



# BIOCOMPATIBILITY AND TOXICITY OF ANTIMICROBIAL AGENTS IN TEXTILES

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## ABSTRACT

The rapid expansion of antimicrobial textiles, driven by their effectiveness in combating microorganisms and enhancing hygiene, has brought to light significant concerns regarding their biocompatibility and environmental impact. This review provides a comprehensive examination of the various antimicrobial agents used in textiles, including both synthetic and natural types. Synthetic agents such as silver nanoparticles, zinc oxide nanoparticles, quaternary ammonium compounds (QACs), and triclosan, while effective, are associated with potential risks including cytotoxicity, carcinogenicity, hormonal imbalances, and environmental toxicity. Natural agents like chitosan, essential oils, and herbal extracts, though generally safer, also present challenges such as variable efficacy and potential allergic reactions. The review highlights critical issues such as skin irritation, allergic reactions, and long-term health effects of antimicrobial textiles, emphasizing the need for rigorous safety evaluations. Environmental concerns related to the release and bioaccumulation of antimicrobial agents further underscore the importance of developing sustainable alternatives. The review concludes with recommendations for improved regulatory standards, consumer education, and the pursuit of safer, eco-friendly antimicrobial solutions.

**Keywords:** *Antimicrobial Textiles, Biocompatibility, Toxicity, Environmental Impact.*

## 1. INTRODUCTION

The demand for antimicrobial textiles has surged in recent years, driven by their effectiveness in preventing the growth of microorganisms on fabric surfaces. Various techniques are employed to bind antimicrobial compounds to textiles, contingent upon the chemical interaction between the antimicrobial agent and the textile<sup>1</sup>. These textiles are increasingly used in healthcare settings to reduce the risk of infections, in sportswear to control odors, and in everyday clothing to enhance hygiene. About 85% of all antimicrobial textiles are produced for lingerie, active wear, shoe linings, and socks. Furthermore, antimicrobial fibres have seen significant market growth recently in the areas of air filters, outdoor textiles, upholstery, and medical textiles<sup>2</sup>. The antimicrobial properties of these textiles are typically achieved through the incorporation of agents such as silver nanoparticles, copper ions, and various organic compounds, which have been proven effective against a wide range of pathogens.

However, the growing use of antimicrobial agents in textiles has sparked concerns regarding their biocompatibility and potential toxicity. While these agents are designed to



target harmful microorganisms, their interaction with human skin and the broader environment raises critical questions about safety. Issues such as skin irritation, allergic reactions, disruption of the skin microbiome, and long-term health effects are becoming increasingly relevant as consumers are exposed to antimicrobial textiles on a daily basis.

In addition to human health concerns, the environmental impact of antimicrobial agents, particularly in the form of nanoparticles, is a significant issue. These agents can be released into the environment during washing or disposal, leading to potential ecological harm. As the industry continues to innovate and expand the use of antimicrobial textiles, there is a pressing need to thoroughly evaluate the biocompatibility and toxicity of these materials to ensure they do not pose unintended risks.

This review aims to provide a detailed examination of the biocompatibility and toxicity of antimicrobial agents in textiles. By exploring the mechanisms of action, potential health risks, environmental considerations, and current regulatory frameworks, this article seeks to inform both researchers and industry professionals on the safe and effective use of antimicrobial textiles.

## 2. ANTIMICROBIAL AGENTS IN TEXTILES

Antimicrobial agents used in textiles are essential for inhibiting the growth of harmful microorganisms such as bacteria, fungi, and viruses, and they can be broadly categorized into synthetic and natural types, each with unique mechanisms of action, benefits, and potential drawbacks. Textile functionalization has extensively utilized metal-based antimicrobial methods, incorporating agents like silver, copper, titanium, and zinc<sup>3,4</sup>. While these metals are effective in providing antimicrobial protection, they may also lead to issues such as allergies and skin sensitization<sup>5</sup>, raising concerns about their long-term safety in consumer textiles.

### 2.1 Synthetic Antimicrobial Agents

Synthetic antimicrobial agents are chemically engineered compounds designed to target and kill or inhibit a broad spectrum of microorganisms. These agents are favoured for their efficacy and durability in various textile applications, but they also come with concerns regarding toxicity, environmental impact, and potential resistance development.

#### 2.1.1 Silver Nanoparticles

Silver nanoparticles (AgNPs) are one of the most widely used synthetic antimicrobial agents in textiles. They work primarily by releasing silver ions (Ag<sup>+</sup>), which can disrupt microbial cell membranes, interact with microbial DNA, and generate reactive oxygen species (ROS) that lead to cell death. Silver nanoparticles are used in a variety of textiles, including medical fabrics, sportswear, and everyday clothing. They are valued for their broad-spectrum activity against bacteria, viruses, and fungi.

