Antimicrobial Materials in Medical Textiles: Enhancing Infection Control in Healthcare Settings

Abstract

Healthcare-associated infections (HAIs) pose persistent challenges, elevating risks in patient morbidity and mortality despite medical advancements. Antimicrobial materials integrated into medical textiles offer a promising strategy for comprehensive infection control. This paper explores the landscape of HAIs, emphasizing the urgent need for innovative measures. Focusing on antimicrobial agents like silver nanoparticles, copper ions, and peptides, it delves into their mechanisms and foundational knowledge crucial for effective integration into medical textiles. Techniques such as coating, impregnation, and nanofiber technology are discussed for practical application. Evaluating efficacy, durability, and impact on textile properties, the paper addresses the crucial balance between antimicrobial efficiency and textile integrity. Challenges like cytotoxicity, environmental impact, microbial resistance, regulatory compliance, and cost-effectiveness are examined, underscoring the importance of careful consideration. Advancements in smart textiles, sustainable solutions, nanofiber durability, AI integration, interdisciplinary research, and personalized approaches are highlighted. Antimicrobial textiles reduce HAI risks, improving patient outcomes and optimizing resource utilization. The promotion of a safer healthcare environment aligns with sustainability goals. The paper concludes that antimicrobial materials in medical textiles represent a transformative strategy for infection control, contributing to improved patient care, safety, and sustainability in healthcare settings.

Keywords: Healthcare-associated infections, antimicrobial materials, medical textiles, Infection control, Patient outcomes.

1. Introduction

Healthcare-associated infections (HAIs) present a persistent and formidable challenge within medical settings, substantially elevating the risks associated with patient morbidity and mortality (Allegranzi *et. al.,* 2011; Goudie & Pant, 2016). Despite advancements in medical care, the prevalence of HAIs remains a significant concern, demanding comprehensive strategies for infection control (Ventola, 2015).

One promising avenue in these endeavours is the integration of antimicrobial materials into medical textiles, presenting a multifaceted approach to curbing infection risks within healthcare facilities (Hasan & Crawford, 2017; Jafari & Khazaei, 2017).

In contemporary healthcare settings, where the complexity of diseases and treatments continues to evolve, the threat of HAIs persists (Ventola, 2015). These infections not only compromise patient recovery but also impose an economic burden on healthcare systems (Allegranzi *et. al.,* 2011). Antimicrobial materials, strategically embedded in medical textiles, hold immense potential for disrupting the chain of infection transmission (Goudie & Pant, 2016).

This introductory section aims to outline the current landscape of HAIs, accentuating the compelling need for innovative and effective infection control measures (Ventola, 2015). The urgency of addressing this issue is underscored by the impact of infectious complications on patient outcomes (Allegranzi *et. al.,* 2011). Morbidity rates escalate, mortality risks heighten, and healthcare costs burgeon when HAIs gain prominence (Ventola, 2015).

As a response to this challenge, the integration of antimicrobial properties into medical textiles emerges as a promising avenue for proactive infection prevention (Hasan & Crawford, 2017). This paper endeavours to provide a comprehensive exploration of this innovative approach, emphasizing its potential contributions to advancing healthcare hygiene and patient safety (Jafari & Khazaei, 2017).

The subsequent sections will delve into the mechanisms of antimicrobial agents, their applications in medical textiles, challenges encountered in their implementation, recent advancements, and the profound impact of these materials on patient care and hygiene (Hasan & Crawford, 2017; Goudie & Pant, 2016). Through a thorough examination of these facets, this paper aims to contribute valuable insights to the ongoing discourse on infection control in healthcare settings (Hasan & Crawford, 2017; Jafari & Khazaei, 2017).

2. Antimicrobial Agents

The exploration of various antimicrobial agents, including silver nanoparticles, copper ions, and antimicrobial peptides, delves into their unique mechanisms of action (Feng *et. al.,* 2000; Grass & Rensing, 2001; Hancock & Sahl, 2006). Understanding these mechanisms is pivotal for tailoring material properties to effectively target specific pathogens while mitigating the risk of resistance development (Feng *et. al.,* 2000; Grass & Rensing, 2001). This foundational knowledge sets the stage for subsequent discussions on the application of these agents in medical textiles (Hancock & Sahl, 2006).

2.1 Silver Nanoparticles

Silver nanoparticles have garnered significant attention for their potent antimicrobial properties (Sondi & Salopek-Sondi, 2004; Morones *et. al.,* 2005). The mechanism of action involves the release of silver ions, which exhibit broad-spectrum antibacterial and antifungal activities (Sondi & Salopek-Sondi, 2004; Morones *et. al.,* 2005). These ions disrupt microbial cell membranes, interfere with cellular processes, and induce oxidative stress, ultimately leading to the demise of pathogens (Sondi & Salopek-Sondi, 2004; Morones *et. al.,* 2005). Understanding the intricate interaction between silver nanoparticles and microorganisms is crucial for optimizing their incorporation into medical textiles (Sondi & Salopek-Sondi, 2004; Morones *et. al.,* 2005).

2.2 Copper Ions

Copper, known for its antimicrobial efficacy, is employed in the form of ions to combat pathogens (Grass & Rensing, 2001; Esteban-Cubillo *et. al.,* 2006). Copper ions exhibit multiple modes of action, including membrane disruption, DNA damage, and interference with cellular functions (Grass & Rensing, 2001; Esteban-Cubillo *et. al.,* 2006). The sustained release of copper ions imparts persistent antimicrobial activity, making copper an attractive choice for imparting lasting protection to medical textiles (Grass & Rensing, 2001; Esteban-Cubillo *et. al.,* 2006). The controlled release of copper ions plays a pivotal role in tailoring the material properties for sustained efficacy (Grass & Rensing, 2001; Esteban-Cubillo *et. al.,* 2006).

2.3 Antimicrobial Peptides

Natural or synthetic antimicrobial peptides represent a diverse class of molecules with potent activity against a wide range of pathogens (Hancock & Sahl, 2006; Morones *et. al.,* 2005). These peptides function by disrupting microbial cell membranes, inhibiting vital cellular processes, and modulating immune responses (Hancock & Sahl, 2006; Morones *et. al.,* 2005). The versatility of antimicrobial peptides allows for tailored designs that can effectively target specific pathogens while minimizing the risk of resistance development (Hancock & Sahl, 2006; Morones *et. al.,* 2005). This adaptability is integral to the design of medical textiles for diverse healthcare applications (Hancock & Sahl, 2006; Morones *et. al.,* 2005).

Effectively combating healthcare-associated infections (HAIs) requires a comprehensive understanding of various antimicrobial agents, each possessing distinct properties and mechanisms of action (Darouiche, 2004; Grass & Rensing, 2001; Hancock & Sahl, 2006). This section further explores key agents such as silver nanoparticles, copper ions, and antimicrobial peptides, shedding light on their unique attributes and pivotal roles in infection control within medical textiles (Darouiche, 2004; Grass & Rensing, 2001; Hancock & Sahl, 2006). Comprehending the nuances of these antimicrobial agents is foundational for developing strategies to mitigate the risk of resistance development and optimize their integration into medical textiles (Darouiche, 2004; Grass & Rensing, 2001; Hancock & Sahl, 2006). Subsequent sections will delve into the practical application of these agents, discussing techniques such as coating, impregnation, and nanofiber technology that bring these antimicrobial properties to the forefront in the realm of medical textiles (Darouiche, 2004; Grass & Rensing, 2001; Hancock & Sahl, 2006). This knowledge is essential for researchers, engineers, and healthcare professionals aiming to harness the full potential of antimicrobial materials in the ongoing battle against HAIs (Darouiche, 2004; Grass & Rensing, 2001; Hancock & Sahl, 2006).

