A REVIEW ON COMPARATIVE ANALYSIS OF ANTIMICROBIAL ACTIVITY OF DIFFERENT METAL AND METAL OXIDE NANOPARTICLE-BASED FABRIC

By

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Declaration

It is hereby declared that

1. The thesis submitted is my own original work while completing degree at BRAC University.
2. The thesis does not contain material previously published or written by a third party, except where this is appropriately cited through full and accurate referencing.
3. The thesis does not contain material which has been accepted, or submitted, for any other degree or diploma at a university or other institution.
4. I have acknowledged all main sources of help.

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Abstract

Nanoparticles have managed to revolutionize many different sectors and industries, such as biomedicine, pharmaceuticals, electrical appliances, agriculture, food, biosensors, etc. Nanoparticles have also successfully proven its ability to coat textiles and thus impart antimicrobial properties onto the fabrics. This review concerns with antimicrobial activity of fabrics coated with nanoparticles of metals and metal oxides, namely silver, copper oxide, zinc oxide and titanium oxide, using various different methods of synthesis, modification and subsequent coating. Descriptive comparative analysis of the antimicrobial efficiency, durability and economic factors between the four nanoparticles suggest that copper oxide nanoparticles have the most promising activity as impregnating material for textiles, owing to its broad-spectrum antibacterial, antiviral and antifungal activity. There is scope for further research on the antiviral efficiency of copper oxide nanoparticles, particularly against coronaviruses or surrogate coronaviruses, especially during this ongoing COVID-19 pandemic.

Keywords: Nanoparticles; silver; copper oxide; zinc oxide; titanium oxide; antimicrobial properties

Dedicated to my loving parents

Farhana Haq and Harisur Rahman,

my brother Tahmid and my sister-in-law Fairooz

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List of Acronyms

AgNP	Silver nanoparticle
CuONP	Copper oxide nanoparticle
ZnONP	Zinc oxide nanoparticle
TiO_2NP	Titanium oxide nanoparticle
CMC	Carboxymethyl chitosan
CS	Chitosan
BR	Bacterial reduction rates
FTIR	Fourier transform infrared spectroscopy
EDX	Energy dispersive X-ray spectroscopy
TEM	Transform electron microscopy
SEM	Scanning electron microscopy
HR-TEM	High resolution transform electron microscopy
XRD	X-ray Diffraction
XPS	X-ray photoelectron spectroscopy
TGA	Thermogravimetric analysis
DLS	Dynamic light scattering
AFM	Atomic force microscopy
MAP	Elemental mapping analysis
HBP-NH_2	Amino-terminated hyperbranched polymer
p-NIPAM	Poly-N-Isopropylacrylamide
K-S1 & K-S3	Knit fabric samples 1&3
UPF	Ultraviolet protection factor
BFE	Bacterial filtration efficacy

ΔP	Differential pressure
SDS	Sodium dodecyl sulphate
CTAB	Cetrimonium bromide
SPE	*Salvadora persica* extract

Chapter 1

Introduction

Diseases have been a part of human life since the beginning of time. The immune system is the one that protects us from all kinds of foreign substances, and develops immunity and memory against those foreign antigens. Sometimes our immune system can attack our own antigens, a phenomenon which gives rise to autoimmune reactions leading to autoimmune disorders, however, the body can also develop tolerance to those antigens, a phenomenon called self-tolerance. Aside from these, the bigger plethora of diseases that can completely tame us include cancer, cardiovascular diseases, diabetes, neurological disorders, and many more. Most of these are caused by or aided by pathogenic microorganisms, like bacteria, viruses, fungi, etc. According to the World Health Organization, as of 2019, cardiovascular disease was the leading cause of death worldwide, followed by cancer in the second position (Cardiovascular Diseases, n.d.)

Other than these conventional diseases, infections caused by pathogenic microorganisms have been the center of concern for scientists, researchers, and of course the general population worldwide. Among such infections, the most serious and prevalent is nosocomial infections, or hospital-acquired infections (HAIs). Nosocomial infections, or HAIs, are those that were not present at the time of admitting the patient to the hospital, but appear about 48hrs into the admission or about 30 days after discharge (Revelas, 2012). HAIs are a growing concern and it has been reported that in the USA, HAIs occur in about 4% of all hospital-admitted patients, and are one of the top 10 causes of death (Health Care-Associated Infections | Agency for Healthcare Research and Quality, n.d.). They are spread by a wide range of bacteria, viruses and fungi. Many of these organisms are a part of the commensal flora that coexist in the natural equilibrium with the human body (Singh et al., 2012). In the hospital setting, they spread mostly from the microorganisms harboring in the textiles used by the patients, and also as bedsheets, towels, scrubs, and even the room curtains. This is why it is important that these particular fabrics possess some antimicrobial activity in order to combat these pathogenic microorganisms and protect the transplant patients, immunodeficient patients and others (Tinker, 2010).

A large number of microorganisms are rapidly growing resistance to antibiotics and antimicrobial agents (Perelshtein et al., 2016). In the hospital setting, alcohol-based disinfectants are frequently used on surfaces like tables, counters, bedrails, hands of nurses and doctors, etc. Thus, the hospital textiles serve as a hot spot for the colonization of these pathogenic microorganisms (Holt et al., 2018). Keeping the growing concerns of health and hygiene in mind, intensive research has been going on in developing textiles with antimicrobial properties. New strategies are being considered where metals or metal oxides are being used in order to impart the textiles with desirable antimicrobial properties (El-Nahhal et al., 2020). Antimicrobial textiles provide a few aspects of antimicrobial protection: they help to protect the wearer from pathogenic microbes, prevent over-colonization by bacteria, odor formation and discoloration, the spread of pathogenic microorganism, and lastly, the loss of performance of textiles by developing moulds, mildew, etc (Ferrero & Periolatto, 2012; Holt et al., 2018). Cotton-based textiles are the most widely used worldwide, especially in the medical and healthcare sector, owing to their numerous advantages of biodegradability, moisture absorbability, breathability, comfort to skin, sweat abruption, etc. (Shaheen & Abd El Aty, 2018). It is also widely used as gauge materials for wound dressing (Marković et al., 2018). Cotton is a natural fiber that consists of cellulose with 1,4-Dglucopyranose as its repeat unit (Shahidi, 2016). However, cotton fiber on its own has some negative aspects, such as lack of strength, ease of flammability, low protection to Sun’s ultraviolet (UV) rays, and is extremely hydrophilic (Dhineshbabu & Rajendran, 2016). These properties also make cotton a very suitable surface for growth of pathogenic microorganisms, mainly because of its large surface area and ability to retain moisture (El-Nahhal et al., 2017). So in order to combat these negative sides, nanotechnology has been earning quite the attention over the past decade and more, and has shown some impressive results. Inorganic metal and metal oxides have been used as nanoparticles to coat the surface of cotton fabrics, to provide them with antimicrobial activity. Inorganic metal and metal oxides are widely used because of their selective toxicity towards microbes, high stability, large surface area to volume ratio that increases their efficacy (Rajendran et al., 2013). The nanoparticles have certain mechanisms of action upon the microorganisms that will be further discussed in the later parts of this review.

Therefore, the aim of this review is to focus on and compare the different kinds of modification processes used to produce nanoparticles of metals and metal oxides, namely silver, copper oxide, zinc oxide and titanium oxide, in context of their functionalization on cotton fabrics, the efficacy and durability of their antimicrobial properties, and also keeping in mind about their environmental impacts and cost effectiveness.

Chapter 2

Nanobiotechnology and nanaoparticles in textile industry

According to the peer-reviewed journal Nature Research, nanobiotechnology is defined as "a discipline in which tools from nanotechnology are developed and applied to study biological phenomena, mainly through the use of functional nanoparticles for our own desired purpose". Nanobiotechnology has been extensively used in the textile industry over the last decade and more, in order to produce nanoparticles with antimicrobial properties that can be coated onto different textiles. Various techniques are used for this, such as physical modification, chemical modification and also biological synthesis. This technology can produce modified fabrics with high durability and stability (Rajendran et al., 2013).

In the last few years, there have been booming research in the field of nanoparticles, especially because of their exciting properties of electrical conductivity, magnetic, catalytic, etc. (Maghimaa & Alharbi, 2020). Among the nanoparticles, inorganic metal oxides have earned a great interest because of their antimicrobial activity, owing to their selective toxicity, high surface area to volume ratio, tolerance and resistance to heat and also ability to withstand intense processing steps without being damaged or losing integrity (Fu et al., 2005). Nanoparticles are used in a number of various fields, including but not limited to biomedicine, agriculture, food, cosmetics, textiles (Sathiyavimal et al., 2018), and also in photocatalytic industry, pharmaceutical industry as drug deliver and drug vehicles, biosensors, etc. (Vasantharaj et al., 2019). The use of nanoparticles includes both metals and non-metals, however reports have shown that metal or metal oxide nanoparticles are more active and efficient that the non-metal ones. (Vasantharaj et al., 2019).