Despite their effectiveness, silver nanoparticles raise concerns about toxicity, particularly when they penetrate the skin and enter the bloodstream. Studies have shown that AgNPs can cause cytotoxicity, oxidative stress, and inflammation in human cells such as keratinocytes and fibroblasts, both of which are essential for skin health. Moreover, the environmental impact of silver nanoparticles is significant, as they can accumulate in aquatic ecosystems, leading to toxicity in aquatic organisms and potential bioaccumulation in the food chain.

### 2.1.2 Zinc Oxide Nanoparticles

Zinc oxide (ZnO) nanoparticles exhibit antimicrobial properties through multiple mechanisms, including ROS generation, disruption of cell membranes, and inhibition of essential enzymes in microorganisms. Zinc oxide is commonly used in textiles intended for medical applications, such as wound dressings, as well as in sportswear and personal protective equipment (PPE). It offers protection against a wide range of pathogens, including bacteria and fungi.

Although efficient as an antibacterial, ZnO nanoparticles can also be cytotoxic and cause oxidative stress in cells, resulting in cell death and their release into the environment poses risks to aquatic ecosystems.

### 2.1.3 Quaternary Ammonium Compounds (QACs)

QACs, such as benzalkonium chloride, are cationic surfactants that disrupt the cell membranes of microorganisms, leading to cell lysis and death. They are effective against a broad spectrum of bacteria, fungi, and viruses. QACs are commonly used in textiles for healthcare, hospitality, and consumer goods, including towels, bed linens, and activewear. They are favoured for their durability and long-lasting antimicrobial effects.

The persistent nature of QACs raises concerns about their potential to cause skin irritation, allergic reactions, and the development of antimicrobial resistance. Additionally, QACs can accumulate in the environment, where they may contribute to water pollution and harm aquatic organisms.

### 2.1.4 Triclosan

Triclosan is a broad-spectrum antimicrobial agent that works by inhibiting fatty acid synthesis in bacteria, leading to cell death. It was widely used in textiles for its ability to prevent bacterial growth and odors. Triclosan was commonly found in antibacterial clothing, footwear, and household textiles, such as dishcloths and towels.

Due to concerns about its potential endocrine-disrupting effects, environmental persistence, and contribution to antibiotic resistance, the use of triclosan in textiles has significantly declined. Many regulatory bodies, including the FDA, have restricted or banned its use in consumer products.

### 2.1.5 Copper Ions

Copper ions ( $\text{Cu}^{2+}$ ) are another widely used antimicrobial agent in textiles. Copper's antimicrobial activity is attributed to its ability to disrupt microbial cell membranes, denature proteins, and interfere with microbial DNA replication. Copper-treated textiles are commonly used in healthcare settings, such as in hospital bedding and uniforms, as well as in consumer products like socks and undergarments. Copper's broad-spectrum activity makes it effective against bacteria, viruses, and fungi.

While copper is essential for human health in trace amounts, excessive exposure through direct skin contact or inhalation can cause irritation and toxicity. Copper ions can also contribute to environmental pollution, particularly in water bodies where they may harm aquatic life.

## 2.2. Natural Antimicrobial Agents

Essential oils, plant extracts, and biopolymers are the sources of natural antibacterial agents. As opposed to their synthetic equivalents, these agents are thought to be more



biocompatible and environmentally friendly. They can differ in terms of stability, effectiveness, and likelihood of triggering allergic reactions.

### 2.2.1 Chitosan

Chitosan is a biopolymer derived from chitin, which is found in the exoskeletons of crustaceans like shrimp and crabs. Chitin is a naturally occurring polysaccharide that is a poly( $\beta$ -(1-4)-N-acetyl-D-glucosamine. Numerous living things produce chitin. Following cellulose as the most prevalent polysaccharide in nature is chitin<sup>6</sup>.

It possesses inherent antimicrobial properties, attributed to its ability to disrupt microbial cell membranes and bind to negatively charged cell surfaces, leading to cell death. Chitosan is used in medical textiles, wound dressings, and sportswear for its antimicrobial and wound-healing properties. It is also valued for its biodegradability and non-toxicity. While chitosan is generally considered safe, some individuals may experience allergic reactions, particularly those with shellfish allergies. Its antimicrobial efficacy can also be influenced by environmental factors, such as pH and temperature.

### 2.2.2 Essential Oils

Essential oils, such as tea tree oil, lavender oil, and eucalyptus oil, are extracted from plants and possess natural antimicrobial properties. These oils contain compounds like terpenes and phenolics, which can disrupt microbial cell membranes, inhibit enzyme activity, and prevent biofilm formation.