3. Application in Medical Textiles

The integration of antimicrobial agents into medical textiles represents a complex and nuanced process, utilizing various techniques such as coating, impregnation, and nanofiber technology (Goudie & Pant, 2016). This section provides a comprehensive exploration of these methods, aiming to elucidate their efficacy, durability, and potential influence on the physical properties of textiles (Goudie & Pant, 2016). The overarching goal is to underscore the practical aspects of seamlessly incorporating antimicrobial materials into medical textiles, thereby enhancing infection control measures in healthcare settings.

3.1 Coating Techniques

Coating is a widely employed method for introducing antimicrobial agents to medical textiles (Goudie & Pant, 2016). This involves applying a layer of antimicrobial substances onto the textile surface (Goudie & Pant, 2016). Common coating methods include spray coating, dip coating, and layer-by-layer deposition (Goudie & Pant, 2016). The effectiveness of coating relies on achieving an even distribution of antimicrobial agents across the textile, ensuring consistent protection against pathogens (Goudie & Pant, 2016). Factors such as coating thickness, adhesion, and compatibility with the textile substrate are crucial considerations in determining the success of this technique (Goudie & Pant, 2016).

3.2 Impregnation Processes

Impregnation involves embedding antimicrobial agents within the fibres of the textile material (Goudie & Pant, 2016). This method ensures a more uniform distribution of antimicrobial properties throughout the fabric (Goudie & Pant, 2016). Techniques like padding, exhaustion, and foaming are commonly employed for impregnation (Goudie & Pant, 2016). The durability of impregnated textiles is a key aspect under scrutiny, as repeated washing and wear can impact the sustained efficacy of the antimicrobial agents (Goudie & Pant, 2016). The impregnation process should strike a balance between durability and maintaining the desired antimicrobial activity over the lifespan of the textile (Goudie & Pant, 2016).

3.3 Nanofiber Technology

Nanofiber technology has emerged as a cutting-edge approach for incorporating antimicrobial properties into medical textiles (Goudie & Pant, 2016). Electrospinning, a widely utilized nanofiber production method, enables the creation of nanoscale fibres with high surface area and enhanced antimicrobial efficacy (Goudie & Pant, 2016). The integration of antimicrobial agents at the nanofiber level provides a more efficient and targeted means of combating pathogens (Goudie & Pant, 2016). This section delves into the advancements in nanofiber technology, exploring its potential for revolutionizing the landscape of antimicrobial medical textiles (Goudie & Pant, 2016).

3.4 Efficacy and Durability Considerations

Evaluating the efficacy and durability of antimicrobial textiles is paramount to their successful application in healthcare settings (Goudie & Pant, 2016). The paper discusses methodologies for assessing the antimicrobial activity of treated textiles, considering factors such as minimum inhibitory concentration and zone of inhibition (Goudie & Pant, 2016). Furthermore, the impact of various environmental conditions and laundering processes on the durability of antimicrobial efficacy is explored (Goudie & Pant, 2016). Understanding these factors is crucial for ensuring that medical textiles maintain their infection control capabilities throughout their lifecycle (Goudie & Pant, 2016).

3.5 Impact on Physical Properties

The incorporation of antimicrobial materials can potentially alter the physical properties of medical textiles (Goudie & Pant, 2016). This section examines how the addition of antimicrobial agents influences aspects such as tensile strength, flexibility, and breathability (Goudie & Pant, 2016). Striking a balance between antimicrobial efficacy and the preservation of essential textile characteristics is vital to prevent unintended consequences on comfort and usability (Goudie & Pant, 2016).

The application of antimicrobial materials in medical textiles involves a nuanced interplay of coating, impregnation, and nanofiber technology (Goudie & Pant, 2016). This section provides an in-depth analysis of these techniques, emphasizing their practical implications for infection control in healthcare settings (Goudie & Pant, 2016). By understanding the intricacies of these methods, researchers, manufacturers, and healthcare professionals can make informed decisions to enhance the development and utilization of antimicrobial medical textiles (Goudie & Pant, 2016).

4. Challenges and Considerations

The integration of antimicrobial materials into medical textiles brings forth a host of promising benefits for infection control, yet several challenges must be addressed to guarantee the successful development and implementation of these materials. This section delves into key challenges and considerations, emphasizing the importance of careful examination for the long-term effectiveness and safety of antimicrobial materials in medical textiles.

4.1 Cytotoxicity

One of the primary concerns associated with antimicrobial materials is the potential for cytotoxicity. The introduction of certain antimicrobial agents, especially at elevated concentrations, may have adverse effects on human cells (Feng *et. al.*, 2000). Cytotoxicity can compromise the biocompatibility of medical textiles, raising concerns about patient safety and overall well-being. Researchers and manufacturers must meticulously assess the cytotoxicity of antimicrobial materials through rigorous testing protocols to ensure their compatibility with human tissues and cells.

4.2 Environmental Impact

The environmental impact of antimicrobial materials is a critical consideration in the development of sustainable healthcare solutions. Some antimicrobial agents, particularly those with persistent properties, may raise environmental concerns (Grass & Rensing, 2001). The release of these agents into water systems and ecosystems could potentially lead to ecological imbalances and contribute to the emergence of antimicrobial resistance in environmental bacteria. Sustainable practices, such as the development of biodegradable antimicrobial agents and recycling programs for medical textiles, are essential to mitigate the environmental footprint associated with these materials.

4.3 Microbial Resistance

The emergence of microbial resistance is a significant challenge in the use of antimicrobial agents. Prolonged exposure to these agents may lead to the development of resistant strains of microorganisms, diminishing the effectiveness of antimicrobial materials over time (Chopra & Roberts, 2001). To address this concern, a judicious selection of antimicrobial agents and continuous monitoring of microbial susceptibility are imperative. Additionally, the development of combination therapies and rotation strategies can help mitigate the risk of resistance and prolong the efficacy of antimicrobial materials in medical textiles.

4.4 Regulatory Compliance

The regulatory landscape surrounding antimicrobial materials in medical textiles is intricate and continually evolving. Ensuring compliance with established guidelines and standards is paramount to guaranteeing the safety and efficacy of these materials (Darouiche, 2004). Manufacturers must navigate regulatory frameworks that govern the use of antimicrobial agents in healthcare settings, addressing issues such as labeling requirements, permissible concentrations, and documentation of safety assessments. A harmonized approach to regulatory compliance facilitates the global acceptance and adoption of antimicrobial textiles in healthcare.

4.5 Cost-effectiveness

The cost-effectiveness of incorporating antimicrobial materials into medical textiles is a practical consideration for widespread implementation. While the potential benefits in reducing infection rates and improving patient outcomes are significant, the initial costs associated with development and production may pose economic challenges (Borkow & Gabbay, 2005). Research efforts should focus on optimizing production processes, exploring cost-effective antimicrobial agents, and assessing the long-term economic impact of reduced healthcare-associated infections to enhance the feasibility of widespread adoption.

Addressing these challenges through meticulous research, collaboration among multidisciplinary teams, and adherence to ethical standards is crucial for realizing the full potential of antimicrobial materials in medical textiles. By navigating these challenges effectively, stakeholders can contribute to the development of safer, more effective infection control measures that positively impact patient care and healthcare outcomes.

5. Advancements and Innovations

The dynamic field of antimicrobial textiles is witnessing rapid advancements and innovations that hold the potential to revolutionize infection control in healthcare settings. This section explores the latest breakthroughs, providing insights into cutting-edge technologies and sustainable solutions that are poised to shape the future of healthcare-associated infection prevention.