The benefits of using nanoparticles are diverse. Nanoparticles show enhanced activity because of their high surface energy and high surface area to volume ratio (Rajendran et al., 2013; Singh et al., 2012), and also their ease of manipulation by either physical, chemical or biological methods. The most commonly used nanoparticles with the hope of imparting antimicrobial activity in textiles are silver nanoparticles (AgNPs), copper/copper oxide nanoparticles (Cu/CuO NPs), zinc oxide nanoparticles (ZnO NPs) and titanium oxide nanoparticles (TiO2 NPs). Intensive research has been conducted using each of these to enhance the antimicrobial effects and also durability of the cotton textiles mainly, among others.

Chapter 3

Silver Nanoparticles (AgNPs)

Silver has been the most widely and extensively studied element since the ancient times (Dastjerdi & Montazer, 2010). Silver is used in a variety of different sectors, including medicine, electronics, household application, toiletries, jewellery, electrical appliances because of its electric and thermal conductivity, and also in the coin-making industry (Salleh et al., 2020; Windler et al., 2013). However, despite all its uses, silver is perhaps the best known for its antimicrobial activity. Owing to this significant characteristic, silver can be modified into silver nanoparticles for use in various biomedical and healthcare sectors, such as patient scrubs, privacy drapes, doctor and nurse scrubs in hospitals, protective clothing, personal clothing as well. The exact mechanism of action of silver is not quite known, however, some studies suggest that the antimicrobial effect of silver is because of its ionic form, Ag+. (Salleh et al., 2020; Windler et al., 2013).

The biological activity of AgNPs is hugely dependent on its size, shape, morphology, chemical composition, particle distribution and reducing agents used in its synthesis. (Salleh et al., 2020). AgNPs work better than their bulk counterparts, because the smaller size increases their surface area and these particles can then easily interact with the microbial membranes and cause damage to them. AgNPs work using different bacteriocidal mechanisms, some of which include attachment to the cell wall and cell membrane lipids and proteins and disrupt the cell wall integrity, leading to loss of cell contents and eventually cell lysis (El-Rafie et al., 2014). It also works by producing reactive oxygen species (ROS), like superoxide (SO2-), hydrogen peroxide (H2O2), etc. These ROS can disrupt the DNA and protein synthesis pathways, and also affect cell metabolism, all of which ultimately cause death of the microorganism (Ibrahim & Hassan, 2016). According to the literature review conducted, AgNPs are effective against both Gram positive and Gram negative bacteria, as well as certain fungi and also viruses. Among the Gram positive ones, the most commonly tested bacteria is *Staphylococcus aureus,* and among the Gram negative ones, the standard organism served as *E.coli,* while the modified AgNPs in almost all the studies, showed above 90% antibacterial efficacy for both. (Ibrahim & Hassan, 2016; Qasim et al., 2018; Salleh et al., 2020; Xu et al., 2018, 2019; D. Zhang et al., 2013). Other than the aforementioned two, experiments have also been conducted where AgNPs showed excellent antibacterial activity against *P.aeruginosa,* (Maghimaa & Alharbi, 2020) and others. Fungi susceptible to the antifungal effect of AgNPs commonly include *C.albicans and A.niger* (Maghimaa & Alharbi, 2020; Shaheen & Abd El Aty, 2018). Lastly, there has been limited study in the antiviral effect of the AgNPs (Salleh et al., 2020), however, the limited study that exists has shown that AgNPs have antiviral effect against rotavirus. Furthermore, certain theories suggest that AgNPs might prove to be useful in the treatment of COVID19, since the AgNPs can bind the viral spikes and thus prevent attachment and entry of virus into host cells (Salleh et al., 2020).

AgNPs have a great selective toxicity towards microorganisms, however, studies have shown that these AgNPs are not toxic to the human skin (Chatha et al., 2019). Literature review has revealed that silver has antimicrobial activity against over 650 microorganisms even at low concentrations, but not to human skin (Dastjerdi & Montazer, 2010; El-Rafie et al., 2014). These binders can be a wide range of molecules, starting from biopolymer-based compounds like carboxymethyl chitosan (Xu et al., 2018, 2019), to some synthetic polymers (Qasim et al., 2018; D. Zhang et al., 2013).

3.1 Synthesis and modification processes

Various modification methods exist, by which silver-containing compounds can be reduced to silver nanoparticles (AgNPs). In the broader sense, these are comprised of photocatalytic reduction, chemical reduction, sol-gel coating, sonochemical method and pad-dry-cure method (Dastjerdi & Montazer, 2010; Maghimaa & Alharbi, 2020). These methods include physical, chemical and also biological synthesis (Salleh et al., 2020). Physical synthesis methods include vapor condensation method, laser ablation method. Chemical modification processes usually include reduction of silver-based compounds using some reducing agents in combination with other reagent (Song et al., 2009; Yu, 2007). However, these physical and chemical methods have been associated with certain negative aspects and causes problems, including weak coating of the AgNPs, leading to reduced durability as well as release of harmful chemicals in the environment. These methods also have a huge energy-requirement. Keeping all these factors in mind, biological synthesis of AgNPs have been rapidly gaining the trust and attention of researchers worldwide, owing to their low energy-consumption, biodegradability, biocompatibility, reduced used of harmful chemicals, and also cost-effectiveness (Salleh et al., 2020). Biological synthesis includes using fungal filtrate from *Curcuma longa* leaf extracts, carboxymethyl chitosan, etc. (Maghimaa & Alharbi, 2020; Xu et al., 2018, 2019). This review will give an overview of the existing modification methods and also try to compare among them in order to select the best suited methods, in terms of efficiency, durability, environmental friendliness and cost effectiveness. In this section, the main focus is the biological synthesis and modification of AgNPs, which are then functionalized onto textile fabrics to impart them with antimicrobial properties.

3.1.1 Chemical synthesis

Here, some of the approaches for the chemical synthesis of AgNPs have been discussed.

3.1.1.1 Synthesis of AgNPs using carboxymethyl chitosan as binders or crosslinking agents

Although it is a well-known fact that silver has its own antimicrobial properties and is frequently used in textiles or other sectors to impart their antimicrobial property, however, despite such high efficiency as antimicrobials, these nanoparticles lack the necessary functional groups required to bind with the textile fibers. As a result, certain binders or cross-linking agents have to be used in order for better and stronger attachment of the AgNPs to the fabrics, improving its durability and thus retaining its antimicrobial activity for longer periods of time (El-Rafie et al., 2014; Xu et al., 2018, 2019; D. Zhang et al., 2013). Therefore, the following study was conducted utilising the polymer carboxymethyl chitosan as the binder for the synthesized AgNPs (Xu et al., 2018, 2019).

Chitosan is a carbohydrate polymer derived from the deacetylation of chitin (Ferrero & Periolatto, 2012). It has its own antimicrobial activity, along with anti-tumor and immunoenchancing properties. Because of its broad-spectrum antimicrobial activities, it can be used in combination with AgNPs in order to produce a synergistic antimicrobial effect onto the coated textile. Chitosan has been modified to carboxymethyl chitosan (CMC), which is considered to be stable, non-toxic, biodegradable and biocompatible, and is also cost-effective. (Xu et al., 2018).

Xu et al. (2018, 2019) have demonstrated the use of CMC as a binding agent for AgNPs. They have added the CMC to the cellulosic fibers of the cotton by esterification reaction between the carboxyl group of CMC and the hydroxyl group of cellulose. The amino groups of the CMC were then free, which were used to form coordination bond with the AgNPs. This mixture was then used to coat the cotton fabrics via pad-dry-cure method to enhance their antibacterial activity and also durability of the synthesized AgNPs. The modified fabrics were characterized and analysed using Fourier-transform infrared spectroscopy (FTIR), field emission scanning electron microscope (FESEM), X-ray diffraction (XRD) and X-ray photoelectron spectroscopy (XPS). All these analyses showed required peaks of the functional groups present, and showed the uniform and even distribution of the synthesized AgNPs onto the cotton surface. The coated fabrics were then tested for their antimicrobial properties against Gram-positive *S. aureus,* and

Gram-negative *E.coli* as the standard bacteria, using agar disk diffusion technique. Results showed large zones of inhibition for both *E.coli* and *S.aureus* when the modified Ag-CMC cotton fabrics were used, supported by satisfactory bacterial reduction rates (BR) of 100% for both (Xu et al., 2019). However, when only the CMC-coated fabric was used, it showed a bacterial reduction rate of only 43% (Xu et al., 2018).

Durability tests were carried out to determine if the modified AgNPs retained their antibacterial action even after repeated washings. It has been shown that even after 50 washings, there remained about 88% of the modified AgNPs on the fabric surface (Xu et al., 2018, 2019), and thus retained their antibacterial property. In addition to that, cytotoxicity tests were carried out to determine whether these modified AgNPs used any allergenic reaction to human skin. The test was carried out using human immortalized keratinocytes (Hacat), and results showed no morphological changes to these cells, thereby indicating that these modified AgNPs were not harmful to human skin.

