An In-depth Investigation of Emerging Nanomaterial Technologies for Antimicrobial Textiles

Abstract

Pharmaceutical companies have shifted towards the production of non-traditional drugs and alternatives for antimicrobial purposes. Nanotechnology industries have also started investing in the development of new nano-materials which can fight against the bacteria that can resist traditional antibiotics. It has not only impacted the medicine industry but also impacted the textile industry. In the recent past, many scientific findings in the context of nanoparticles have led to increased interest in their potential use as antibacterial and antiviral agents. The reason behind conducting the present study is the growing significance of nanomaterials in the textile industry and the need for understanding the types of nanomaterials, their functionalization, applications and toxicity considerations. In this study, different types of nanomaterials have been discussed, along with the integration of antimicrobial nanoparticles, applications, toxicity associated with nanoparticles, and prospects, all within the context of textiles.

Keywords: Nanomaterial, Nano-Particles, Anti-Microbial, Anti-Bacterial, Anti-Viral, Textile

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1. Introduction to the Study

The very first living organism to exist on the earth was Bacterium. It has adapted in many ways since then (Woese, 1987). Antibiotics were discovered in the 20th century, and it is one of the biggest medical achievements in history. Zaffiri et al. (2012) wrote that the concept of antibiotics was discovered with the discovery of Salvarsan, which is one of the first medicines that had the capability to cure syphilis (an infectious disease). Salvarsan proved to be non-toxic for the patients. Research into the field of antibiotics was not started until 1928 when the accidental discovery of penicillin took place. Alexander Fleming discovered penicillin. Antibiotics became a highly researched topic between the 1950s and 1960s, which is known to be the “golden age” in this context (Zaffiri et al., 2012). Between 1930 and 1962, 20+ new classes of antibiotics were produced (Refer to Figure 1), however, bacteria became more resistant as they evolved. Therefore, it became a challenge for the pharmaceutical industry to produce new molecules with antibacterial activity.

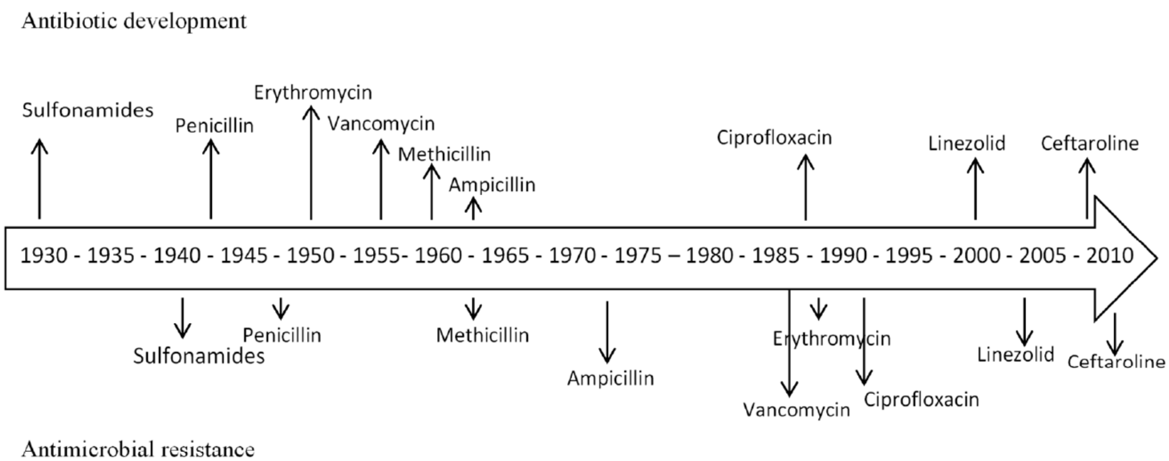

Figure 1: Antibiotics Evolution: Development vs. Resistance (Sánchez-López et al., 2020)

According to the World Health Organization (WHO), there is a real possibility of a pre-antibiotic era. WHO also mentions that there might be an existence of 12 emerging superbugs resistant to many antibiotics (Hall et al., 2018). According to estimates, 230 million people will be affected due to antimicrobial resistance by the year 2050, which will result in 10 million deaths annually (Fong, 2023). This situation is taking a drastic negative turn because, since 1987, the discovery of novel classes of antimicrobials has slowed down. This poses a risk of getting back to the 'medical dark ages' for the world (Salam et al., 2023). This is why it is necessary to develop novel alternative approaches that can effectively deal with the crisis of pathogens that show antimicrobial resistance.