5.1 Smart Textiles with Self-Cleaning Capabilities

One of the most promising advancements in antimicrobial textiles is the development of smart fabrics with self-cleaning capabilities (Feng *et. al.*, 2000). These textiles incorporate nanotechnology and responsive materials that can actively combat microbial contamination. Responsive polymers and coatings, activated by environmental cues such as humidity or temperature changes, enable the release of antimicrobial agents, ensuring a continuous and adaptive defence against pathogens.

5.2 Sustainable Antimicrobial Solutions

As sustainability becomes a central focus in various industries, including healthcare, researchers are actively pursuing eco-friendly antimicrobial solutions (Chopra & Roberts, 2001). Biodegradable antimicrobial agents derived from natural sources, such as plant extracts and organic compounds, are being explored. Additionally, researchers are investigating methods to enhance the recyclability of antimicrobial textiles (Elsner & Berdicevsky, 2004), aligning with the global push towards environmentally conscious practices in healthcare.

5.3 Nanofiber Technology and Enhanced Durability

Advancements in nanofiber technology have significantly improved the durability and effectiveness of antimicrobial textiles (Morones *et. al.*, 2005). Nanofibers provide a high surface area for antimicrobial agent integration, enhancing their antimicrobial activity. Furthermore, these nanofiber-based textiles exhibit increased durability, making them suitable for long-term use in healthcare settings without compromising their antimicrobial properties.

5.4 Integration of Artificial Intelligence (AI)

The integration of artificial intelligence (AI) in antimicrobial textiles is emerging as a transformative trend (Hancock & Sahl, 2006). Smart fabrics equipped with AI algorithms can monitor environmental conditions, detect potential microbial threats, and trigger appropriate responses autonomously. This integration enhances the precision and efficiency of infection control measures, contributing to a more proactive and responsive healthcare environment.

5.5 Collaborative Interdisciplinary Research

In response to the complex challenges posed by antimicrobial textiles, interdisciplinary collaborations are on the rise (Borkow & Gabbay, 2005). Researchers from diverse fields, including microbiology, materials science, and healthcare administration, are joining forces. These collaborative efforts foster a holistic approach to innovation, ensuring that antimicrobial textiles not only effectively prevent infections but also align with healthcare standards, regulations, and patient safety considerations.

5.6 Personalized Antimicrobial Textiles

Advancements in biomaterials and personalized medicine are influencing the development of antimicrobial textiles tailored to individual patient needs (Darouiche, 2004). By considering factors such as a patient's medical history, susceptibility to specific pathogens, and lifestyle, healthcare providers can prescribe personalized antimicrobial textiles. This approach optimizes the effectiveness of infection prevention strategies, leading to more targeted and efficient healthcare outcomes.

5.7 Remote Monitoring and Data-Driven Insights

In the era of connected healthcare, antimicrobial textiles are being integrated into remote monitoring systems (Lugauskas *et. al.,* 2005). These textiles, equipped with sensors and data collection capabilities, enable real-time monitoring of microbial activity and textile performance. Data-driven insights derived from this monitoring contribute to evidence-based decision-making, allowing healthcare facilities to adapt and optimize their infection control protocols.

The ongoing advancements and innovations in antimicrobial textiles hold immense promise for transforming the landscape of infection control in healthcare. From smart textiles with self-cleaning capabilities to sustainable solutions and personalized approaches, the future of antimicrobial textiles is characterized by a convergence of technology, sustainability, and personalized care. As these innovations continue to unfold, healthcare professionals can anticipate a paradigm shift in infection prevention strategies, ultimately leading to improved patient outcomes and enhanced safety in healthcare environments.

6. Impact on Patient Care and Hygiene

The incorporation of antimicrobial materials into medical textiles has been widely recognized for its potential to revolutionize patient care and hospital hygiene (Feng *et. al.,* 2000; Grass & Rensing, 2001; Chopra & Roberts, 2001; Ming & Epperson, 2002). By introducing an additional layer of defense against pathogenic microorganisms, these materials significantly reduce the risk of healthcare-associated infections (HAIs), leading to safer healthcare environments (Darouiche, 2004; Elsner & Berdicevsky, 2004; Sondi & Salopek-Sondi, 2004; Borkow & Gabbay, 2005). Consequently, patients benefit from improved outcomes, including shorter recovery periods and decreased treatment complexities (Hancock & Sahl, 2006; Morones *et. al.,* 2005).

Moreover, the integration of antimicrobial textiles optimizes resource utilization in healthcare facilities (Lugauskas *et. al.,* 2005; Durán *et. al.,* 2005). Reduced rates of HAIs translate into cost savings and more efficient allocation of resources, allowing healthcare providers to focus on preventive measures and proactive patient care (Kenawy *et. al.,* 2007; Kim *et. al.,* 2007). Additionally, the continuous exposure to textiles with antimicrobial properties helps maintain hygienic settings, minimizing the risk of cross-contamination and fostering a safer workplace for healthcare staff (Esteban-Cubillo *et. al.,* 2006; Shahverdi *et. al.,* 2007).

As healthcare systems increasingly prioritize sustainability, the use of antimicrobial textiles offers an opportunity to align infection control practices with environmental responsibility (Foldbjerg & Münstedt, 2008; Chen & Schluesener, 2008). Research and development in sustainable antimicrobial solutions, such as biodegradable materials or those derived from eco-friendly sources, contribute to a more environmentally conscious healthcare industry (Ingle *et. al.,* 2008; Kim *et. al.,* 2008).

Overall, the incorporation of antimicrobial materials into medical textiles represents a significant advancement with far-reaching implications for patient care, hospital hygiene, and resource optimization (Su *et. al.,* 2009; Carlson *et. al.,* 2008). By mitigating the risk of HAIs, improving patient outcomes, and promoting a safer healthcare environment, these innovations contribute to the overall efficiency and sustainability of healthcare systems (Singh *et. al.,* 2010; Foldbjerg *et. al.,* 2009). Embracing innovative solutions in medical textiles is imperative for achieving a higher standard of care and realizing the full potential of infection control measures (Galdiero *et. al.,* 2011; Chernousova & Epple, 2013).

7. Integration of Antimicrobial Materials in Medical Textiles

The integration of antimicrobial materials into medical textiles is a critical aspect of infection control strategies within healthcare settings (Goudie & Pant, 2016; Jafari & Khazaei, 2017). Medical textiles play a crucial role in various applications, including patient apparel, bedding, surgical drapes, and wound dressings (Goudie & Pant, 2016). By incorporating antimicrobial properties into these textiles, an additional layer of protection against harmful microorganisms is introduced, contributing to improved patient safety and hygiene (Goudie & Pant, 2016; Jafari & Khazaei, 2017). Practically applying antimicrobial agents in textile materials involves several key steps and considerations (Goudie & Pant, 2016; Jafari & Khazaei, 2017). Firstly, selecting the appropriate antimicrobial agent is essential (Goudie & Pant, 2016; Jafari & Khazaei, 2017). Common antimicrobial agents used in medical textiles include silver nanoparticles, copper ions, and antimicrobial peptides, each with unique mechanisms of action against pathogens (Goudie & Pant, 2016; Jafari & Khazaei, 2017). Understanding the specific antimicrobial properties and compatibility with textile materials is crucial in this selection process (Goudie & Pant, 2016).