3.1.1.2 Using polymers such as amino-terminated hyperbranched polymer, and poly-N-isopropylacrylamide

These are two different studies carried out by Qasim et al. (2018) and Zhang et al. (2013). Dendrimers and hyperbranched polymers have been in the use for over two decades because of their excellent and unique chemical and physical properties, as well as broad applicability in a variety of fields, including nanotechnology, pharmaceutical, etc. (Gao & Yan, 2004; Menjoge et al., 2010). So Zhang et al. (2013) used the amino-terminated hyperbranched polymer (HBP-HN2) as stabilizer for the AgNPs onto the cotton fabrics, using a one-step process in order to reduce the use of excess chemicals, reducing agents or other stabilisers. In this study, the synthesized AgNPs were attached firmly to the HBP-NH2 molecules using their amino groups. The numerous imino and amino groups of the HBP-NH2 had successfully reduced the Ag+ ions into AgNPs, which were analysed using TEM. After coating onto the cotton fabrics, this was again characterized using EDS and FTIR, which showed the necessary peaks and functional groups proving the strong attachment of the grafted AgNPs with the cotton fibers.

Antimicrobial activity of this modified cotton was tested against *S.aureus* and *E.coli,* the results of which showed BR rates of above 96% for both the bacteria. Durability tests even after 50 launderings have shown very slight reduction in the quantity of the modified silver, and thus supporting the long-lasting antibacterial effect. This process is also considered to be a "green" process as it does not use any toxic chemicals, and contributes to minimalistic amount of silver being washed out.

In a different study, Qasim et al. (2018) had demonstrated the enhanced antimicrobial activity of AgNPs by encapsulating them using poly-N-isopropylacrylamide (p-NIPAM) and p-NIPAM-NH2 based polymeric nanoparticles. This encapsulation was achieved using in-situ reduction of silver nitrate using sodium borohydrate, NaBH4. Use of polymeric nanoparticles come with a plethora of advantages, such as serving as excellent drug delivery vehicles due to their controllable size and morphology (Huang et al., 2016), low reactivity when exposed to nanoparticles, and also helping to reduce the cytotoxic effects of silver by covering them in a capsule (Mohan et al., 2006).

The surface morphology and characterisation of the modified and encapsulated AgNPs were done using TEM analysis, which showed formation of spherical nanoparticles. Antimicrobial efficiency was tested using the zone of inhibition method, which showed excellent results for both *E.coli* and *S.aureus* tested. However, this particular encapsulated AgNPs showed a better activity against *E.coli* compared to *S.aureus* as shown by the larger sizes of clear zones. Cytotoxicity tests against the microbial cells were carried out using MTT assay, which revealed that the smaller AgNPs had higher cytotoxicity and thus higher antibacterial activity. Repeated launderings have shown a better durability of AgNPs encapsulated by p-NIPAM than those encapsulated by p-NIPAM-NH2 (Qasim et al., 2018).

3.1.2 Biological synthesis/Green synthesis of AgNPs

Biological synthesis of silver nanoparticles has been more promptly used by researchers all over the world, because it provides a more environmental friendly approach, by replacing the use of toxic and hazardous chemicals by biological extracts from plants, fungi, etc. (Maghimaa & Alharbi, 2020; Rajaboopathi & Thambidurai, 2018; Salleh et al., 2020; Shaheen & Abd El Aty, 2018). Because of this reason, this particular technique has earned the name of green synthesis.

Over the years, green synthesis has earned worldwide attention in order to synthesise nanoparticles using plant extracts or fungal extracts, as these active phyto-compounds can act as both the reducing agent and also capping agent (Maghimaa & Alharbi, 2020). In this section, a handful of the green synthesis techniques will be discussed, along with their results and the antimicrobial efficiency of each of the green-synthesised AgNPs.

3.1.2.1 Myco-synthesis of AgNPs

It is clear from the sub-title itself that this section will focus on the use of fungus and fungal filtrates in order to synthesise and modify AgNPs. This particular approach has a number of advantages, including but not limited to being clean and environmental friendly, not requiring the use of additional reducers and stabilisers, and also the added bonus of the experiment being conducted at room temperature (Ibrahim & Hassan, 2016). Fungi serve as excellent choice for this method because they can produce a large biomass of desired product, including large number of enzymes and proteins, and easy downstream processing, and are also tolerant of extreme growth conditions (Shaheen & Abd El Aty, 2018). There have been quite a few studies conducted involving the use of fungal filtrates for AgNP synthesis. Here, three of those studies will be summarized.

(a) **Using fungus *Alternaria alternata*:** This study was carried out by *Ibrahim & Hassan (2016)*, where they characterized and demonstrated the synthesis of modified AgNPs with enhanced antimicrobial activity and better durability. This method proves to be quite cost-effective, eco-friendly and safe. In this study, the fungal filtrate was first prepared and then added to the silver nitrate in the solution in order to reduce it to silver atoms, and thus produce AgNPs. The synthesized AgNPs were characterized using SEM, TEM, DLS and energy dispersive X-ray spectroscopy (EDX). All these analyses collectively showed the morphology of the synthesized AgNPs, which were then coated onto cotton fabrics and characterized using thermogravimetric analysis (TGA) and SEM. These results also showed successful coating of the cotton fabrics with AgNPs. Next, the antimicrobial activity of the treated cotton fabrics was tested both qualitatively and quantitatively. These results have shown that treated fabrics showed about 99.9% inhibition against *E.coli* and *S.aureus* at only 1mM AgNP concentration, while a concentration of 5mM completely stopped bacterial growth. Additionally, soil burial tests were carried out to determine whether this AgNP coating could be used to protect the coated cotton fabric from microbial degradation. Surely enough, the coated fabric remained unchanged in terms of colour, whereas the uncoated fabric showed formation of brown colour. Durability tests were carried out using gamma radiation-curing and thermal-curing as the two methods. Even after 20 washings, the thermally-cured fabric retained antimicrobial activity at 99.1% and 98.7%, whereas the gamma radiation-cured fabric showed 99% and 98.6% activity against *E.coli* and *S.aureus* respectively. Thereby, the results of study conducted by Ibrahim & Hassan (2016) show that myco-synthesis has a positive influence over the antimicrobial activity and durability of the synthesized AgNPs.

(b) **In-situ myco-synthesis of AgNPs:** Based on the literature review conducted, this study was the first one to opt for the in-situ synthesis of AgNPs from fungal filtrates, owing to their benefits of stability and durability. Ex-situ synthesis is widely conducted, however, this method might cause aggregation of the synthesized AgNPs (Shaheen & Abd El Aty, 2018). In this study, five different fungal strains from medicinal plants were extracted and used to reduce the silver ions into AgNPs. These fungal strains were *Alternaria arborescens* (1), *Alternaria alternate* (2), *Alternaria brassicae* (3), *Nigrospora oryzae* (4), and *Penicilium crustosum* (5). The cotton fabrics were inoculated with the biomass containing silver nitrate solution. Deposition of AgNPs was confirmed by a colour change into brown. This incorporation was characterised using FTIR and EDX, which confirmed the successful deposition of the AgNPs. Antimicrobial activity of this modified fabric was tested using agar diffusion method, using the organisms *E.coli*, *C.albicans* and *A.niger.* The highest activity was shown by the AgNPs synthesized using fungal strains 1&2, while moderate activity was shown by those produced from strains 3,4&5, against all the tested organisms. This could be attributed to the fact that the strains had different release rates leading to different sized zones of inhibition. Durability tests have shown that the in-situ synthesized AgNPs were more durable than the ex-situ ones, owing to the better interaction and attachment of the in-situ AgNPs with the cotton fibers.

3.1.2.2 Using seaweed extract

Seaweeds can be classified into green, red and brown algae, among which, the brown algae are rich in alginic acid that acts as a potent reducer and stabilizer. This can be used to reduce silver nitrate into AgNPs, which are then coated into cotton fabrics using pad-dry-cure method in order to enhance their antimicrobial properties (Rajaboopathi & Thambidurai, 2018). Citric acid was used as the crosslinking agent. The successful synthesis and coating were characterized using UV-vis spectroscopy, FTIR, SEM, TEM, EDX, and atomic force microscopy (AFM). All these collectively showed the successful incorporation of the AgNPs onto cotton fabrics, which were then subjected to antimicrobial and durability tests. The AgNP-coated fabric showed better UV protection factor (UPF) than the uncoated one, and also showed better antibacterial activity against *S.aureus* than *E.coli.* Durability tests after 10 washings have somehow shown a better UPF and antibacterial activity than before washing, even though the fabrics showed slight morphological changes. This study has once again proved the beneficial aspects of green synthesis of AgNPs.

3.1.2.3. Using Curcuma longa leaf extracts

There have been widespread usage of medicinal plants and their leaf extracts for healing purposes for ages now. *Curcuma sp.* has been extensively used for their pharmaceutical and medicinal benefits, and was also employed in the treatment of respiratory diseases, digestive illnesses, and a broad range of other diseases (Maghimaa & Alharbi, 2020). So it was hypothesized that the leaf extracts can also be used to synthesise and functionalise AgNPs onto textiles, to enhance their antimicrobial action. This study was conducted by Maghimaa & Alharbi (2020) where they utilized the leaf extract of *Curcuma longa* for this purpose. Just like any other process, the synthesized AgNPs were characterized using HR-TEM, FTIR, followed by coating onto the fabric, which was analysed and confirmed using SEM and EDX. The antimicrobial activity of the coated fabric was tested against human pathogenic organisms like *S.aureus, P.aeruginosa, S.pyogenes* and *C.albicans.* In addition to that, the wound-healing efficiency of the coated fabric was also checked using fibroblast L929 cells. Different doses of the extract were used for the antimicrobial tests, which showed high activity against all the tested microorganisms, with the highest activity shown against *P.aeruginosa* compared to the others. The formulated AgNPs also had little to no cytotoxicity towards the L929 cells, hence proving to be safe for use having both antimicrobial as well as wound-healing potential.