The interests of pharmaceutical companies have shifted towards the production of non-traditional drugs and alternatives (Kirienko et al., 2019). Wani and Ahmad (2023) noted that the nanotechnology industries have also started investing in the development of new nano-materials which can fight against the bacteria that can resist traditional antibiotics. Nanomaterials contain special physical and chemical properties which have high stability, low density, and high specific surface area (Khan et al., 2019). Nanoscience can be considered as a significant technological advancement of this century. It has not only impacted the medicine industry but also impacted the textile industry (Lam et al. 2018). Gulati et al. (2022) wrote that the fabrics are now being made in a way that integrates nanoparticles. Moreover, continuous evolution with the development of nanostructured fabric surfaces and nanofibers is being seen. Sawhney et al. (2008) wrote that nanofibres are stain-resistant, self-cleaning, antistatic, antimicrobial, UV protective, etc. In the recent past, many scientific findings in the context of nanoparticles have led to increased interest in their potential use as antibacterial and antiviral agents (Zille et al., 2014). Functionalization can enhance antimicrobial properties which can help prepare antimicrobial textiles.

The reason behind conducting the present study is the growing significance of nanomaterials in the textile industry and the need for understanding the types of nanomaterials, their functionalization, applications and toxicity considerations. Nanomaterials have many special properties like high surface area, enhanced strength, and improved conductivity, which makes them an ideal option for different textile applications, like fabric coatings, sensors, and smart textiles (Sawhney et al., 2008).

Nanomaterials may have a lot of benefits, but they also come with a concern regarding their toxicity. Therefore, it is important to thoroughly examine their safety implications. The present study aims to explore all the relevant aspects in detail and derive valuable insights for researchers, industry professionals, and policymakers who are involved or interested in the development and regulation of nanomaterial-based textiles. It is also important to understand the present state of the use of nanomaterials in textiles, as well as its future direction. This will guide the research efforts and foster innovation in this field. In this study, different types of nanomaterials have been discussed, along with the integration of antimicrobial nanoparticles, applications, toxicity associated with nanoparticles, and future prospects, all within the context of textiles.

2. Antimicrobial Textile and Clothing

Textiles are an important part of society as it is a need for humans. Pieces of cloth may contain some microbes, which might affect the human skin once they come in contact with it. This has been recently discussed as clothing microbiology (Hassan et al., 2019). During the Second World War, as written by Rajendran (2010), antimicrobials were also being used to prevent textiles from rotting. Antibiotics were being used consistently to protect fabrics from being colonized by the microbes, many military fabrics were treated with antimony salts, copper and a mixture of chlorinated waxes. This also helped in increasing the durability of textiles.

The antimicrobial textile market dynamically expanded with an increasing concern for human protection, and the rapid development of health, safety and environmental legislation. The main products flourishing in this market were sutures, bandages, specialized wound dressings, gauze, masks, surgical gowns and hospital linen (Sánchez-López et al., 2020). According to Sharmin et al. (2021), several chemicals have been used as a part of the industrial practice, to obtain antibacterial activity on textiles. Such chemicals are toxic to humans, and cannot easily degrade in the natural environment. Due to this, the textile industry is still searching for eco-friendly processes that do not involve the use of toxic textile chemicals. Nanoparticle-based coatings are more commonly used in both natural and synthetic textiles, among the other available compounds (Rawat et al., 2023).

Nanotechnology has seen a lot of advancements recently, which has highlighted different ways to improve the efficiency of antimicrobial therapies. It has been proven that nanomaterials and nanoparticles have a high antimicrobial activity against bacteria, viruses, fungi and other microorganisms. A nanoparticle's antimicrobial activity is affected by a lot of variables like chemistry, particle size and shape, surface-to-volume ratio, and zeta potential (Ahmed et al., 2024; Mercan et al., 2022).