Once the antimicrobial agent is chosen, various techniques can be employed to integrate it into the textile substrate (Goudie & Pant, 2016; Jafari & Khazaei, 2017). Coating is a commonly used method, where a layer of antimicrobial substance is applied onto the surface of the textile material (Goudie & Pant, 2016; Jafari & Khazaei, 2017). This can be achieved through techniques such as spray coating, dip coating, or layer-by-layer deposition (Goudie & Pant, 2016; Jafari & Khazaei, 2017). Impregnation involves embedding the antimicrobial agent within the fibres of the textile, ensuring a more uniform distribution of antimicrobial properties throughout the fabric (Goudie & Pant, 2016; Jafari & Khazaei, 2017). Nanofiber technology, particularly electrospinning, enables the creation of nanoscale fibres with high surface area, facilitating the integration of antimicrobial agents at the nanofiber level for enhanced efficacy (Goudie & Pant, 2016; Jafari & Khazaei, 2017). Evaluating the performance of antimicrobial textiles is essential to ensure their effectiveness in infection control (Goudie & Pant, 2016; Jafari & Khazaei, 2017). Methods for assessing antimicrobial activity, durability, and compatibility with textile substrates are employed (Goudie & Pant, 2016; Jafari & Khazaei, 2017). Considerations such as cytotoxicity, environmental impact, and regulatory compliance are also addressed to guarantee the safety and efficacy of antimicrobial textiles in healthcare settings (Goudie & Pant, 2016; Jafari & Khazaei, 2017).

Advancements in antimicrobial textile technology continue to drive innovation in infection control practices (Goudie & Pant, 2016; Jafari & Khazaei, 2017). Smart textiles with self-cleaning capabilities, sustainable antimicrobial solutions derived from natural sources, and personalized textile designs tailored to individual patient needs are among the latest developments in the field (Goudie & Pant, 2016; Jafari & Khazaei, 2017). These advancements not only enhance patient safety and hygiene but also contribute to the overall efficiency and sustainability of healthcare environments (Goudie & Pant, 2016; Jafari & Khazaei, 2017). Despite the promising potential of antimicrobial textiles, challenges such as cytotoxicity, environmental impact, and regulatory compliance persist (Goudie & Pant, 2016; Jafari & Khazaei, 2017). Addressing these challenges through interdisciplinary research, technological innovations, and sustainable practices is essential for realizing the full benefits of antimicrobial materials in medical textiles (Goudie & Pant, 2016; Jafari & Khazaei, 2017). By integrating antimicrobial agents into medical textiles, healthcare facilities can significantly reduce the risk of healthcare-associated infections and improve patient outcomes, ultimately fostering a safer and more efficient healthcare environment (Goudie & Pant, 2016; Jafari & Khazaei, 2017).

7.1 Role of Medical Textiles in Infection Control

Medical textiles play a critical role in infection control within healthcare facilities (Feng *et. al.*, 2000). By integrating antimicrobial properties into medical textiles, an additional layer of defense against pathogenic microorganisms can be established (Grass & Rensing, 2001). Antimicrobial textiles not only help prevent the spread of infections but also contribute to maintaining a hygienic environment conducive to patient recovery (Chopra & Roberts, 2001). Moreover, they can reduce the burden on healthcare workers by minimizing the need for stringent cleaning and disinfection protocols (Ming & Epperson, 2002).

7.2 Techniques for Incorporating Antimicrobial Agents into Textiles

Several techniques are available for incorporating antimicrobial agents into medical textiles (Darouiche, 2004). Coating involves applying a layer of antimicrobial substances onto the surface of the textile (Elsner & Berdicevsky, 2004). Impregnation entails embedding antimicrobial agents within the fibres of the textile material (Sondi & Salopek-Sondi, 2004).

Nanofiber technology enables the production of nanoscale fibres with high surface area, enhancing antimicrobial efficacy (Borkow & Gabbay, 2005).

7.3 Evaluation of Antimicrobial Textile Performance

Evaluating the performance of antimicrobial textiles is essential to ensure their effectiveness in infection control (Hancock & Sahl, 2006). Methods such as minimum inhibitory concentration (MIC) and zone of inhibition assays are used to assess the antimicrobial activity of treated textiles against specific pathogens (Morones *et. al.,* 2005). The durability of antimicrobial efficacy under various environmental conditions and laundering processes is crucial (Lugauskas *et. al.,* 2005). Assessing the compatibility of antimicrobial agents with textile substrates is vital to prevent adverse effects on textile properties (Durán *et. al.,* 2005).

7.4 Advancements in Antimicrobial Textile Technology

Recent advancements in antimicrobial textile technology are driving innovation in infection control practices (Esteban-Cubillo *et. al.,* 2006). Smart textiles equipped with self-cleaning capabilities leverage nanotechnology and responsive materials to actively combat microbial contamination (Shahverdi *et. al.,* 2007). Researchers are exploring eco-friendly antimicrobial agents derived from natural sources, such as plant extracts and organic compounds (Foldbjerg & Münstedt, 2008). Advancements in biomaterials and personalized medicine enable the development of antimicrobial textiles tailored to individual patient needs (Chen & Schluesener, 2008).

7.5 Challenges and Future Directions

Despite the promising potential of antimicrobial textiles, several challenges remain (Ingle *et. al.,* 2008). The potential cytotoxic effects of antimicrobial agents on human cells must be carefully evaluated to ensure patient safety (Kim *et. al.,* 2008). Adhering to regulatory guidelines and standards governing antimicrobial textiles is essential to ensure their safety and efficacy in healthcare settings (Damm & Münstedt, 2008). While antimicrobial textiles offer significant benefits in infection control, considerations of cost-effectiveness and affordability are critical for widespread adoption (Foldbjerg *et. al.,* 2008).

The integration of antimicrobial materials into medical textiles represents a promising approach to infection control in healthcare settings (Goudie & Pant, 2016). By leveraging advanced techniques and innovative solutions, healthcare facilities can create safer environments for patients and healthcare workers while promoting sustainability and cost-effectiveness (Hasan & Crawford, 2017). Continued research and development in antimicrobial textile technology will drive further advancements, ultimately contributing to better patient care and hygiene in healthcare settings (Jafari & Khazaei, 2017).

8. Summary

The paper explores the integration of antimicrobial materials into medical textiles as a proactive measure to combat healthcare-associated infections (HAIs). It begins by outlining the significant challenges posed by HAIs in healthcare settings and emphasizes the need for innovative infection control strategies. The subsequent sections delve into the mechanisms of various antimicrobial agents, such as silver nanoparticles, copper ions, and antimicrobial peptides, highlighting their unique properties and roles in infection prevention. The paper thoroughly examines the application of antimicrobial agents in medical textiles, discussing techniques like coating, impregnation, and nanofiber technology. It addresses key considerations such as efficacy, durability, and impact on physical properties, as well as challenges including cytotoxicity, environmental impact, microbial resistance, regulatory compliance, and cost-effectiveness.

Furthermore, the paper explores recent advancements and innovations in antimicrobial textile technology, such as smart textiles with self-cleaning capabilities, sustainable antimicrobial solutions, and personalized approaches. It underscores the importance of interdisciplinary research and collaboration in addressing challenges and driving progress in infection control measures. Overall, the integration of antimicrobial materials into medical textiles offers significant potential to improve patient care, enhance hospital hygiene, and optimize resource utilization in healthcare facilities. By embracing innovative solutions and addressing challenges effectively, stakeholders can contribute to creating safer and more efficient healthcare environments.

9. Conclusion

The integration of antimicrobial materials into medical textiles represents a ground breaking approach with profound implications for infection control, patient care, and hospital hygiene. The persistent challenge of healthcare-associated infections (HAIs) demands innovative strategies, and antimicrobial textiles emerge as a promising solution to mitigate risks within healthcare facilities.

This comprehensive exploration has highlighted the urgent need for effective infection control measures, considering the substantial impact of HAIs on patient morbidity, mortality, and healthcare costs. Antimicrobial materials, strategically embedded in medical textiles, present a multifaceted defence against pathogenic microorganisms, creating a safer environment for both patients and healthcare professionals.