3.2 Summarising AgNPs

The methods of synthesis of AgNPs, followed by their characterization and efficacy in terms of antimicrobial activity and durability are all very diverse, and can sometimes be tedious when considered all together. Chemical synthesis has some advantages, particularly the high yield of product in a shorter time and also the lower cost of production compared to physical methods (Salleh et al., 2020). Despite the positive results, this approach is not as environmentally friendly because of the usage of large amounts of chemicals, which can be toxic and hazardous for both humans and also animals (Gasaymeh et al., 2010). Additional hazards include genotoxicity, carcinogenicity, cytotoxicity and general toxicity (Ibrahim & Hassan, 2016). Chemical synthesis can also cause contamination of the synthesized nanoparticles due to overexposure to chemicals. Overall, considering all aspects together, it has been proved time and time again that biological synthesis of nanoparticles possesses far better advantages than any other methods. This is because this method uses the natural extracts from plants and fungi for example, instead of using any harmful and hazardous chemicals that may be toxic to humans as well as the environment. This method also improves the aspects of biodegradability, biocompatibility, stability and also enhance the antimicrobial effects of the treated textiles, along with providing them with any additional benefits such as protection from harmful UV rays. This is why the following **Table 1** will help to provide an overview of all these aspects at once.

Synthesis method		**Antimicrobial activity**		**Durability tests**	**Additional properties**	**References**
		***E.coli* (%)**	***S.aureus* (%)**			
Chemical	Using CMC	100	100	50w; 88%	(N/A)	(Xu et al., 2018, 2019)
	Using HBP-NH2	>96	>96	50w	(N/A)	(D. Zhang et al., 2013)
	Using p-NIPAM	(More)	(relatively less)	(N/A)	(N/A)	(Qasim et al., 2018)
Biological	Using *Alternaria alternata*	99.9 (1Mm) 100 (5Mm)	99.9 (1Mm) 100 (5Mm)	20w; >98%	(N/A)	(Ibrahim & Hassan, 2016)
	In-situ myco-synthesis	(good)	(good)	In-situ>ex-situ	(N/A)	(Shaheen & Abd El Aty, 2018)
	Seaweed extract	(relatively less)	(more)	10w; activity increased	UV protection	(Rajaboopathi & Thambidurai, 2018)
	C.longa leaf extracts	Relatively less	(relatively less)	(N/A)	Wound-healing	(Maghimaa & Alharbi, 2020)

Table 1 Various modification processes of AgNPs, along with their antimicrobial efficiency and durability. (N/A indicates no usable data recorded). Abbreviations used: CMC; Carboxymethyl chitosan; HBP-NH2; Amino-terminated hyperbranched polymer; p-NIPAM; Poly-N-Isopropylacrylamide; *C.longa; Curcuma longa* (highest activity against *Pseudomonas aeruginosa);* 50w; 50 weeks.

Chapter 4

Copper or copper oxide nanoparticles

The use of copper and copper oxide as nanoparticles is at par with the usage of silver, if not more. It has already been proven through a number of studies that metal and metal oxides serve as more potent, stable and effective nanoparticles compared to non-metals (Hameed et al., 2016). Even though silver is considered to be one of the most widely used metal as nanoparticles, however, there are demerits associated with the usage of silver. These include the prime fact that silver is quite unstable in the air, and so if not protected or covered properly using encapsulation for example, risks remain of the silver turning brown due to oxidation. Additionally, the silver can cause discoloration of the skin due to prolonged exposure and can also cause resurgence of silver-resistant microbes (Hamdan et al., 2017). As a result, most researchers turn to copper because of their widespread and broad applicability in a number of interdisciplinary fields. Compared to silver, copper is cheaper, more easily miscible with any polymer and is more stable (Sathiyavimal et al., 2018).

Copper is one of the most widely used nanoparticle because of its many desirable properties (Almasi et al., 2018; Borkow & Gabbay, 2004, 2005; Sathiyavimal et al., 2018). Copper is most famously known for its broad-spectrum antimicrobial activity, and has been used as an antimicrobial agent since the ancient times (Borkow & Gabbay, 2004). Its antimicrobial function includes being used as a disinfectant, bactericide, fungicide, molluscicide, nematocide, anti-fouling agent and also as a water-purifier (Borkow & Gabbay, 2005). In case of humans, copper has also demonstrated its beneficial properties, being used in dentistry, foodborne disease reduction and also as contraceptives in the intra-uterine devices (IUDs) since a long time now (Borkow & Gabbay, 2005; Lazary et al., 2014).

Copper-based nanoparticles have better antimicrobial activity than silver, and they are also abundant and inexpensive (Marković et al., 2018). It also has widespread antiviral and antifungal activity. There is not one fixed mechanism of action by which copper kills microorganisms. Rather, this exact property is what makes copper even more desirable, seeing as how microbes cannot grow resistance to copper. Microbes can develop antibiotic resistance very soon, but the occurrence of copper-resistant microbes is very rare. Copper has proven to be effective against antibiotic-resistant and also antiviral-resistant microorganisms (Lazary et al., 2014). Higher concentration of copper leads to increased antimicrobial activity of copper (Humphreys, 2014). Copper oxide as nanoparticles have higher durability and do not wash off into water, or even if it does so, then does not harm water because of its insoluble nature (Lazary et al., 2014). The proposed mode of action of copper killing microbes include inhibition of DNA and protein synthesis in microbes, along with disruption of cell wall and cell membrane components, leading to leaking of cell contents and lysis of the cell. Copper can inactivate bacteria, particularly *L.monocytogenes, S.typhimurium, s.enterica* and *C.jejuni* (Araújo et al., 2018), viruses including bronchitis virus, poliovirus, HSV, HIV, human influenza virus (H1N1), avian influenza virus (H9N2) (Borkow et al., 2010). It is also used in treatment of *Tinea pedis,* a fungal infection of the foot which is common in diabetic patients (Borkow & Gabbay, 2005).

Reports have shown that copper has little to no toxicity to human cells but has extremely high toxicity to microbes (Borkow & Gabbay, 2005). Various studies have provided evidence of copper not being sensitive to human skin; using double-blind clinical trials, use of hospital sheets impregnated with copper lining for 300 nights, and as much as use of adult diapers lined with copper for 6 months. None of these showed any allergenic reactions in humans (Lazary et al., 2014). Copper has also been used as a treatment agent for allergic rhinitis and fomites (Borkow & Gabbay, 2005). Similar to the silver nanoparticles, copper nanoparticles (CuNPs) also function better than their bulk counterparts because of high surface area, and thus can interact with the microbial cell membranes more easily (Araújo et al., 2018).

4.1 Synthesis and modification processes

According to Araújo et al. (2018), copper nanoparticles can be synthesized by a number of physical and chemical methods. The physical methods include but are not limited to pulsed laser ablation method, vapor deposition, high energy mechanical milling, etc. Among the chemical methods includes microemulsion, sonochemical/electrochemical reduction, microwave or ultrasound irradiation (for better coating) and also hydrothermal synthesis. Studies involving the biological synthesis of CuNPs also exist. The following section will look into some of the work conducted by researchers all over the world using various novel processes to synthesise and impregnate textile materials using CuNPs, in order to enhance antimicrobial action of the modified textiles.

4.1.1 Hybrids of CuNP/CuONP and chitosan molecules

Chitosan (CS) is extensively known for its biodegradability, biocompatibility, non-toxicity, stability and most importantly its inherent antimicrobial properties (Costa et al., 2018). Chitosan is a carbohydrate polymer and an N-acetylated form of chitin (Shahid-ul-Islam & Butola, 2019). Chitosan is considered as the second most abundant polysaccharide on earth after cellulose (Sutirman et al., 2019). It is widely used in fields of biotechnology, therapeutics, food and beverage industries, and also as antioxidants, emulsifying and thickening agents (Rinaudo, 2006).

Extensive work already exists using chitosan and modified versions of chitosan to be used as antimicrobial coatings on cotton, nonwovens and linen fabrics (Chatha et al., 2019; Klaykruayat et al., 2010). Additionally, chitosan has also been used in combination with CuNPs to produce a synergistic antimicrobial effect from both. Dhineshbabu & Rajendran (2016) have produced a hybrid of chitosan-cupric oxide nanoparticles on cotton fabrics. This was done by mixing together a solution of sonochemically produced CuONPs and colloidal chitosan to produce the hybrid, which was then coated onto cotton fabrics using sonication method followed by pad-dry-cure method. This was then characterized and confirmed using SEM, FTIR and XRD, all of which showed successful coating. Comparison of antimicrobial activity of the coated vs uncoated fabrics against *S.aureus* and *E.coli* using the zone of inhibition method showed that the uncoated fabrics showed no clear zones. On the other hand, the fabrics coated with the hybrid CS-CuONP showed greater activity than the ones coated with just chitosan, by producing bigger clear zones. This was thought to be due to the production of reactive oxygen species (ROS) by the copper, which has deleterious effects on the test microorganisms. Hence this proves the synergistic antimicrobial effect of CS-CuONP hybrid.