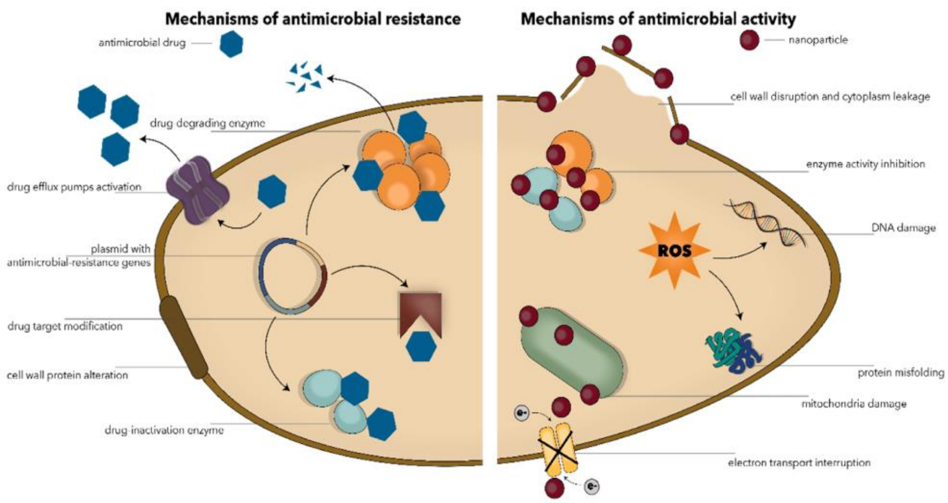

Figure-2: Mechanisms involved in the antimicrobial resistance (left) and the antimicrobial activity of nanoparticles (right). (Spirescu et al., 2021)

Nanostructured antimicrobial textiles have gotten a lot of attention in the last few years because of their superior advantages. The demand for antimicrobial textiles and clothing is growing intending to provide a more healthy and comfortable environment to people. The value of the global antimicrobial textiles market in 2019 was $10.0 billion. According to Allied Market Research (2020), this market is projected to reach a whopping $18.2 billion by the year 2027, with a CAGR of 7.4% from 2020 to 2027. Increasing concerns regarding health and hygiene among people have positively affected the demand for antimicrobial textiles. In the last few years, antimicrobial textiles have become more popular because of their ability to prevent infection transmission, especially in medical environments.

3. Antimicrobial Textile and Clothing using Nanomaterial

A paradigm shift has been seen in the textile industry with the introduction of Nanotechnology. Nanotechnology has highly impacted antimicrobial nanoparticles have unique properties like silver, zinc oxide, and titanium dioxide, which can be leveraged by manufacturers to develop imbue fabrics with antimicrobial capabilities (Wang et al., 2017). The antimicrobial properties of nanoparticles allow them to inhibit the growth and proliferation of bacteria, fungi, and other harmful microorganisms on the surface of textiles. This functionality is highly beneficial in environments like hospitals, medical care centers, food processing industries, etc. as it helps in maintaining hygiene and preventing the spread of infections (Zille et al., 2014).

Different methods can be used to integrate antimicrobial nanoparticles into textiles. These methods include coating, impregnation, or functionalization (Gulati et al., 2022), which have been explained in detail in the subsections below. All these methods have their own set of advantages in terms of effectiveness, durability, and ease of application. For example, nanoparticle coatings protect the textile surface by forming a layer on it. However, impregnation embeds nanoparticles in the fabric structure of textiles. The main advantage of the functionalization method is to enable the chemical bonding of nanoparticles to textile fibres, which ensures long-lasting antimicrobial efficacy (Singh, 2021). Such strategies ensure the safety of customers as well as the environment as they improve the antimicrobial performance of textiles along with minimizing the risk of nanoparticle leaching or migration (Buşilă et al., 2015).

The benefits of antimicrobial textiles that have nanoparticles go beyond their hygiene-improving properties. Such fabrics also help in maintaining freshness, reducing odor, and preventing microbial contamination which is why they are being highly used in everyday items like clothing, bedding, and personal protective equipment (McArthur et al., 2012). In the healthcare industry and medical environments, antimicrobial nanoparticle-treated textiles prevent infection transmission which ensures patient safety. Antimicrobial textiles have a huge potential, but it is important to research more about optimizing nanoparticle formulations, manufacturing processes, and regulatory standards to get solutions to the problems regarding efficacy, safety, and environmental impact (Hassan et al., 2019). This will help in unlocking the full potential of nanotechnology in the textile industry.

An antimicrobial fabric may be the leaching type or non-leaching type, depending on the treatment and antimicrobial compound used (Ibrahim et al., 2021). Windler et al. (2013) said that antimicrobial fabric can also be biocide or biostatic, depending on its mechanism. Biocides tend to kill the microorganisms, while biostatics tend to inhibit their growth. Biocides and biostatics can also be further categorized, depending on their target microorganisms- bacteria, fungi, or viruses. Biostatic fabrics are generally preferred for clothing items because they preserve the skin's natural bacterial flora and they don't adversely affect the human skin. Meanwhile, the biocidal fabric is generally used for medical and environmental applications (Ibrahim et al., 2021; Windler et al., 2013; Rajendran, 2010).