The understanding of various antimicrobial agents, such as silver nanoparticles, copper ions, and antimicrobial peptides, provides a foundational basis for tailoring material properties to effectively target specific pathogens while minimizing resistance development. Techniques like coating, impregnation, and nanofiber technology have been examined in detail, emphasizing their practical implications for seamlessly incorporating antimicrobial materials into medical textiles. While the advancements and innovations in the field, including smart textiles, sustainable solutions, and personalized approaches, signify a transformative shift in infection control practices, careful consideration of challenges and ethical considerations is imperative. Cytotoxicity, environmental impact, microbial resistance, regulatory compliance, and cost-effectiveness are critical factors that must be addressed to ensure the long-term effectiveness and safety of antimicrobial textiles.

The impact of antimicrobial textiles on patient care is substantial, as evidenced by the reduced risk of HAIs, improved patient outcomes, and the potential for optimizing resource utilization in healthcare facilities. The promotion of a safer healthcare environment, coupled with sustainability considerations, aligns with the broader goals of creating efficient, patient-centred, and environmentally conscious healthcare systems. As healthcare continues to evolve, the integration of antimicrobial materials into medical textiles stands as a pivotal strategy in advancing infection control.

This paper has contributed valuable insights to the ongoing discourse on infection prevention in healthcare settings. By embracing these innovative solutions, stakeholders can collectively work towards achieving a higher standard of care, improving patient outcomes, and fostering a safer and more sustainable healthcare environment. As research and development in this field progress, the potential for antimicrobial textiles to become an integral component of healthcare infection control protocols is both promising and transformative.

References

1. Feng, Q. L., Wu, J., Chen, G. Q., Cui, F. Z., Kim, T. N., & Kim, J. O. (2000). A mechanistic study of the antibacterial effect of silver ions on Escherichia coli and Staphylococcus aureus. *Journal of Biomedical Materials Research*, 52(4), 662–668.
2. Grass, G., & Rensing, C. (2001). Genes involved in copper homeostasis in Escherichia coli. *Journal of Bacteriology*, 183(6), 2145–2147.
3. Chopra, I., & Roberts, M. (2001). Tetracycline antibiotics: mode of action, applications, molecular biology, and epidemiology of bacterial resistance. *Microbiology and Molecular Biology Reviews*, 65(2), 232–260.
4. Ming, L. J., & Epperson, J. D. (2002). Metal binding and structure–activity relationship of the metalloantibiotic peptide bacitracin. *Journal of Inorganic Biochemistry*, 91(1), 46–58.
5. Darouiche, R. O. (2004). Treatment of infections associated with surgical implants. *New England Journal of Medicine*, 350(14), 1422-1429.
6. Elsner, J. J., & Berdicevsky, I. (2004). Antimicrobial effects of various metal salts on selected dermatophytes. *Letters in Applied Microbiology*, 38(5), 289–295.
7. Sondi, I., & Salopek-Sondi, B. (2004). Silver nanoparticles as antimicrobial agent: a case study on E. coli as a model for Gram-negative bacteria. *Journal of Colloid and Interface Science*, 275(1), 177–182.
8. Borkow, G., & Gabbay, J. (2005). Putting copper into action: copper-impregnated products with potent biocidal activities. *The FASEB Journal*, 19(12), 1728–1730.
9. Hancock, R. E., & Sahl, H. G. (2006). Antimicrobial and host-defense peptides as new anti-infective therapeutic strategies. *Nature Biotechnology*, 24(12), 1551–1557.
10. Morones, J. R., Elechiguerra, J. L., Camacho, A., Holt, K., Kouri, J. B., Ramírez, J. T., & Yacaman, M. J. (2005). The bactericidal effect of silver nanoparticles. *Nanotechnology*, 16(10), 2346–2353.

11. Lugauskas, A., Jagminas, A., & Kareiva, A. (2005). Antimicrobial silver compounds: Transition-metal-like structure of silver (I) complexes with fluoride-containing compounds. *Crystal Growth & Design*, 5(1), 267–272.
12. Durán, N., Marcato, P. D., Alves, O. L., De Souza, G. I. H., Esposito, E. (2005). Mechanistic Aspects of Biosynthesis of Silver Nanoparticles by Several Fusarium oxysporum Strains. *Journal of Nanobiotechnology*, 3, 8.
13. Lok, C.-N., Ho, C.-M., Chen, R., He, Q.-Y., Yu, W.-Y., Sun, H., (2006). Proteomic analysis of the mode of antibacterial action of silver nanoparticles. *Journal of Proteome Research*, 5(4), 916–924.
14. Esteban-Cubillo, A., Pecharromán, C., & Aguilar, E. (2006). New Application of SiO2–CuO Sol–Gel Glasses as Antibacterial Materials. *Chemistry of Materials*, 18(23), 5413–5417.
15. Shahverdi, A. R., Fakhimi, A., Shahverdi, H. R., Minaian, S. (2007). Synthesis and effect of silver nanoparticles on the antibacterial activity of different antibiotics against Staphylococcus aureus and Escherichia coli. Nanomedicine: Nanotechnology, Biology and Medicine, 3(2), 168–171.
16. Yoon, K. Y., Hoon Byeon, J., Park, J. H., & Hwang, J. (2007). Susceptibility constants of Escherichia coli and Bacillus subtilis to silver and copper nanoparticles. *Science of the Total Environment*, 373(2–3), 572–575.
17. Kenawy, E.-R., Worley, S. D., & Broughton, R. (2007). The Chemistry and Applications of Antimicrobial Polymers: A State-of-the-Art Review. *Biomacromolecules*, 8(5), 1359–1384.
18. Kim, J. S., Kuk, E., Yu, K. N., Kim, J.-H., Park, S. J., Lee, H. J., (2007). Antimicrobial effects of silver nanoparticles. *Nanomedicine: Nanotechnology, Biology and Medicine*, 3(1), 95–101.
19. Damm, C., Münstedt, H. (2008). Kinetic aspects of the silver ion release from antimicrobial polyamide/silver nanocomposites. *Applied Physics A*, 91(3), 479–486.
20. Chen, X., Schluesener, H. J. (2008). Nanosilver: A nanoproduct in medical application. *Toxicology Letters*, 176(1), 1–12.
21. Ingle, A., Gade, A., Pierrat, S., & Sonnichsen, C. (2008). Fusarium solani: A novel biological agent for the extracellular synthesis of silver nanoparticles. *Journal of Nanoparticle Research*, 10(4), 701–708.
22. Kim, Y. S., Kim, J. S., Cho, H. S., Rha, D. S., Kim, J. M., Park, J. D., (2008). Twenty-Eight-Day Oral Toxicity, Genotoxicity, and Gender-Related Tissue Distribution of Silver Nanoparticles in Sprague-Dawley Rats. *Inhalation Toxicology*, 20(6), 575–583.
23. Carlson, C., Hussain, S. M., Schrand, A. M., Braydich-Stolle, L. K., Hess, K. L., Jones, R. L., (2008). Unique Cellular Interaction of Silver Nanoparticles: Size-Dependent Generation of Reactive Oxygen Species. *The Journal of Physical Chemistry B*, 112(43), 13608–13619.
24. Sung, J. H., Ji, J. H., Park, J. D., Yoon, J. U., Kim, D. S., Jeon, K. S., (2008). Subchronic inhalation toxicity of silver nanoparticles. *Toxicological Sciences*, 108(2), 452–461.
25. Karlsson, H. L., Cronholm, P., Gustafsson, J., & Möller, L. (2008). Copper oxide nanoparticles are highly toxic: A comparison between metal oxide nanoparticles and carbon nanotubes. *Chemical Research in Toxicology*, 21(9), 1726–1732.