Another similar study was conducted by Almasi et al. (2018) where they tested and compared the antimicrobial effect of CuONPs after impregnation onto organic-inorganic nanohybrids of bacterial cellulose nanofibers (BCNF) and chitosan nanofibers (CSNF). Another study where bacterial cellulose was impregnated with CuONP was conducted by Araújo et al. (2018). They used hydrothermal synthesis of the CuONPs, which were then incorporated into the BC fibers and their antimicrobial activity tested. They also demonstrated that the CuONP-BC fabrics showed clear zones for all of the Gram positive *S.aureus, Enterococcus sp.* and *S.epidermidis* tested, along with Gram negative *E.coli, S.enteritidis* and *P.aeruginosa*, as well as the yeast *C.albicans.*

As reported by Almasi et al. (2018), the modified nanofibers were again characterized and confirmed by FTIR, XRD and SEM, which all showed successful CuONP impregnation. When antimicrobial activity was compared for both, it was seen that the CuO-BCNF showed lesser activity than the combined antibacterial effect of CuO-CSNF. As seen from the SEM micrographs, the CuO attached more tightly to CS because of its abundant hydroxyl groups on its backbone, whereas BC itself is quite hydrophilic, and so binds very weakly to the CuO and thus releases it easily. So the activity is weakened. (Almasi et al., 2018; Dhineshbabu & Rajendran, 2016). Here also the exact mechanism of CuONP is not known, but though to include ROS production, interaction with and disruption of microbial cell wall and cell membrane, leading to cell lysis. They have also demonstrated that the Gram positive *L.monocytogenes* are more susceptible to CuONPs than the Gram negative bacteria, owing to the thick cell wall of Gram negative bacteria that makes them more resistant to the copper attack.

4.1.2 Biological synthesis of CuONPs

Copper nanoparticles have been successfully synthesized using plant extracts from *Sida acuta*. (Sathiyavimal et al., 2018). *Sida acuta* is itself known for its use as antiplasmodial, antimicrobial and antioxidant agents. It contains many active molecules such as flavonoids, phenolics, steroids, alkaloids, etc. which can be used for better coating of the synthesized CuONPs onto the cotton fabrics. The successful coating was characterized and confirmed by UV-vis, SEM, TEM and FTIR. Antimicrobial activity tested using disk diffusion method against *E.coli* and *S.aureus*, where the CuONPs showed greater activity towards *E.coli* than *S.aureus.* Here also, the mode of action is thought to involve cell wall disintegration, along with inhibition of cytochromes in the membrane. In another similar study using biological synthesis of CuONPs (Vasantharaj et al., 2019), the synthesized CuONPs showed a greater bactericidal effect against *S.aureus* followed by *E.coli* and *K.pneumoniae.* This difference in activity could be a result of the different unspecified antimicrobial mechanism that the copper uses, since there is not just one fixed method for the bactericidal activity of copper.

Sathiyavimal et al. (2018) also demonstrated that Cu coated polyester had a combination of antibacterial, antifungal and antiviral activity, while the Cu-coated nylon had bactericidal activity. Additionally, CuONPs also have photocatalytic activity which depends on the size, shape and synthesis methods. In this particular study, the biologically synthesized CuONPs showed about 93% and 87% of photocatalytic activity against crystal violet and methylene red dyes, respectively. Similar photocatalytic activity was also seen by the CuONPs synthesized by Vasantharaj et al. (2019), where the nanoparticles showed gradual degradation of the crystal violet dye, confirmed by the disappearance of specific peak at 586 nm when exposed to sunlight for longer time periods.

4.1.3. Role of CuO-impregnated linens in reducing HAIs

Considering the beneficial properties of copper in mind, it was tested whether replacing the normal hospital beddings with copper oxide-impregnated linens could help to reduce HAIs. Over a long period of study of 1 year, Lazary et al. (2014) had shown positive results in this aspect. They carried out the study in a long-term care brain injury ward. Results have shown significant reduction in both Gram positive and Gram negative bacterial load after just 6-7 hours, showing reduction by 50% and 43% respectively. Additionally, using the CuO-impregnated linens have also reduced the number of days of fever in the patients, along with reduced duration of antibiotic consumption, occurrence of gastrointestinal and eye infections. Therefore, some hopes still exists that use of CuONPs or CuO-impregnated linens can be used to at least try and control HAIs.

4.2 Antiviral activity of copper

Copper is particularly the most well-known because of its antiviral activity, being active against a broad category of both enveloped and non-enveloped viruses. Extensive research highlighting the antiviral activity of copper has already been carried out (Borkow et al., 2010; Borkow & Gabbay, 2004, 2005). Airborne bacteria and viruses cause a wide range of diseases, in which the respiratory openings serve as the main portals of entry into the human body. That knowledge was utilized to develop copper or copper oxide impregnated nonwoven surgical gowns, or respiratory masks. These are extremely beneficial in trying to reduce the spread of nosocomial infections as well (Borkow et al., 2010; Borkow & Gabbay, 2004, 2005; Lazary et al., 2014).

Borkow & Gabbay (2004) had portrayed the potent biocidal activity of copper in a number of scenarios. They showed that copper-impregnated hospital textiles can help in controlling nosocomial infections to a limit. Additionally, they showed that copper-impregnated mattresses and beddings can help to combat allergic reactions and asthmatic attacks, along with its usage in socks is able to cure and prevent athlete’s foot caused by fungus *Tinea pedis* (common in diabetic patients), and also protect the toes from further bacterial invasion. The Cu+ and Cu2+ ions are heavily responsible in inactivating viruses, because of their production of ROS that interfere with viral activity, leading to death. Viruses are particularly more sensitive to copper because they are mainly host-dependent, and themselves lack the protective mechanisms like DNA repairing, protective barrier, etc. like other bacteria and organisms.

A novel anti-influenza mask was developed lined with copper oxide in multiple layers, without altering the filtering efficiency of the masks (Borkow et al., 2010). Their results have shown excellent inactivation of viruses by the CuO-impregnated masks within 30 minutes, whereas not so efficient results were given by the control masks. This was due to direct contact inactivation of both the test viruses, which were the human influenza A virus (H1N1) and the avian influenza virus (H9N2). The CuO-impregnated masks had successfully passed all the necessary tests for it to be accepted for use, which included the bacterial filtration efficacy (BFE) test, differential pressure (ΔP), latex particle challenge, and also resistance to synthetic blood tests. The last one is necessary since the usage of these masks by doctors, nurses, and also patients can protect from any blood spillage. The masks showed complete resistance to blood penetration even after constant exposure of 30 minutes. Moreover, electron microscopy had revealed morphological abnormalities in the test viruses, alongside the fact that increasing the copper concentration in the masks up to 6 times still did not show any human skin sensitization effects, as confirmed by animal skin test results.

In a different study, Imai et al. (2012) had also incorporated the use of copper-zeolite textile in prevention of avian influenza viruses H5N1 and H5N3. Here, the cotton textiles were modified with zeolite that contained Cu2+ ions because of its negative surface charge. Zeolite is a “microporous, alluminosilicate mineral that has adsorption capabilities”, as quoted by Imai et al. (2012). The results showed that the two different strains of H5N1 tested showed different reactions to the Cu-zeolite coated textiles, however, previous studies using Cu2+ from CuCl2 showed no effect upon these H5N1 viruses even after 6 hours exposure. Thus the Cu2+ ions held by zeolite and those in CuCl2 show different antiviral actions; instead, the same concentration of CuCl2 had completely inactivated the H5N3 viruses. Hence, copper has been widely used as a potent antiviral agent. Further studies are going on investigating the effects of copper as algaecide, fungicide, molluscicide, nematocide, etc. (Borkow & Gabbay, 2005; Imai et al., 2012).

Given the current world pandemic going on because of SARS-CoV-2, the antiviral effects of copper could really come in handy. Therefore, further investigations need to be done in this field.

4.3 Summarising CuONPs

Based on the literature review and also the aforementioned points, there is no shred of doubt that copper or copper oxide nanoparticles can be successfully used as broad spectrum antibacterial, antifungal and also antiviral agents in order to reduce the incidence of HAIs, as well as its use in respiratory masks, gloves, socks, and other medical necessities. All these findings have been summarized in **Table 2.**

Modification process	**Antibacterial activity**		**Antiviral activity**	**Antifungal activity**	**Additional properties**	**References**
	Gram +ve	**Gram –ve**				
Hybrids with chitosan	*S.aureus*	*E.coli*	(N/A)	(N/A)	(N/A)	(Dhineshbabu & Rajendran, 2016)
CuO-BCNF and CuO-CSNF	*S.aureus, Enterococcus sp., S.epidermidis*	*E.coli, P.aeruginosa, S.enteritidis*	(N/A)	*C.albicans*	(N/A)	(Almasi et al., 2018; Araújo et al., 2018)
CuONP from *Sida acuta* extract	*S.aureus*	*E.coli*	(N/A)	(N/A)	Photocatalytic activity, UV protection, dye degradation (93% for CV; 87% for MR)	(Sathiyavimal et al., 2018)
CuO-impregnated linens, hospital textiles, masks	(N/A)	(N/A)	Human influenza A (H1N1), Avian influenza (H9N2)	*Tinea pedis*	(N/A)	(Borkow et al., 2010; Borkow & Gabbay, 2004; Lazary et al., 2014)
Cu-Zeolite cotton	(N/A)	(N/A)	Different strains of H5N1, H5N3.	(N/A)	(N/A)	(Imai et al., 2012)

Table 2 Different modifications and combinations of CuONPs with other compounds and their diverse antimicrobial and additional properties. (N/A indicates no usable data recorded*)*. Abbreviations used: CuO-BCNF & CuO-CSNF; Copper-oxide impregnated bacterial cellulose nanofibers and chitosan nanofibers; CV; Crystal violet; MR; Methyl red; HAIs; Hospital-acquired infections; GI infection; Gastrointestinal infection; H5N1, H5N3; Two different subtypes of Human influenza A virus. The CuO-impregnated linens also reduced HAIs, fever days, antibiotic consumption, GI infection, eye infection.