4. Processes for Integration of Antimicrobial Nanoparticles into Textiles

As mentioned earlier, the three most commonly used processes for integrating antimicrobial nanoparticles into textiles are coating, impregnation, and functionalization (Gulati et al., 2022). These approaches allow flexibility in customizing the antimicrobial properties of textiles to particular applications, which ensures protection against microbial contamination, along with maintaining durability and safety for all users (Sawhney et al., 2008). These methods have different advantages and considerations depending on many factors like desired antimicrobial efficacy, fabric type, manufacturing process, and the intention behind the use of antimicrobial textile products.

4.1 Coating

In this method, a layer of antimicrobial nanoparticles is coated onto the surface of the textile fabric. Many techniques can be used to do so, some of which include spraying or roll-to-roll coating (Tania et al., 2021). When it comes to the spraying technique, a solution of suspended antimicrobial nanoparticles is gently sprayed on the surface of textile fabric, which then forms a uniform layer of the solution coating (Tania et al., 2021). Gulati et al. (2022) mentioned that the textile fabric is passed through a series of rollers in the Roll-to-roll coating technique, wherein the nanoparticle solution comes into contact with the fabric for efficient coating. The coated fabric is left to dry or cure after the application of the solution to make sure that the coated nanoparticle layer remains adhesive and durable. Some new antibacterial processing techniques include pad-dry-cure, spraying, exhaust methods, screen-printing, surface modification and many others. (Tania et al., 2021).

4.2 Impregnation

In this method, according to Raza et al. (2015), an antimicrobial nanoparticle is embedded into the fiber structure. This is done by completely immersing the textile fiber into a solution of suspended nanoparticles. This allows nanoparticles to enter the fiber matrix. This method can also be performed using an extrusion or spinning process, to ensure homogeneous distribution of nanoparticles within the structure of textile fiber. There are many advantages of this method, some of which are- better durability and enhanced longevity of antimicrobial activity (Raza et al., 2015). This happens because the nanoparticles are securely embedded within the fiber, reducing the overall risk of leaching or efficacy loss over a period of time.

4.3 Functionalization

In this method, the nanoparticles are chemically bonded with the surface of the textile fabric. Surface activation or modification is done in the initial stage of this method to create reactive sites on the surface of the fabric (Singh, 2021). This facilitates the attachment of nanoparticles.

Adhesion between the textile fabric surface and nanoparticles can be ensured through several chemical agents or coupling agents. Nanoparticles tend to become a part of the fabric after they're chemically bonded with it, providing antimicrobial activity for a long time (Morais et al., 2016). Gulati et al. (2022) opined that the coverage in this method is uniform because it allows precise control over the nanoparticle placement and distribution. It also ensures the optimized performance of the fabric. There is a low possibility of detachment or degradation of chemically bonded nanoparticles in the fabric structure during washing or prolonged use which leads to sustained antimicrobial activity.

5. Nanomaterial Used for Making Textile Antimicrobial

Antimicrobial textiles are developed through two main categories of compounds- organic and non-organic nanomaterials (Abdul-Reda Hussein et al., 2023; Buşilă et al., 2015). Organic nanomaterials include compounds which are derived from natural sources or carbon-based polymers. For example, Chitosan nanoparticles are one of the key organic compounds (Li et al., 2021). Chitosan is a derivative of chitin which is significantly found in crustacean exoskeletons. It shows many antimicrobial properties because of its cationic nature. Microbial cell membranes are easily disrupted by Chitosan nanoparticles through electrostatic interactions, leading to the prevention of microbial growth and proliferation. Many techniques can be used to apply nanoparticles onto textile substrates. These techniques include dip-coating, pad-dry-cure, or layer-by-layer assembly, which ensure a durable antimicrobial functionality to textiles without hampering their tactile properties. Chitosan particles are highly biocompatible and biodegradable, which makes them a suitable option for eco-friendly textile applications. This helps in taking care of the sustainability concerns and the environmental impact of antimicrobial textiles (Li et al., 2021).