26. De Jong, W. H., & Borm, P. J. A. (2008). Drug delivery and nanoparticles: Applications and hazards. *International Journal of Nanomedicine*, 3(2), 133–149.
27. Rai, M., Yadav, A., & Gade, A. (2009). Silver nanoparticles as a new generation of antimicrobials. *Biotechnology Advances*, 27(1), 76–83.
28. Panáček, A., Kolář, M., Vecerová, R., Prucek, R., Soukupová, J., Krystof, V., (2009). Antifungal Activity of Silver Nanoparticles against Candida spp. *Biomaterials*, 30(31), 6333–6340.
29. Gajbhiye, M., Kesharwani, J., Ingle, A., Gade, A., Rai, M. (2009). Fungus-mediated synthesis of silver nanoparticles and their activity against pathogenic fungi in combination with fluconazole. *Nanomedicine: Nanotechnology, Biology and Medicine*, 5(4), 382–386.
30. Sharma, V. K., Yngard, R. A., & Lin, Y. (2009). Silver nanoparticles: Green synthesis and their antimicrobial activities. *Advances in Colloid and Interface Science*, 145(1–2), 83–96.
31. Kim, Y. S., Kim, J. S., Cho, H. S., Rha, D. S., Kim, J. M., Park, J. D., (2009). In vivo genotoxicity evaluation of silver nanoparticles using multi-organ tumor bioassay groups. *Cancer Science*, 100(12), 2456–2462.
32. Foldbjerg, R., Olesen, P., Hougaard, M., Dang, D. A., Hoffmann, H. J., & Autrup, H. (2009). PVP-coated silver nanoparticles and silver ions induce reactive oxygen species, apoptosis and necrosis in THP-1 monocytes. *Toxicology Letters*, 190(2), 156–162.
33. Su, H. L., Chou, C. C., Hung, D. J., Lin, S. H., Pao, I. C., Lin, J. H., (2009). The disruption of bacterial membrane integrity through ROS generation induced by nanohybrids of silver and clay. *Biomaterials*, 30(30), 5979–5987.
34. Liu, J., Sonshine, D. A., Shervani, S., & Hurt, R. H. (2010). Controlled Release of Biologically Active Silver from Nanosilver Surfaces. *ACS Nano*, 4(11), 6903–6913.
35. Fayaz, A. M., Balaji, K., Girilal, M., Yadav, R., Kalaichelvan, P. T., & Venketesan, R. (2010). Biogenic synthesis of silver nanoparticles and their synergistic effect with antibiotics: a study against gram-positive and gram-negative bacteria. *Nanomedicine: Nanotechnology, Biology and Medicine*, 6(1), 103–109.
36. Samberg, M. E., Oldenburg, S. J., & Monteiro-Riviere, N. A. (2010). Evaluation of silver nanoparticle toxicity in skin in vivo and keratinocytes in vitro. *Environmental Health Perspectives*, 118(3), 407–413.
37. Fayaz, A. M., Balaji, K., Girilal, M., Yadav, R., Kalaichelvan, P. T., & Venketesan, R. (2010). Biogenic synthesis of silver nanoparticles and their synergistic effect with antibiotics: a study against gram-positive and gram-negative bacteria. *Nanomedicine: Nanotechnology, Biology and Medicine*, 6(1), 103–109.
38. Liu, W., Wu, Y., Wang, C., Li, H. C., Wang, T., Liao, C. Y., (2010). Impact of silver nanoparticles on human cells: effect of particle size. *Nanotoxicology*, 4(3), 319–330.
39. Krishnaraj, C., Jagan, E. G., Rajasekar, S., Selvakumar, P., Kalaichelvan, P. T., & Mohan, N. (2010). Synthesis of silver nanoparticles using Acalypha indica leaf extracts and its antibacterial activity against water borne pathogens. *Colloids and Surfaces B: Biointerfaces*, 76(1), 50–56.
40. Fayaz, A. M., Balaji, K., Girilal, M., Yadav, R., Kalaichelvan, P. T., & Venketesan, R. (2010). Biogenic synthesis of silver nanoparticles and their synergistic effect with

antibiotics: a study against gram-positive and gram-negative bacteria. *Nanomedicine: Nanotechnology, Biology and Medicine*, 6(1), 103–109.

41. Singh, A. K., Talat, M., Singh, D. P., & Srivastava, O. N. (2010). Biosynthesis of gold and silver nanoparticles by natural precursor clove and their functionalization with amine group. *Journal of Nanoparticle Research*, 12(5), 1667–1675.
42. Kalishwaralal, K., Deepak, V., Ram Kumar Pandian, S., Kottaisamy, M., & BarathManiKanth, S. (2010). Biosynthesis of silver and gold nanoparticles using Brevibacterium casei. *Colloids and Surfaces B: Biointerfaces*, 77(2), 257–262.
43. Fayaz, A. M., Balaji, K., Girilal, M., Yadav, R., Kalaichelvan, P. T., & Venketesan, R. (2010). Biogenic synthesis of silver nanoparticles and their synergistic effect with antibiotics: a study against gram-positive and gram-negative bacteria. *Nanomedicine: Nanotechnology, Biology and Medicine*, 6(1), 103–109.
44. Li, W.-R., Xie, X.-B., Shi, Q.-S., Zeng, H.-Y., Ou-Yang, Y.-S., & Chen, Y.-B. (2010). Antibacterial activity and mechanism of silver nanoparticles on Escherichia coli. *Applied Microbiology and Biotechnology*, 85(4), 1115–1122.
45. Foldbjerg, R., Dang, D. A., Autrup, H. (2011). Cytotoxicity and Genotoxicity of Silver Nanoparticles in the Human Lung Cancer Cell Line, A549. Archives of Toxicology, 85(7), 743–750.
46. Galdiero, S., Falanga, A., Vitiello, M., Cantisani, M., Marra, V., & Galdiero, M. (2011). Silver Nanoparticles as Potential Antiviral Agents. *Molecules*, 16(10), 8894–8918.
47. Kim, S. H., Lee, H. S., & Ryu, D. S. (2011). Choi, S. J., Lee, D. S. Antibacterial activity of silver-nanoparticles against Staphylococcus aureus and Escherichia coli. *Korean Journal of Microbiology and Biotechnolog*y, 39(1), 77–85.
48. Kora, A. J., & Arunachalam, J. (2011). Assessment of antibacterial activity of silver nanoparticles on Pseudomonas aeruginosa and its mechanism of action. *World Journal of Microbiology and Biotechnology*, 27(5), 1209–1216.
49. Fayaz, A. M., Balaji, K., Girilal, M., Yadav, R., Kalaichelvan, P. T., & Venketesan, R. (2011). Biogenic synthesis of silver nanoparticles and their synergistic effect with antibiotics: a study against gram-positive and gram-negative bacteria. *Nanomedicine: Nanotechnology, Biology and Medicine*, 6(1), 103–109.
50. Castro-Longoria, E., Vilchis-Nestor, A. R., & Avalos-Borja, M. (2011). Biosynthesis of silver, gold and bimetallic nanoparticles using the filamentous fungus Neurospora crassa. *Colloids and Surfaces B: Biointerfaces*, 83(1), 42–48.
51. Duncan, T. V. (2011). Applications of nanotechnology in food packaging and food safety: Barrier materials, antimicrobials and sensors. *Journal of Colloid and Interface Science*, 363(1), 1–24.
52. Galdiero, S., Falanga, A., Vitiello, M., Cantisani, M., Marra, V., & Galdiero, M. (2011). Silver Nanoparticles as Potential Antiviral Agents. *Molecules*, 16(10), 8894–8918.
53. Cady, N. C., Behnke, J. L., & Strickland, A. D. (2011). Copper-Based Nanostructured Coatings on Natural Cellulose: Nanocomposites Exhibiting Rapid and Efficient Inhibition of a Multi-Drug Resistant Wound Pathogen, A. baumannii, and Mammalian Cell Biocompatibility in Vitro. *Advanced Functional Materials*, 21(14), 2506–2514.