Chapter 5

Zinc/zinc oxide nanoparticles (ZnONPs)

Just like silver and copper nanoparticles discussed above, nanoparticles made of zinc oxide are just as useful, if not more. Zinc oxide has already been in use in a diverse category of fields, including drug delivery, disintegrating tumor cells, piezoelectric devices, semiconductors, transparent electronics, personal care products, gas sensors, UV-protection cosmetics, paints, and also the medical textiles (Dastjerdi & Montazer, 2010; Fouda et al., 2018; Rajiv et al., 2013; Windler et al., 2013). Holt et al. (2018) have reported that zinc oxide nanoparticles can withstand vigorous commercial drying processes. All these are attributed to the broad range properties of zinc oxide that involve piezoelectric, pyroelectric, photocatalytic, semi-conducting, durability, stability and biocompatibility. (Rajiv et al., 2013; Silva et al., 2019).

Various studies and reviews have previously demonstrated the broad spectrum antibacterial and antifungal characteristics of zinc oxide. This made for the integration of zinc oxide nanoparticles into textiles to provide them with improved antimicrobial action. Zinc oxide nanoparticles have better antimicrobial activity than their bulk counterparts because of their small size and hence higher surface area, which allow them to interact closely with the microbial structures. (Fouda et al., 2018; Silva et al., 2019; Singh et al., 2012). They also have additional benefits of photocatalytic and UV-protection capabilities that work in their favour (Fouda et al., 2018). Their antimicrobial action mostly composes of production of ROS, disintegration of cell wall, photoconductivity, inhibition of DNA replication by binding with phosphate groups in DNA, inhibitory effects on proteins and enzymes due to binding with the thiol (-SH) groups in their structure (Fouda et al., 2018; Rajiv et al., 2013; Silva et al., 2019). ZnO is effective against both Gram positive and Gram negative bacteria in different rates, as well as fungi and yeasts. Various studies exist regarding synthesis of zinc oxide nanoparticles

(ZnONPs) using physical, chemical and also biological methods. These methods consist of sonochemical and enzymatic methods (El-Nahhal et al., 2020; Petkova et al., 2016; Singh et al., 2012), sol-gel methods (Hasnidawani et al., 2016), chemical vapor synthesis (Lobiak et al., 2015), thermal decomposition, sonication, UV irradiation and surfactants for better stabilization (El-Nahhal et al., 2017; Y. Y. Zhang et al., 2016). Each method has its own advantages and disadvantages, however, reports have shown better acceptability of the biosynthesis methods. The following section will focus on a few of the works conducted over the years into synthesizing and modifying ZnONPs onto cotton fabrics to enhance their properties.

5.1 Biosynthesis of ZnONPs

Fouda et al. (2018) have reported the biosynthesis of ZnONPs using extracts of proteins and enzymes from the fungus *Aspergillus terrus AF-1*. The proteins mainly served as both the reducing agents and also capping agent for the synthesized ZnONPs. The cytotoxicity, antibacterial activity and also UV-protection factor (UPF) were subsequently tested. Results from FTIR, UV-vis spectroscopy, TEM, SEM, XRD and DLS have cumulatively shown the formation of ZnONPs that were spherical in shape, uniformly distributed, and polydispersed. The microbes tested for susceptibility to synthesized ZnONPs included Gram positive *B.subtilis* and *S.aureus*, and Gram negative *E.coli* and *P.aeruginosa.* The ZnONPs showed bigger clear zones of inhibition for the Gram positive than the Gram negative bacteria. Light microscopy and MTT assay results for cytotoxicity showed severe phenotypic changes in the exposed microbial cells, as well as mortality of cells, both of which were dose-dependent on the ZnONPs. Additionally, these biosynthesized ZnONPs also showed good blocking ability of UVA (76.3%) and UVB (85.4%) within the UV-rays, both of which are considered the most dangerous in terms of human health as they can cause DNA damage and skin cancer. Therefore, these biosynthesized ZnONPs could be then used for application in medical textiles in order to combat bacterial infections.

Another study involving biosynthesis of ZnONPs use leaf extracts of *Parthenium hysterophorus L.*, which is considered as one of the 10 worst weeds in the world (Rajiv et al., 2013). It is poisonous, pernicious, and yet has been reported to have pharmacological properties against many diseases (Kumar et al., 2011; Mew et al., 1982). In this study as well, different concentrations of the leaf extracts were used as both reducing and capping agents for the ZnONP synthesis of different sizes, followed by investigating the size-dependent antimicrobial efficiacy of the synthesized ZnONPs. However, in this study, the focus was given on the antifungal effect of ZnONPs on plant fungal pathogens, namely *A.flavus* and *A.niger,* instead of human pathogenic organisms. The formation of biosynthesized ZnONPs was confirmed with UV-vis spectroscopy, FTIR, SEM, TEM, XRD and TEM analyses. The highest antifungal activity of the synthesized ZnONPs based on size of zones of inhibition was observed against *A.flavus,* values of which were more than the positive control of the study. Lowest activity seen in *F.culmorum.* Besides, the antibacterial activity of ZnONPs was inversely proportional to their size, which once again stands by the previously established fact that smaller NPs have higher activity (Raghupathi et al., 2011).

5.2 Sonochemical and sonoenzymatic synthesis of ZnONPs

Over the years, El-Nahhal et al. (2020), Petkova et al. (2016) and Singh et al. (2012), among others, have used the methods of sonochemical and sonoenzymatic synthesis of ZnONPs, which were then used in combination with starch and silver (El-Nahhal et al., 2020) for functionalizing ZnONPs onto cotton fabrics. Corn starch was reported to improve the adhesion capabilities of ZnONPs with the cotton fibers, which ultimately works towards improving the durability of the ZnONPs by reducing its leaching into the environment.

One of the first implementations of sonochemical coating of ZnONPs through UV irradiation was employed by (Singh et al., 2012), where they used a single-step process to synthesise and coat ZnONPs onto fabrics. This method reduced the cost and energy requirements, producing uniform and even coating of the NPs at very high speeds that ensure strong attachment with the fibers. The antibacterial activity of the coated fabrics against *S.aureus* and *E.coli* was then tested semi-quantitatively using agar disk diffusion techniques and shake flask method (using nutrient broth), and also done quantitatively using absorption method and again shake flask method (using saline solution). All of 4 types of testing procedures showed good antibacterial activity of the coated fabrics, exhibiting a better antibacterial activity towards *S.aureus* than *E.coli*. The mechanism of action of the ZnONPs is thought to involve ROS production, particularly hydrogen peroxide that interacts and ultimately damages the microbial cell wall and cell membrane, killing the bacteria.

Petkova et al. (2016) reported a single-step synthesis of ZnONP using simultaneous sonochemical-enzymatic coating of the nanoparticles onto medical textiles. They achieved multilayer coating of the synthesized ZnONPs which ensured better adhesion and hence stability of the nanoparticles onto the fabrics. The antimicrobial activity of the treated fabrics was then tested against *S.aureus* and *E.coli*, which showed 67% and 100% growth inhibition, respectively. The ultrasound treatment has been seen to improve cellulase efficiency although at times it can lead to production of ROS that can inhibit cellulase activity. Durability tests after 10 washings in presence of a non-ionic surfactant has resulted in 67% NP loss when active enzyme was present, whereas it showed a whopping 95% NP loss when the enzyme was denatured. This further solidifies the fact that enzymatic method acts to improve stability of the ZnONPs. Once again, the unwashed fabric treated with both active and denatured enzymes showed approximately 70% bacterial reduction, while a series of 10 washing resulted in entire loss of antibacterial property in the fabric containing denatured enzyme, whereas the active enzyme-treated fabric retained about 50% of its antibacterial activity.

One of the very recent works of El-Nahhal et al. (2020) accounted for utilizing UV irradiation and sonoenzymatic processes for the coating of ZnONPs onto cotton fibers. The ZnONPs were synthesized using sodium hydroxide in the media, which served as the reducing agent for Zn(OH)2 into spherical ZnONPs using ultrasonication methods. The antibacterial activity of the starch/ZnONP-coated cotton fabrics against *S.aureus* and *E.coli* showed better results than only cotton fibers. It was observed that increasing the starch concentration improved antibacterial activity since it held more amount of ZnONPs. In an alternate study by the same group, functionalization of ZnONPs with silver/curcumin showed synergistic antimicrobial effect than just Zn-cotton fabrics (El-Nahhal et al., 2020). In a previous work by El-Nahhal et al. (2017), UV irradiation and different surfactants were used to improve adhesion capabilities of the ZnONPs onto the cotton fibers. These surfactants helped to produce smaller ZnONPs that were hence more active because of higher exposed surface area. Best stabilization and thus least leaching of the ZnONPs were obtained when using the following surfactants (in order of reducing attachment): SDS, followed by HY, CTAB and finally TX-100. These produced differently sized NPs and thus different antibacterial activities were seen against *S.aureus* and *E.coli* tested, with higher activity seen in *S.aureus* than *E.coli* when the surfactants SDS and HY were used, compared to the other two. These ZnONPs also showed a greater antifungal activity against *C.albicans* than *M.canis.* however, the synthesized ZnONPs still showed overall better antibacterial activity than antifungal activity.