In contrast to this, non-organic nanomaterials used in antimicrobial textiles include inorganic compounds like metals, metal oxides, and metal salts, which are known for their potent antimicrobial efficacy (Abdul-Reda Hussein et al., 2023). Sánchez-López et al. (2020) noticed that Silver nanoparticles have a broad spectrum of antimicrobial activity and they perform well even at low concentrations, therefore, they're one of the main non-organic compounds. They function by releasing silver ions as soon as they interact with microbial contaminants or moisture. This disrupts many important cellular processes within microorganisms, thereby inhibiting microbial growth. Silver nanoparticles make textiles resistant to bacterial colonization, which makes them a suitable option for applications in healthcare textiles, protective clothing, and food packaging. Another key non-organic compound is Zinc Oxide which is known for its photocatalytic activity (Sánchez-López et al., 2020). When exposed to ultraviolet radiation, Zinc Oxide nanoparticles generate reactive oxygen. This damages microbial cells by exerting oxidative stress on them. Textiles incorporating Zinc Oxide nanoparticles have better antimicrobial efficacy, especially under UV irradiation. This is why it is a suitable option for outdoor applications or environments where ample sunlight is present to activate the zinc oxide nanoparticles.

Various factors are considered while choosing between organic and non-organic nanomaterials for antimicrobial textiles. Some of these factors include the desired efficacy, environmental considerations, and regulatory constraints (Gulati et al., 2022). Organic nanomaterials, especially Chitosan nanoparticles, generally have many benefits in terms of biocompatibility, biodegradability, and sustainability which makes them a suitable choice as per the emerging trends towards more eco-friendly textile production (Li et al., 2021). Non-organic nanomaterials like silver nanoparticles, tend to show a higher antimicrobial efficacy at low concentrations, however, concerns related to toxicity and environmental impact make it necessary to make sure they're being applied appropriately and thoroughly regulated (Sánchez-López et al., 2020). Organic and non-organic nanomaterials in antimicrobial textiles are chosen after completely evaluating their performance attributes, environmental implications, and regulatory frameworks to make sure that their use brings efficacy as well as sustainability to the textiles.

Textiles can be made anti-microbial by using various nanomaterials, out of which Chitosan, Silver nanoparticles and their oxides, Copper oxide, and Zinc oxide nanomaterials are used very commonly. A comparison is drawn below, based on their advantages, toxicity, applications, and future prospects.

6. Comparative Analysis

6.1 Chitosan Nanoparticles

Chitosan nanoparticles have unique properties and potential benefits for textiles, therefore, they have been getting a lot of attention in this regard. The key advantages of these nanoparticles are their biocompatibility and biodegradability, which makes them an eco-friendly choice for textile treatments (Buşilă et al., 2015). According to Teixeira-Santos et al. (2021), Chitin is a natural polymer, significantly found in crustacean shells, which leads to the formation of chitosan nanoparticles. It is a sustainable alternative to synthetic antimicrobial agents. Chitosan nanoparticles have many antimicrobial properties rooted in their ability to damage microbial cell membranes for inhibiting their growth. This allows the nanoparticles to show antimicrobial activity against different microorganisms like bacteria, fungi, and viruses, thereby, making them a choice for many antimicrobial textile applications (Li et al., 2021).

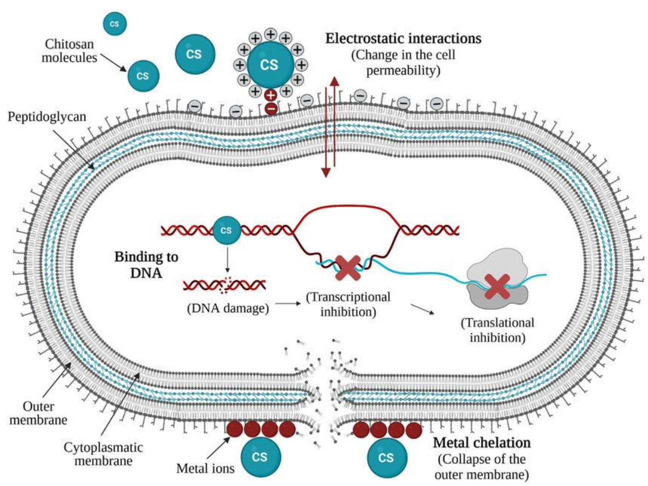

Figure-3: Antibacterial activity of chitosan (Teixeira-Santos et al., 2021)

Li et al (2021) write that Chitosan nanoparticles face many challenges regardless of their promising attributes. These challenges are related to their stability and efficacy under certain conditions. Stability and efficacy are affected by different factors like pH, temperature, and environmental exposure, which limits the practical application of Chitosan nanoparticles in certain conditions (Li et al., 2021). They are not being adopted at large in the industry because of their reproducibility and scalability. Research and innovation are required to address these challenges and develop new formulations and fabrication techniques which can improve the stability, efficacy, and versatility of chitosan nanoparticles in the context of antimicrobial textiles.