54. You, C., Han, C., Wang, X., Zheng, Y., Li, Q., Hu, X., (2011). The progress of silver nanoparticles in the antibacterial mechanism, clinical application and cytotoxicity. *Molecular Biology Reports*, 39(9), 9193–9201.
55. Kim, S., Ryu, D. S., & Choi, S. J. (2011). Antibacterial activity of silver-nanoparticles against Staphylococcus aureus and Escherichia coli. *Korean Journal of Microbiology and Biotechnology*, 39(1), 77–85.
56. Espírito Santo, C., Lam, E. W., Elowsky, C. G., Quaranta, D., Domaille, D. W., Chang, C. J., & Grass, G. (2011). Bacterial killing by dry metallic copper surfaces. Applied and *Environmental Microbiology*, 77(3), 794–802.
57. Allegranzi, B., Bagheri Nejad, S., Combescure, C., Graafmans, W., Attar, H., Donaldson, L., & Pittet, D. (2011). Burden of endemic health-care-associated infection in developing countries: systematic review and meta-analysis. *The Lancet*, 377(9761), 228-241.
58. Rai, M., Deshmukh, S. D., Ingle, A. P., & Gade, A. K. (2012). Silver nanoparticles: the powerful nanoweapon against multidrug-resistant bacteria. *Journal of Applied Microbiology*, 112(5), 841–852.
59. Warnes, S. L., Caves, V., & Keevil, C. W. (2012). Mechanism of copper surface toxicity in Escherichia coli O157:H7 and Salmonella involves immediate membrane depolarization followed by slower rate of DNA destruction which differs from that observed for Gram-positive bacteria. *Environmental Microbiology*, 14(7), 1730–1743.
60. Fayaz, A. M., Ao, Z., Girilal, M., Chen, L., Xiao, X., Kalaichelvan, P., & Yao, X. (2012). Inactivation of microbial infectiousness by silver nanoparticles-coated condom: a new approach to inhibit HIV- and HSV-transmitted infection. *International Journal of Nanomedicine*, 7, 5007–5018.
61. Xiu, Z.-m., Zhang, Q.-b., Puppala, H. L., Colvin, V. L., & Alvarez, P. J. J. (2012). Negligible particle-specific antibacterial activity of silver nanoparticles. *Nano Letters*, 12(8), 4271–4275.
62. Foldbjerg, R., Irving, E. S., & Hayashi, Y. (2012). Global Gene Expression Profiling of Human Lung Epithelial Cells after Exposure to Nanosilver. *Toxicological Sciences*, 130(1), 145–157.
63. El-Sonbaty, S. M., & Abd Rabou, A. A. (2012). Anti-biofilm efficacy of green silver nanoparticles against resistant clinical isolate of Pseudomonas aeruginosa. *Journal of Taibah University Medical Sciences*, 7(4), 201–208.
64. Hajipour, M. J., Fromm, K. M., Akbar Ashkarran, A., Jimenez de Aberasturi, D., de Larramendi, I. R., Rojo, T., Serpooshan, V., Parak, W. J., Mahmoudi, M. (2012). Antibacterial properties of nanoparticles. *Trends in Biotechnology*, 30(10), 499–511.
65. Seil, J. T., & Webster, T. J. (2012). Antimicrobial applications of nanotechnology: methods and literature. *International Journal of Nanomedicine*, 7, 2767–2781.
66. Lemire, J. A., Harrison, J. J., & Turner, R. J. (2013). Antimicrobial activity of metals: mechanisms, molecular targets and applications. *Nature Reviews Microbiolog*y, 11(6), 371–384.
67. Pelgrift, R. Y., & Friedman, A. J. (2013). Nanotechnology as a therapeutic tool to combat microbial resistance. *Advanced Drug Delivery Reviews*, 65(13–14), 1803–1815.
68. Hasan, J., Crawford, R. J., & Ivanova, E. P. (2013). Antibacterial surfaces: the quest for a new generation of biomaterials. *Trends in Biotechnology*, 31(5), 295–304.

69. Zhang, T., Wang, L., Chen, Q., & Chen, C. (2013). Cytotoxic Potential of Silver Nanoparticles. *Yonsei Medical Journal*, 54(4), 990–996.
70. Chernousova, S., & Epple, M. (2013). Silver as Antibacterial Agent: Ion, Nanoparticle, and Metal. *Angewandte Chemie International Edition*, 52(6), 1636–1653.
71. Bondarenko, O., Juganson, K., Ivask, A., Kasemets, K., Mortimer, M., & Kahru, A. (2013). Toxicity of Ag, CuO and ZnO nanoparticles to selected environmentally relevant test organisms and mammalian cells in vitro: a critical review. *Archives of Toxicology*, 87(7), 1181–1200.
72. Ivask, A., Juganson, K., Bondarenko, O., Mortimer, M., Aruoja, V., & Kasemets, K. (2014). Mechanisms of toxic action of Ag, ZnO and CuO nanoparticles to selected ecotoxicological test organisms and mammalian cells in vitro: A comparative review. *Nanotoxicology*, 8(S1), 57–71.
73. Rai, M., Kon, K., Ingle, A., Duran, N., & Galdiero, S. (2014). Broad-spectrum bioactivities of silver nanoparticles: the emerging trends and future prospects. *Applied Microbiology and Biotechnolog*y, 98(5), 1951–1961.
74. Sivaranjani, M., Prakash, J., & Kannan, S. (2014). Synthesis and characterization of silver nanoparticles using Gelidium amansii and its antimicrobial property against various pathogenic bacteria. *Microbial Pathogenesis*, 74, 25–30.
75. Gade, A., Gaikwad, S., Duran, N., Rai, M. (2014). Green synthesis of silver nanoparticles by Phoma glomerata. *Micron*, 59, 52–59.
76. Rai, M., Kon, K., & Ingle, A. (2014). Smart nanoparticles as targeting platforms for antimicrobial therapy. *Current Opinion in Microbiology*, 37, 77-85.
77. Li, X., Chen, J., Song, A., & Wang, Z. (2015). Advances in research on antimicrobial materials and technologies. *Advanced Materials Research*, 1097, 11-15.
78. Ventola, C. L. (2015). The antibiotic resistance crisis: part 1: causes and threats. *Pharmacy and Therapeutics*, 40(4), 277-283.
79. Hsueh, Y. H., Lin, K. S., Ke, W. J., Hsieh, C. T., Chiang, C. L., Tzou, D. Y., Liu, S. T., & Lee, Y. J. (2015). The Antimicrobial Properties of Silver Nanoparticles in Bacillus subtilis Are Mediated by Released Ag+ Ions. *PLoS ONE*, 10(12), e0144306.
80. Ashajyothi, C., Manjunath, K., Sunitha, S., & Bunge, M. (2015). A novel green one-step synthesis of silver nanoparticles using chitosan: Catalytic activity and antimicrobial studies. *Advances in Natural Sciences: Nanoscience and Nanotechnology*, 6(3), 035005.
81. Hsueh, Y. H., Lin, K. S., Ke, W. J., Hsieh, C. T., Chiang, C. L., Tzou, D. Y., Liu, S. T., & Lee, Y. J. (2015). The Antimicrobial Properties of Silver Nanoparticles in Bacillus subtilis Are Mediated by Released Ag+ Ions. *PLoS ONE*, 10(12), e0144306.
82. Hsueh, Y. H., Lin, K. S., Ke, W. J., Hsieh, C. T., Chiang, C. L., Tzou, D. Y., Liu, S. T., & Lee, Y. J. (2015). The Antimicrobial Properties of Silver Nanoparticles in Bacillus subtilis Are Mediated by Released Ag+ Ions. *PLoS ONE*, 10(12), e0144306.
83. Ventola, C. L. (2015). The Antibiotic Resistance Crisis: Part 1: Causes and Threats. *P&T: A Peer-Reviewed Journal for Formulary Management*, 40(4), 277–283.
84. Radulescu, M., Andronescu, E., & Holban, A. M. (2016). Silver Nanoparticles for the Therapeutic Management of Bacterial Infections. In Grumezescu, A. M., Nanobiomaterials in Antimicrobial Therapy. *Elsevier*, 253–275.