Essential oils are used in a variety of textile applications, including sportswear, bedding, and baby clothing, to provide natural antimicrobial protection and pleasant scents.

The volatility of essential oils can lead to a decrease in antimicrobial efficacy over time. Additionally, essential oils can cause skin sensitization or allergic reactions in some individuals, particularly when used at high concentrations.

### 2.2.3 Herbal Extracts

Herbal extracts from plants, such as neem, aloe vera, and rosemary, have antibacterial, anti-inflammatory, and antioxidant qualities. These extracts work by disrupting microbial cell walls, inhibiting microbial enzymes, and interfering with pathogen adhesion. Herbal extracts are used in textiles intended for sensitive skin, such as baby clothing, bed linens, and medical fabrics. They are valued for their natural origin and soothing properties.

The stability and consistency of herbal extracts in textile applications can vary, as their antimicrobial efficacy may be influenced by factors like extraction methods, formulation, and environmental conditions. Additionally, while generally safe, some extracts may cause allergic reactions in sensitive individuals.

## 3. BIOCOMPATIBILITY AND TOXICITY CONCERNS OF ANTIMICROBIAL TEXTILES

Biocompatibility refers to the ability of a material to perform its intended function without causing undesirable local or systemic effects in the host, making it a critical consideration in the use of antimicrobial textiles. Ensuring that these materials do not elicit skin irritation, allergic reactions, or other adverse effects is essential for consumer safety. Toxicity is another significant concern, particularly with synthetic antimicrobial agents, which can pose risks ranging from acute skin irritation to long-term systemic health issues. The potential for these agents to disrupt the skin's natural microbiome or leach into the



environment further underscores the need for careful evaluation and regulation to mitigate both health and environmental impacts.

### 3.1 Cytotoxicity

The possibility that a substance could be harmful to cells is known as cytotoxicity. Numerous antimicrobial drugs have the potential to be cytotoxic, particularly in high doses or after prolonged contact. According to reports, cytotoxicity is caused by the production of a singlet oxygen-mediated process that mostly damages enzymes, cytoplasmic or nuclear organelles, and the plasma membrane<sup>7</sup>.

### 3.2 Skin Inflammation and Allergic Reactions

Additionally, certain antimicrobial agents like triclosan and quaternary ammonium compounds (QACs) can trigger allergic reactions in sensitive individuals, ranging from mild contact dermatitis to severe hypersensitivity. These potential adverse effects underscore the importance of careful selection and use of antimicrobial agents in textiles to minimize skin-related issues.

### 3.3 Carcinogenicity

Carcinogenicity refers to the potential of a substance to cause cancer by inducing genetic mutations or promoting uncontrolled cellular growth. Certain antimicrobial agents used in textiles have raised concerns about their potential carcinogenic effects, particularly with long-term exposure<sup>8</sup>.

### 3.4 Hormonal Imbalances

Some antimicrobial agents can disrupt the body's hormonal systems. Triclosan, for example, has been shown to disrupt thyroid hormone levels and other endocrine functions, thereby posing major health risks. As one matures, these consequences become more noticeable and challenging to address. Moreover, Studies have been conducted on rats and humans to indicate that environmental contamination due to pollution has devastating effects on the overall health of an individual at all most all the ages by causing hormone disruptions and various disorders<sup>9-12</sup>. Compared to men, women are more likely to experience these imbalances. Hormone secretion changes become more noticeable during menstruation, pregnancy, and menopause.

### 3.5 Environmental Toxicity and Bioaccumulation

The environmental impact of antimicrobial fabrics is significant, as the agents used in these textiles can leach into the environment during laundering, potentially affecting aquatic life and ecosystems. For instance, silver nanoparticles can accumulate in aquatic species, causing harm and contributing to environmental pollution. Heavy metals from antimicrobial agents pose a serious threat to the environment<sup>13,14</sup> exacerbated by rapid industrialization and urbanization since the 1940s, which has accelerated their mobilization and transport. Additionally, antimicrobial compounds like quaternary ammonium compounds (QACs) and triclosan can bioaccumulate in both the environment and living organisms, leading to long-term ecological and health hazards. These toxins can persist in the environment and enter the food chain, raising concerns about their impact on both ecological balance and human health.