5.3. Antimicrobial activity of aqueous zinc salts

In addition to synthesizing and investigating the antimicrobial efficiency of ZnONPs, scientists have also conducted studies on the antimicrobial activity of simply aqueous zinc compounds.

Holt et al. (2018) checked whether aqueous solutions of zinc salts contained any residual antimicrobial action. They found out that aqueous solutions of zinc salts, particularly zinc chloride ($ZnCl_2$), retained residual antimicrobial activity upto 30 days and can also survive intense industrial drying processes. Compared to $ZnCl_2$, the same was not observed for ZnO salts as they failed the abrasive testing procedures. This could be attributed to the chemical attachment of $ZnCl_2$ with the textile fibers, whereas ZnO was seen to attach only physically, resulting in weaker bonds and thus easier leaching. The antimicrobial efficacy was tested against Gram positive and Gram negative bacteria, and also yeast, using 4 salt zinc salt solutions containing $ZnCl_2$, $ZnSO_4$, $ZnNO_3$ and ZnO. This revealed highest effectiveness against Gram positive bacteria of the three Zn salts except ZnO, although it showed better results than the control. Moreover, abrasion testing on untreated fabric showed no loss of mass but treated fabric showed some, which could only be accounted for mass loss of zinc. According to their reports, $ZnCl_2$-treated fabrics showed no mass loss whereas the ZnO-treated ones showed 30% loss in mass, once again justifying the weak physical attachment of the ZnO salts to the textile fibers.

5.4. Summarizing ZnONPs

Based on the studies reviewed above, it is quite evident how ZnONPs have proved to be very useful in antimicrobial coating of textiles, thereby aiding in increased chances of developing antimicrobial medical textiles. Zinc is less costly, more available and has added benefits of photocatalytic activity along with UV-protection capabilities. All these findings have been summarized in **Table 3** for better understanding.

Synthesis method	Antibacterial activity		Antifungal activity	UV-protection	Durability	References
	Gram positive	Gram negative				
Using *Aspergillus terrus AF-1*	More effective against *B.subtilis, S.aureus*	Relatively less effective against *E.coli, P.aeruginosa*	(N/A)	Blockage of 76.3% UVA; 85.4% UVB	(N/A)	(Fouda et al., 2018)
Using *Parthenium hysterophorus L.*	(N/A)	(N/A)	More effective against *A.flavus* than *A.niger;* least effective against *F.culmorum*	(N/A)	(N/A)	(Rajiv et al., 2013)
Sonochemical, enzymatic and UV irradiation coating	67% reduction in *S.aureus*	100% reduction in *E.coli*	(N/A)	(N/A)	After 10 washings: 67% NP loss with active enzyme; 95% NP loss with denatured enzyme	(Petkova et al., 2016; Singh et al., 2012)
Sonochemical coating in presence of NaOH as reducing agent	Well effective against *S.aureus*	Well effective against *E.coli*	(N/A)	(N/A)	(N/A)	(El-Nahhal et al., 2020)
Aqueous zinc salts	All except ZnO showed highest activity	Relatively less effectivity	Relatively less effectivity	(N/A)	No mass loss(for $ZnCl_2$); 30% mass loss (for ZnO)	(Holt et al., 2018)

Table 3 Antimicrobial, UPF and durability properties of differently synthesised ZnONPs (N/A indicates no usable data recorded*).* Abbreviations used: NaOH; Sodium hydroxide; ZnO; Zinc oxide; ZnCl2; Zinc chloride.

Chapter 6

Titanium oxide nanoparticles (TiONPs)

Finally, the last metal oxide nanoparticle to be reviewed in this paper is titanium oxide nanoparticle. Titanium belongs to the transition metal group, known for its gorgeous silver colour, low density and high strength. It has uses in orthodontic surgeries in the dentistry field, along with being used in the biomedical field as connection between bones and replacing hip joints (Titanium's Special Properties — Science Learning Hub, n.d.). It is also known for its unique property of super-resistance to corrosion in sea water and also chlorine. In addition to that, titanium oxide nanoparticles (TiONPs) have found their way into the bio-nanotechnology field because of their diverse and desirable properties of photocatalytic activity, UV protection, high stability, safety, non-toxicity, low cost, high availability, biocompatibility and of course, antimicrobial, anti-cancer and anti-inflammatory activities. (Ahmadi et al., 2019; Dastjerdi & Montazer, 2010; Humphreys, 2014; Parthasarathi & Thilagavathi, 2013; Rao et al., 2019). Owing to these diverse properties, they are also used in the textile, paper, cosmetics and food industries (Muhd Julkapli et al., 2014). Furthermore, these are also used in the pharmacology sector, for drug delivery, imaging, diagnosis and treatment of various diseases (Ramar et al., 2015). Moreover, they are utilized as packaging materials for food and drugs because of their protective abilities and also help to increase the shelf life of these products (Ahmadi et al., 2019). In combination with other treatment strategies, they have proved their worth as a potential treatment method for cancer because of their anti-tumor effects (Rao et al., 2019).

Considering the literature review covered, TiO_2NPs have most widely been used for their excellent photocatalytic abilities, additionally investigating their antimicrobial and biocompatibility. Hence, some of the works concerning the use of TiO_2NPs in photocatalysis and antimicrobial (antibacterial, antifungal and antiviral) activity have been covered in the following sections.

6.1. Antiviral activity of TiO_2NPs in surgical gowns

Needless to say, surgical gowns in the hospitals must be made of such a material that is resistant to blood, liquids, and abrasion, and of course, resistant to microbial colonization in order to prevent contamination of sterile areas, and thus contribute to prevention or reduction of nosocomial infections (Parthasarathi & Thilagavathi, 2013). The fabrics must be moisture-resistant while still allowing air to pass through, to avoid suffocation. Keeping this in mind, along with the growing concern over health and hygiene, Parthasarathi & Thilagavathi (2013) have put TiO_2-NPs to good use. They prepared a nanodispersion of TiO_2 and then coated it onto nonwoven fabrics using pad-dry-cure method. The nonwoven fabrics were chosen as three-layered fabric, made of polypropylene, polytetrafluoroethylene and polyester for the outer, middle and inner layers, respectively. The synthesized nanoparticles and the coated fabrics were characterized using HR-TEM and SEM, which showed proper coating of the fabrics. The microporosity of the fabric allows good breathability. The nanoparticle-treated fabric had successfully passed all the viral penetration tests, showing excellent resistance to viral penetration. This meant that the treated fabric was resistant to HBV, HCV, HIV and Phi X174. Their findings have shown that these one-time use, disposable gowns account for only 2% of the total hospital waste, meanwhile preventing the release of toxic chemicals into water, a phenomenon that is seen with reusable gowns because of their need for regular washes

6.2. Green synthesis of TiO_2 NPs

Studies have been carried out focusing on the green synthesis of TiO_2 nanoparticles, due to the obvious benefits of environmental friendliness and low cost operations.

In a study carried out by Ahmadi et al. (2019), extracts from *Miswak (Salvadora persica L.)* (SPE) were used for the fabrication of TiO_2 NPs, for use in the food and drugs industry for packaging purposes. *Miswak* is a small shrub tree, native to the Middle East, that has its own antimicrobial and other biological properties. World Health Organisation (WHO) has already acknowledged the utilization of *Miswak* roots for better oral hygiene. SPE possesses qualities of being non-toxic, along with serving as anti-inflammatory, antimicrobial and antioxidant agents (H. Balto et al., 2017; H. A. Balto et al., 2014; Chelli-Chentouf et al., 2012; Mohamed & Khan, 2013). The presence of several bioactive compounds account for these beneficial properties, with the main antimicrobial agent being benzyl isothiocyanate (BITC). Therefore, *Ahmadi et al. (2019)* combined all the diverse properties of these substances together and prepared a mixture, that was blended together with the carboxymethyl cellulose (CMC) to generate films by casting method. The ultimate purpose of this process was to render the treated substance with antimicrobial, thermo-physical and barrier properties. The results were further validated and confirmed by physical and mechanical properties, elemental mapping analysis (MAP), XRD, SEM, FTIR, UV-vis spectroscopy, EDX, and TGA-DTG methods. All of these confirmed the formation of homogenous films, which were then put to antimicrobial test against *S.aureus* and *E.coli.* Pure SPE and the CMC- TiO_2-SPE showed excellent antibacterial properties against both, with the latter showing dose-dependent increase in antibacterial activity.