Chitosan nanoparticles are considered to be non-toxic to humans, therefore, they are generally used in biomedical and food applications. Regardless of that, it is important to evaluate the potential cytotoxicity, genotoxicity, and immunotoxicity of Chitosan nanoparticles to ensure the safety levels of chitosan nanoparticle-treated textiles for the use of consumers (Teixeira-Santos et al., 2021). There are concerns regarding allergic reactions or sensitization to chitosan derivatives, which are addressed through risk assessment and regulatory scrutiny. Chitosan nanoparticles still have a lot of potential for sustainable antimicrobial textile treatments and can be effectively applied in healthcare, personal protective equipment, and functional apparel (Buşilă et al., 2015).

Chitosan nanoparticles can be used at full potential in the future, after overcoming their existing limitations. The advancement in nanoparticle synthesis, functionalization, and application techniques are expected to improve their stability, efficacy, and versatility.

6.2 Silver Nanoparticles and Its Oxides

Silver nanoparticles and their oxides also have a lot of advantages and they are considered to be versatile antimicrobial agents (Xi et al., 2020). They can potentially be used in many fields, including textiles. Raza et al. (2015) noted that silver nanoparticles show antimicrobial activity at low concentrations which makes them highly effective against microorganisms, such as bacteria, fungi, and viruses. They have broad-spectrum activity against microorganisms, therefore, they are suitable for conditions where microbial contamination poses a significant risk, like healthcare textiles, food packaging, and water purification systems. Silver oxide nanoparticles have a higher stability and efficacy than traditional silver nanoparticles (Buşilă et al., 2015). Their antimicrobial efficacy also increases due to their ability to control the size, shape, and surface properties. This makes them more versatile for antimicrobial textiles.

Risk assessment as well as careful consideration is still required in the context of their potential toxicity and environmental impact. Silver nanoparticles reportedly show cytotoxic effects on mammalian cells and aquatic organisms, which raises concerns related to their overall ecological impact in the long run (Gulati et al., 2022). Silver nanoparticles can accumulate in the environment and can lead to ecosystem disruption and bioaccumulation in food chains (Xu et al., 2020). This makes it important to implement regulatory frameworks and protocols to make sure that the silver nanoparticles are responsibly deployed and disposed of. It is also necessary to develop sustainable methods of their synthesis and recycling technologies in order to address the environmental concerns and use these nanoparticles in textile production in an eco-friendly manner.

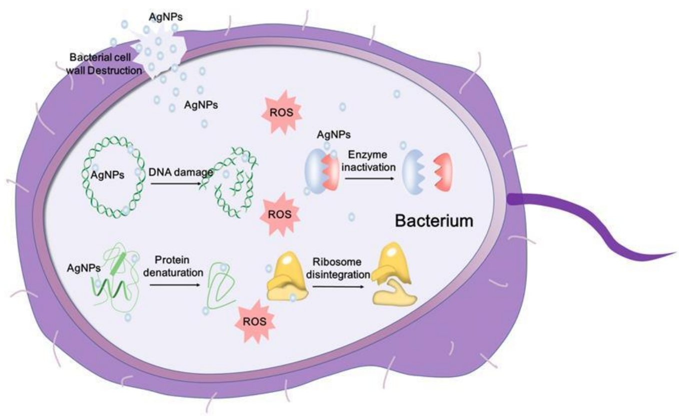

Figure-4: Mechanisms of Silver Nanoparticles against bacteria (Xu et al., 2020)

When it comes to applications, silver nanoparticles are extensively used in healthcare textiles, such as wound dressings, surgical gowns, and medical uniforms, because they prevent healthcare-associated infections and ensure patient safety (Sánchez-López et al., 2020). Similarly, they are also used in functional apparel, sportswear, and personal protective equipment in order to inhibit microbial growth, and also maintain hygiene. They also offer better stability, therefore, they have increased the scope of silver-based antimicrobial textiles in diverse environmental conditions.

By addressing the present challenges and advancement in the synthesis, applications and regulation of silver nanoparticles, their future prospects in the antimicrobial textile industry can be highly positive. It is important to research more about the sustainable synthesis methods, fabrication techniques, and recycling technologies of silver nanoparticles to reduce their overall impact on the environment.