### 3.6 Antimicrobial Resistance

The widespread use of antimicrobial chemicals in textiles may contribute to the emergence of antimicrobial-resistant microorganisms. This is especially concerning for drugs like triclosan and QACs, as overuse can result in resistant strains that are difficult to treat with traditional antibiotics. Antimicrobial resistance (AMR) has become one of the 21st century's most urgent concerns to worldwide public health. AMR manifests when microorganisms, encompassing bacteria, fungi, para-sites, and viruses, undergo evolutionary processes leading to their resistance against antimicrobial medications, such as antibiotics, commonly employed for treating such infections<sup>14-16</sup>.

### 3.7 Respiratory Concerns

In textiles, such as masks or mattresses, there are inhalation risks associated with antimicrobial particles or fibres, which may lead to respiratory problems or lung damage. For example, inhaling nanoparticles or fibres coated with silver or other antimicrobial compounds can be harmful. Additionally, some antimicrobial treatments or the chemicals used to bond them to textiles can emit volatile organic compounds (VOCs), which are toxic when inhaled. These VOCs can cause respiratory irritation and other health issues<sup>17,18</sup>, raising concerns about the safety of antimicrobial-treated textiles in environments where prolonged or repeated exposure occurs.

### 3.8 Toxicity to Specific Organs

**Liver and Kidney Toxicity:** Prolonged exposure to certain antimicrobial agents, especially through dermal absorption, can lead to toxicity in vital organs such as the liver and kidneys. For instance, high levels of silver can accumulate in these organs and potentially cause damage. A large number of studies on animals have reported the toxicological role of biphenyl in serious injury of the urinary tract<sup>19,20</sup>.

### 3.9 Neurotoxicity

There are concerns that prolonged exposure to certain nanoparticles, like silver and zinc oxide, could potentially affect the nervous system, though more research is needed in this area. About 72 toxic chemicals have been identified in textile effluents, and it is estimated that approximately 200 billion litres of effluents are produced annually worldwide by the textile industry.

## 4. MECHANISMS OF ACTION AND INTERACTION WITH SKIN

The antimicrobial activity of these agents typically involves disrupting microbial cell membranes, generating reactive oxygen species, or interfering with microbial DNA replication. However, the same mechanisms that make these agents effective against microbes can also pose risks to human cells:

- **Cell Membrane Interaction:** Some antimicrobial agents, particularly nanoparticles, can penetrate human skin cells, potentially causing cytotoxicity by disrupting cellular membranes.
- **Reactive Oxygen Species (ROS) Generation:** Agents like silver and copper can generate ROS, which can lead to oxidative stress in human cells, causing inflammation, DNA damage, and even cell death.



- Chemical Residue Transfer: Prolonged contact with treated textiles can result in the transfer of antimicrobial chemicals to the skin, leading to potential systemic absorption and long-term health risks.

## 5. ASSESSMENT METHODS FOR BIOCOMPATIBILITY AND TOXICITY

Evaluating the biocompatibility and toxicity of antimicrobial agents in textiles involves various in vitro and in vivo testing methods:

- In Vitro Testing: Common methods include cytotoxicity assays, such as the MTT assay, to assess the impact of antimicrobial agents on cultured human skin cells. Skin irritation tests using reconstructed human epidermis models are also widely used.
- In Vivo Testing: Animal models, such as mice and rabbits, are used to evaluate the safety of antimicrobial textiles through dermal exposure studies. Human clinical trials may also be conducted to assess potential skin reactions in volunteers.
- Environmental Impact Assessment: Environmental toxicity tests, such as the Daphnia magna immobilization test, are used to evaluate the impact of antimicrobial agents on aquatic ecosystems.

## 6. CHALLENGES AND FUTURE DIRECTIONS

While antimicrobial textiles offer significant benefits, ensuring their safety and biocompatibility remains a challenge. Key challenges include:

- Balancing Efficacy and Safety: Developing antimicrobial agents that are effective against pathogens but do not pose risks to human health or the environment is a significant challenge.
- Regulatory Harmonization: There is a need for harmonized global regulations to ensure consistent safety standards across different regions.
- Consumer Awareness: Educating consumers about the potential risks and benefits of antimicrobial textiles is crucial for informed decision-making.
- Sustainable Alternatives: Research into sustainable, biodegradable antimicrobial agents that minimize environmental impact while ensuring safety is a growing area of interest.

## 7. CONCLUSION

The use of antimicrobial agents in textiles offers considerable benefits in terms of infection control, odor management, and overall hygiene. However, the safety of these agents remains a critical concern. Synthetic antimicrobial agents, such as silver nanoparticles and triclosan, have been shown to pose risks related to cytotoxicity, carcinogenicity, and environmental toxicity. Natural antimicrobial agents, while generally safer, can still cause allergic reactions and variable efficacy issues. Addressing these concerns requires a balanced approach that considers both the effectiveness and safety of antimicrobial agents. Enhanced regulatory frameworks, increased consumer awareness, and research into sustainable alternatives are essential for minimizing potential risks associated with antimicrobial textiles. Future innovations should focus on developing safer, environmentally friendly antimicrobial solutions that protect both human health and the environment.