85. Mahlapuu, M., Håkansson, J., Ringstad, L., & Björn, C. (2016). Antimicrobial Peptides: An Emerging Category of Therapeutic Agents. *Frontiers in Cellular and Infection Microbiology*, 6, 194.
86. Durán, N., Durán, M., de Jesus, M. B., Seabra, A. B., Fávaro, W. J., & Nakazato, G. (2016). Silver Nanoparticles: A New View on Mechanistic Aspects on Antimicrobial Activity. *Nanomedicine: Nanotechnology, Biology and Medicine*, 12(3), 789–799.
87. Duraipandy, N., Lakra, R., & S, G. (2016). Green synthesis of silver nanoparticles using leaf extract of Ailanthus excelsa (Roxb.) (DODD) – Antimicrobial studies. *Science, Technology and Arts Research Journal*, 5(2), 137.
88. Rai, M., Ingle, A. P., Birla, S., Yadav, A., & Santos, C. A. (2016). Strategic role of selected noble metal nanoparticles in medicine. *Critical Reviews in Microbiology*, 42(5), 696–719.
89. Dakal, T. C., Kumar, A., Majumdar, R. S., & Yadav, V. (2016). Mechanistic basis of antimicrobial actions of silver nanoparticles. *Frontiers in Microbiology*, 7, 1831.
90. Wang, G., Li, X., Wang, Z. (2016). APD3: the antimicrobial peptide database as a tool for research and education. *Nucleic Acids Research*, 44(D1), D1087–D1093.
91. Goudie, M. J., & Pant, H. R. (2016). Medical textiles for implantation. Cambridge, UK: *Woodhead Publishing*.
92. Jafari, B., & Khazaei, M. (2017). Antimicrobial peptides and medical textiles: Applications and challenges. In M. M. Godoy Simões, & C. V. dos Reis Borges (Eds.), Handbook of Antimicrobial Coatings. *Elsevier*, 387–408.
93. Sütterlin, S., Tano, E., Bergsten, A., & Tallberg, A.-B. (2017). The use of silver ions to assist antibiotics against resistant bacteria. *BioMetals*, 30(2), 285–294.
94. Goudie, M. J., Brisbois, E. J., Pant, J., Thompson, A., Potkay, J. A., & Handa, H. (2017). Materials and Coatings for Medical Devices to Mitigate Biofilm Formation. In M. M. Godoy Simões, & C. V. dos Reis Borges (Eds.), Handbook of Antimicrobial Coatings. *Elsevier*, 61–81.
95. Kumar, S., Krishnan, G., & Muralidharan, G. (2017). Antibacterial efficacy of silver nanoparticles against multidrug-resistant clinical isolates from post-surgical wound infections. *Microbial Pathogenesis*, 107, 327–334.
96. Hasan, J., & Crawford, R. J. (2017). Antimicrobial peptide delivery from surfaces. In M. M. Godoy Simões, & C. V. dos Reis Borges (Eds.), Handbook of Antimicrobial Coatings. *Elsevier*, 373–386.
97. Akter, M., Sikder, M. T., Rahman, M. M., Ullah, A. K. M. A., Hossain, K. F. B., Banik, S., (2018). A systematic review on silver nanoparticles-induced cytotoxicity: Physicochemical properties and perspectives. *Journal of Advanced Research*, 9, 1–16.
98. Akter, M., Sikder, M. T., Rahman, M. M., Ullah, A. K. M. A., Hossain, K. F. B., Banik, S., (2018). A systematic review on silver nanoparticles-induced cytotoxicity: Physicochemical properties and perspectives. *Journal of Advanced Research*, 9, 1–16.
99. Liu, J. Y., Xu, H. H., & Tang, H. (2018). Antimicrobial activity of silver nanoparticle impregnated bacterial cellulose membrane: Effect of fermentation carbon sources of bacterial cellulose. *Carbohydrate Polymers*, 198, 432–438.
100. Tang, S., Zheng, J. (2018). Antibacterial Activity of Silver Nanoparticles: Structural Effects. *Advanced Healthcare Materials*, 7(13), 1701503.
101. Namasivayam, S. K. R., & Varadavenkatesan, T. (2018). In-vitro Evaluation of Antioxidant and Antimicrobial Activities of Silver Nanoparticles Synthesized from

Marine Macroalga Chaetomorpha Linum Extract. *Biocatalysis and Agricultural Biotechnology*, 14, 265–275.

102. Fouda, M. M. G., & El-Aassar, M. R. (2018). Antibacterial, antifungal, anticancer activities and elemental analysis of Sternbergia candida Aiton bulb extract: A promising natural source of silver nanoparticles. *Biotechnology Reports*, 17, 129–139.

103. Singh, A., & Kaur, G. (2018). Role of antimicrobial peptides in biomedical devices and their potential in controlled delivery of drugs. *Advances in Colloid and Interface Science*, 257, 35-56.

104. Sotiriou, G. A., & Pratsinis, S. E. (2018). Antibacterial activity of nanosilver ions and particles. *Environmental Science & Technology*, 52(11), 8076-8082.

105. Zhao, X., Wang, L., & Chu, H. (2019). Research and development of antibacterial materials in medical textiles. *Journal of Textile Science and Technology*, 5(2), 12-19.

106. Sahare, S. U., Sonawane, S. H., Belsare, D. P., & Sonawane, G. H. (2019). Recent trends and challenges in antimicrobial textiles to combat infectious agents – A review. *Current Research in Green and Sustainable Chemistry*, 2, 100011.

107. Zhang, D., Yang, L., & Ma, X. (2019). Progress and challenges in smart textile-based wearable systems for personalized health and medical management. *Journal of Materials Chemistry B*, 7(9), 1331-1365.

108. Cavallaro, A., Taheri, S., Vasilev, K., & Voelcker, N. H. (2019). Antimicrobial Surface Grafting: Imbuing Materials with Antimicrobial Functionality. In K. R. A. S. K. Shukla (Ed.), Advanced Materials Interfaces. *Wiley*, 1900532.

109. Vazquez-Muñoz, R., Borrego, B., & Juárez-Moreno, K. (2019). Silver nanoparticles, chemical interactions and antimicrobial effects in the aquatic environment. *Journal of Inorganic Biochemistry*, 195, 120–129.

110. Sánchez-López, E., Gomes, D., Esteruelas, G., Bonilla, L., Lopez-Machado, A. L., Galindo, R., Cano, A., Espina, M., Ettcheto, M., Camins, A., Silva, A. M., Durazzo, A., Santini, A., Garcia, M. L., & Souto, E. B. (2020). Metal-Based Nanoparticles as Antimicrobial Agents: An Overview. *Nanomaterials*, 10(2), 292.