6.3 Copper Oxide

Another popular antimicrobial agent is copper and its oxides. It has many advantages and potential applications in different sectors, including antimicrobial textiles. Sánchez-López et al. (2020) found that copper nanoparticles show broad-spectrum activity against microorganisms such as bacteria, fungi, and viruses, which is one of its most important advantages. This makes them suitable for industries where microbial contamination poses a significant risk like healthcare textiles, food packaging, and water purification systems (Sharmin et al., 2021). According to Ingle et al. (2014), copper nanoparticles have antimicrobial properties that last for a prolonged time because they are resilient to environmental conditions. This also makes them suitable for application in diverse settings. Copper oxide offers better stability and efficacy as compared to traditional copper nanoparticles. The versatility and efficacy of copper nanoparticles increase with the fact that their size, shape, and surface properties can be controlled.

Copper nanoparticles can be potentially toxic and have a negative impact on the environment, thereby making it necessary to assess risks and ensure careful consideration. They reportedly have cytotoxic effects on mammalian cells and aquatic organisms, which raises more concerns about their impact on the ecology, in the long run (Ingle et al., 2014). Khan et al. (2019) wrote that copper nanoparticles can disrupt the ecosystem with their accumulation in the environment and bioaccumulation in food chains. Therefore, it is necessary to ensure risk assessment of these nanoparticles and implementation of regulatory framework for their use, in order to ensure their responsible and safe use in textiles. Promoting eco-friendly use of copper nanoparticles in antimicrobial textile production is also important, thereby imposing a need to look for more sustainable synthesis methods and recycling technologies (Buşilă et al., 2015).

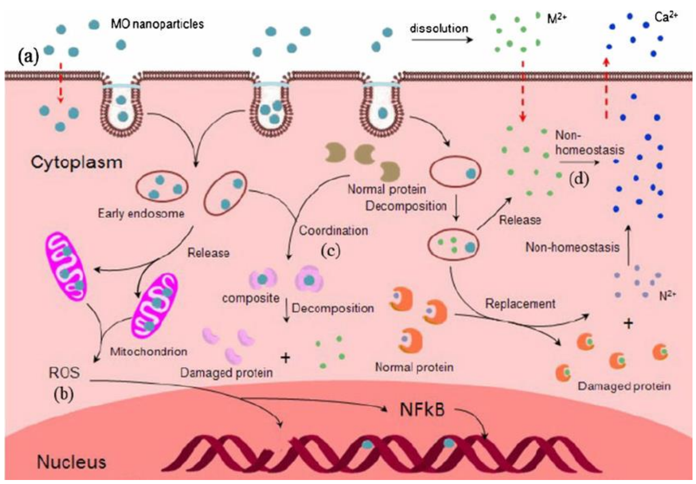

Figure-5: Different Pathways by Copper Oxide Nanoparticle (Ingle et al., 2014)

Copper nanoparticles are highly used in healthcare textiles, like wound dressings, surgical gowns, and medical uniforms because they prevent the spread of healthcare-associated infections and ensure patient safety (Gulati et al., 2022). They have a higher application in antimicrobial textiles as they are versatile and exhibit high efficacy. Copper nanoparticles inhibit microbial growth; therefore, they are also used in textiles related to functional apparel, sportswear, and personal protective equipment (Sharmin et al., 2021). The scope of application for copper-based antimicrobial textiles increases with its enhanced stability and efficacy under different environmental conditions.

The future prospects of copper nanoparticles in antimicrobial textiles highly depend upon overcoming the present challenges in its use and advancement in its synthesis, application, and regulation. It is important to continue the research for sustainable synthesis methods, fabrication techniques, and recycling technologies for copper nanoparticles in order to reduce its environmental impact and make sure that it is being used in textiles in an eco-friendly manner.

6.4 Zinc Oxide

Zinc nanoparticles and their oxides are considered to be notable antimicrobial agents because of their diverse applications across different sectors like textiles, and their advantages. They are highly antimicrobial when activated by ultraviolet (UV) radiation (Abebe et al., 2020). They show photocatalytic properties, which generate reactive oxygen species that damage the microbial cells by inducing oxidative stress on them. This, in turn, inhibits the growth of microorganisms (Buşilă et al., 2015). Zinc nanoparticles also have a broad-spectrum activity against microorganisms, making them valuable for applications where there's a higher risk of microbial contamination, like healthcare textiles, food packaging, and water treatment systems. Moreover, they are less toxic, with a low environmental impact, which makes them a suitable option for sustainable textile applications.