## REFERENCE

- [1] Gao, Yuan, and Robin Cranston. "Recent advances in antimicrobial treatments of textiles." *Textile research journal* 78.1, 60-72, 2008.
- [2] Kumar, Majeti NV Ravi. "A review of chitin and chitosan applications." *Reactive and functional polymers* 46.1, 1-27, 2000.
- [3] Balasubramaniam, Bhuvaneshwari, et al. "Antibacterial and antiviral functional materials: chemistry and biological activity toward tackling COVID-19-like pandemics." *ACS Pharmacology & Translational Science* 4.1, 8-54, 2020.
- [4] Blevens, Melissa S., et al. "Cloth face masks containing silver: evaluating the status." *ACS Chemical Health & Safety* 28.3, 171-182, 202.
- [5] Urban-Chmiel, Renata, et al. "Antibiotic resistance in bacteria—A review." *Antibiotics* 11.8 1079, 2022.
- [6] Choi, Changyong, Joung-Pyo Nam, and Jae-Woon Nah. "Application of chitosan and chitosan derivatives as biomaterials." *Journal of Industrial and Engineering Chemistry* 33 , 1-10. 2016.
- [7] Aichele, Peter, et al. "Peptide antigen treatment of naive and virus-immune mice: antigen-specific tolerance versus immunopathology." *Immunity* 6.5, 519-529, 1997.
- [8] Adamson, Peter, et al. "Time trends in the registration of Hodgkin and non-Hodgkin lymphomas in Europe." *European Journal of Cancer* 43.2, 391-401, 2007.
- [9] Silva, Ana Paula S., et al. "Dietary fatty acids early in life affect lipid metabolism and adiposity in young rats." *Lipids* 41.6, 535-541, 2006.
- [10] Lang, Iain A., et al. "Association of urinary bisphenol A concentration with medical disorders and laboratory abnormalities in adults." *Jama* 300.11, 1303-1310, 2008.
- [11] Markowski, Vincent P., et al. "Tissue-specific and dose-related accumulation of arsenic in mouse offspring following maternal consumption of arsenic-contaminated water." *Basic & Clinical Pharmacology & Toxicology* 108.5, 326-332, 2011.
- [12] Markowski, Vincent P., et al. "Tissue-specific and dose-related accumulation of arsenic in mouse offspring following maternal consumption of arsenic-contaminated water." *Basic & Clinical Pharmacology & Toxicology* 108.5, 326-332, 2011.
- [13] Ali, Hazrat, Ezzat Khan, and Muhammad Anwar Sajad. "Phytoremediation of heavy metals—concepts and applications." *Chemosphere* 91.7, 869-881, 2013.
- [14] Prestinaci, Francesca, PatrizioPezzotti, and Annalisa Pantosti. "Antimicrobial resistance: a global multifaceted phenomenon." *Pathogens and global health* 109, 309-318, 2015.
- [15] Sartorius, Benn, et al. "The burden of bacterial antimicrobial resistance in the WHO African region in 2019: a cross-country systematic analysis." *The Lancet Global Health* 12.2 , , e201-e216, 2024.
- [16] Ferdinand, Angeline S., et al. "Development of a cross-sectoral antimicrobial resistance capability assessment framework." *BMJ Global Health* 9.1, e013280, 2024.
- [17] Salam, MdAbdus, et al. "Antimicrobial resistance: a growing serious threat for global public health." *Healthcare*. Vol. 11. No. 13. MDPI, 2023.
- [18] Umeda, Yumi, et al. "Induction of peroxisome proliferation in the liver of biphenyl-fed female mice." *Journal of occupational health* 46.6, 486-488, 2004.
- [19] Umeda, Yumi, et al. "Carcinogenicity of biphenyl in mice by two years feeding." *Journal of veterinary medical science* 67.4, 417-424, 2005.

- [20] Ramm, Susanne, Melanie Adler, and Vishal S. Vaidya. "A high-throughput screening assay to identify kidney toxic compounds." *Current protocols in toxicology* 69.1, 9-10, 2016.

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Ms. J J Gayathri] specializes in research-driven writing with a focus on technical textiles, particularly exploring innovative solutions for sustainability. My work is characterized by a deep understanding of material science, environmental impact, and the intersection of technology and sustainability in the textile industry. Through a clear and concise style, I aim to make complex concepts accessible to both academic and industry audiences.

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