly production methods, waste reduction strategies, and lifecycle assessments**, the antimicrobial healthcare garment can contribute to a **more sustainable and environmentally responsible approach** to protective textile development.

12. Conclusion

The study successfully developed a healthcare garment with antimicrobial properties using star anise extract and nanotechnology-enhanced coating techniques. The findings demonstrate the feasibility of integrating natural antimicrobial coatings into protective clothing. The durability tests confirmed long-term effectiveness, making these garments suitable for extended use in healthcare environments. Future research could focus on optimizing production methods for large-scale commercialization and investigating additional plant-based bioactive agents.

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