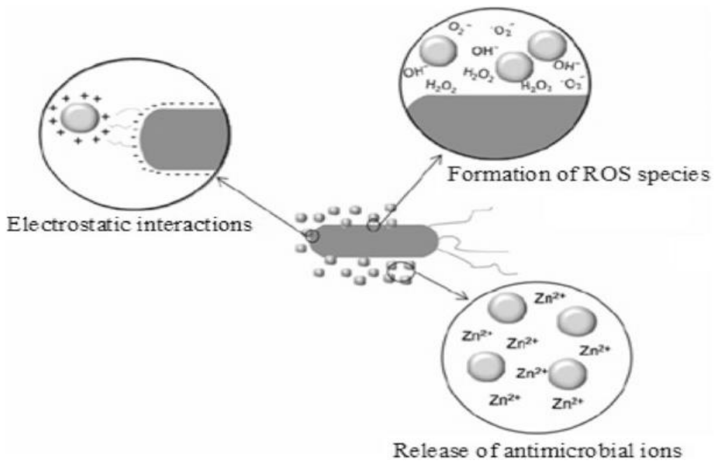

Figure-6: Different mechanisms of antimicrobial activity of ZnO (Abebe et al., 2020)

Careful consideration and optimisation are required when it comes to the non-UV conditions, in the context of Zinc nanoparticles. Their stability and efficacy face challenges under such conditions. When UV radiation is not present, Zinc nanoparticles tend to show low antimicrobial activity (Gulati et al., 2022). Therefore, they cannot be effectively applied in indoor or low-light environments. Zinc nanoparticles can potentially be toxic and have an impact on the environment, which needs to be evaluated and assessed for any future risks. It becomes necessary to implement regulatory frameworks and perform risk assessments to mitigate their potential health and environmental risks. In addition to that, the development of sustainable synthesis methods and recycling technologies is also important for minimising the overall environmental impact of Zinc nanoparticles and promoting their eco-friendly use in antimicrobial textile production (Abebe et al., 2020).

Zinc nanoparticles are extensively used in antimicrobial textiles because of their efficacy and versatility. They are generally used in healthcare textiles, such as wound dressings, surgical gowns, and medical uniforms, as they have antimicrobial properties which prevent the spread of healthcare-associated infections and ensure patient safety (Buşilă et al., 2015). They are known to inhibit microbial growth, which makes them suitable for use in functional apparel, sportswear, and personal protective equipment incorporated for maintaining hygiene in high-contact environments.

Zinc oxide nanoparticles have photocatalytic properties which makes them suitable for use in outdoor textiles or environments where ample sunlight is present. This expands their scope of applications in antimicrobial textiles (Abebe et al., 2020). If the existing challenges related to Zinc nanoparticles are effectively addressed, and constant innovation in their synthesis, application, and regulation is done, their future prospects will be highly positive.

7. Conclusion

Antimicrobial textiles are developed with both synthetic and natural fabrics. Such antimicrobial properties can be added to textiles by applying chemicals, metal-based nanoparticles, plant & animal-derived compounds, dyes and mordants. After introducing the fabrics for antimicrobial properties, the coated fabrics can perform antimicrobial activities against micrograms like bacteria, fungi and viruses. Limited research is available in the context of the environmental impact of synthetic chemicals and metal nanoparticle-based antimicrobial textiles, which is why, regardless of their effectiveness, they could be a threat to the environment. Therefore, it is important to conduct further research in this aspect to explore the potential for natural antimicrobial agents. Domestic antimicrobial textiles are becoming more popular and their use is increasing, which makes it necessary to have well-planned and managed disposal and treatment systems for antimicrobial textiles. Finding a solution for the problem related to their disposal is important to make sure that this doesn’t become a severe problem like plastic waste management.

Concluding this comprehensive investigation, it can be said that nanomaterial technologies show high potential in antimicrobial textile development. By understanding and exploring different nanoparticles, like, Chitosan nanoparticles, silver nanoparticles and their oxides, copper nanoparticles, and zinc nanoparticles and their oxides, their benefits and applications are highlighted. Their key advantages like antimicrobial efficacy, broad-spectrum activity, and low toxicity have been highlighted along with their extensive application in healthcare textiles, food packaging, and water treatment. Continuous research is being performed to address the limitations of nanoparticles and find opportunities for them regardless of challenges like stability, efficacy under certain conditions, and regulatory concerns. Nanomaterial-based antimicrobial textiles can be responsibly used and enhanced with a strong collaboration between academia, industry, and regulatory agencies, which will lead to its advancement and innovation, along with ensuring its regulatory compliance. Overall, this study highlights the significant role that nanomaterial technologies play in reducing microbial contamination in textiles and promises a positive future for the scope of its application and advancement.

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