In a different study, Rao et al. (2019) produced silver-doped TiO2 nanoparticles using aqueous extracts from *Acacia nilotica,* which served as the bio-reductant. Synthesized Ag/TiO_2 were characterized using FTIR, XRD, FESEM, EDS and TEM. These were then subjected to antibacterial and antifungal tests using well diffusion methods, where they displayed their activity in the order *E.coli>C.albicans>MRSA>P.aeruginosa.* hence, these Ag/TiO_2 nanoparticles were active against both Gram positive and Gram negative bacteria, as well as yeasts. The possible mode of action for this is said to be generation of ROS, leading to phospholipid peroxidation and ultimately death of the cells. Furthermore, cytotoxicity and oxidative stress of the synthesized nanoparticles were evaluated using MTT assay in the MCF-7 cells, which belong to a breast cancer cell line. This showed that increasing the concentration of the nanoparticles increases their interaction with the cells, thereby increasing cytotoxic effects and resulting in reduced cell viability. They also reduce the levels of glutathione (GSH) in tumor cells. GSH has functions in signal transduction pathways, among other proliferative mechanisms for tumor cells. Hence, all these are evidence enough that Ag/TiO_2 nanoparticles could serve as an effective anticancer therapy for cancer patients.

All these beneficial properties of the biosynthesized nanoparticles from both the above studies strongly point towards their potential as medical textile coatings. However, that sector is yet to be pursued heavily in the near future.

6.3 Fe-N doped TiO_2 nanoparticles

The photocatalytic property of TiO_2 is one of the most widely studied properties. Stan et al. (2016, 2019) have conducted extensive and detailed experiments concerning the photocatalysis, antimicrobial and biocompatibility of Fe-N doped TiO_2 nanoparticles, ultimately utilizing them to coat onto cotton fibers for use as self-cleaning medical textiles.

Stan et al. had used hydrothermally synthesized (2016) Fe-N doped or graphene oxide (2019) doped TiO_2 nanoparticles as their coating materials for cotton textiles. In the earlier study (2016), the group had particularly focused on coating with reused dispersions of the TiO_2 -1% Fe-N nanoparticles instead of extracting usable nanoparticles from waste which adds immensely to the cost of experimentation. They found out that reusing nanoparticles dispersions caused increased concentration of nanoparticles in the fabric, leading to increased photocatalytic activity, the most efficient activity being observed under visible light compared to UV and solar light, confirmed by trichromatic coordinates method. In the more recent study, they found similar results for photocatalytic activity (Stan et al., 2019).

Antimicrobial efficiency tests showed similar results for both the studies, with varied effects in the fabrics due to fabric composition, microbial strain and incubation period. However, the first study showed antibacterial activity in the order *E.coli>P.aeruginosa>Saureus>E.faecalis* (Stan et al., 2016). On the other hand, the recent study has shown 77% and 33% inhibition of *E.faecalis* growth by knit samples K-S1 and K-S3 samples, respectively, and no significant effect was seen in *E.coli* after 24hrs of contact with the fabrics, with K-S2 showing slight inhibitory effects (Stan et al., 2019). This antimicrobial activity of $\mathrm{TiO_2}$ could be accounted for by the production of ROS which disintegrated the microbial cell membranes along with DNA damage. The difference in this action is thought to be due to the structural and metabolic differences between the Gram positive and Gram negative bacteria, with the outer membrane of lipoproteins in Gram negative bacteria making them more resistant to treatment.

An absence of cytotoxic effects after short-term exposure of 4h contact (Stan et al., 2016), as well as long-term exposure of 24h contact (Stan et al., 2019) was seen when tested on human dermal fibroblasts. This was confirmed by lack of any morphological or cell viability changes. The $\mathrm{TiO_2}$ nanoparticles thus prove their biocompatibility aspects. Additionally, it was also seen that the hydrophobicity of the treated fabric increased because of the multiple layers of coating (mainly due to presence of graphene), which then helps the treated textiles to become more resistant to microbial colonization and hence ensuring self-cleaning.

6.4. Summarising $\mathrm{TiO_2}$NPs

Based on the abovementioned works by various groups of researchers, it is evident how useful titanium oxide nanoparticles can be to the world. The widespread beneficial properties of photocatalysis, UV-protection, biocompatibility, high availability, as well as diverse antibacterial, antifungal as well as antiviral effects of TiO_2NPs make them one of the most prized category of nanoparticles. Despite all these, further studies still need to be carried out in order to solidify these useful properties further, meanwhile looking for some further innovative properties and uses of TiO_2NPs. A short summary of the abovementioned findings about TiO_2NPs s provided in Table 4.

Category	**Antibacterial activity**		**Antifungal activity**	**Antiviral activity**	**Photocatalytic activity & Cytotoxicity**	**References**
	Gram +ve	**Gram –ve**				
TiO_2 in surgical gowns	(N/A)	(N/A)	(N/A)	HBV, HCV, HIV, Phi X174	(N/A)	(Parthasarathi & Thilagavathi, 2013)
Synthesis using SPE	*S.aureus*	*E.coli*	(N/A)	(N/A)	(N/A)	(Ahmadi et al., 2019)
Synthesis using aqueous extracts of *A.nilotica*	*MRSA*	*E.coli, P.aeruginosa*	*C.albicans*	(N/A)	Destroyed MCF-7 cells, displaying anticancer property	(Rao et al., 2019)
Fe-N doped TiO_2 (reused dispersion)	*S.aureus, E.faecalis*	*E.coli, P.aeruginosa*	(N/A)	(N/A)	Better activity under visible light; No effect on human dermal fibroblasts	(Stan et al., 2016)
Graphene oxide/Fe-N doped TiO_2	77% and 33% *E.faecalis* inhibition by K-S1 &K-S3 respectively.	No significant effect on *E.coli* after 24hrs	(N/A)	(N/A)	Better activity under visible light; No effect on human dermal fibroblasts	(Stan et al., 2019)

Table 4 Antimicrobial, photocatalytic and cytotoxicity effects of differently synthesised TiO_2NPs. (N/A: No usable data recorded). Abbreviations used: HBV, HCV; Hepatitis B and Hepatitis C virus (respectively); HIV; Human immunodeficiency virus; SPE; *Salvadora persica* leaf extract; MRSA; Methicillin-resistant Staphylococcus aureus; K-S1 & K-S3; Knit fabric samples 1&3

Chapter 7

Which nanoparticle is better for textile industry?

Actually, there is no hard-and-fast rule that can be followed to determine which nanoparticle is better than the rest. As already discussed in details in the above sections, each of the nanoparticles has its own advantages and some disadvantages as well, in terms of their antimicrobial efficacy, synthesis and modification processes used, cost and energy requirements, as well as their durability of action. In order to mass-produce textiles with excellent antimicrobial and barrier properties, the textile industry will definitely require such a component that can be produced at a large scale and comes with the most minimalistic of problems. The nanoparticle chosen should have a broad spectrum antibacterial, antifungal as well as antiviral properties. In the current world, with the coronavirus pandemic going on, the nanoparticles must be chosen keeping this period of crisis in mind, so that the nanoparticles can be made to provide even a little bit of protection to the mass population. The chosen nanoparticle should be able to serve as effective fabric coatings for masks, personal protective equipments (PPE) for the frontline workers, patient and nurse scrubs, privacy drapes, as well as made into the usual everyday-wear clothes for the general population.

Therefore, in order to choose the most feasible metal or metal oxide nanoparticle to be used in the textile industry, this following paragraphs present a comparative analysis, centered around the different modification processes used, also including their antimicrobial efficacy and durability. Environmental-friendliness and cost effectiveness should also be kept in mind. Due to the lack of enough statistical data, this review represents a descriptive comparison instead of a statistical one.

7.1 Comparison based on modification processes

As already seen above, there are a number of synthesis and modification processes for each of the metal nanoparticles. These involve chemical methods such as sonochemical and enzymatic processes, UV irradiation, uses of different kinds of polymers, biopolymers and chemical molecules as binders and stabilisers, and last but not the least, biosynthesis using various kinds of plant extracts, fungal filtrates, etc. The antimicrobial effect based on the different processes used for each of the AgNPs, CuONPs, ZnONPs and TiO2NPs have been briefly presented in the following **Table 5.**

Modification process	Different nanoparticles and their antimicrobial effect			
	AgNPs	CuONPs	ZnONPs	TiO_2NPs
Chemical	**Antibacterial:** 96-100% for *E.coli, S.aureus*	**Antibacterial:** *S.aureus, Enterococcus sp.* and *S.epidermidis; E.coli, S.enteritidis* and *P.aeruginosa* **Antifungal:** *C.albicans* **Antiviral:** H1N1, H5N1, H5N3, HIV, HBV, HCV, bronchitis virus, poliovirus	**Antibacterial:** *E.coli, S.aureus* **Antifungal**: *C.albicans, M.canis*	**Antibacterial:** *E.coli> P.aeruginosa> S.aureus>E.faecalis* **Antiviral:** HBV, HCV, HIV, Phi X174
Biosynthesis	**Antibacterial:** 99-100% for *E.coli, S.aureus*	**Antibacterial:** *E.coli, S.aureus*	**Antibacterial:** More effective against G+ve *S.aureus* and *B.subtilis* than G-ve *E.coli* and *P.aeruginosa* **Antifungal:** *A.flavus, A.niger*	**Antibacterial:** *S.aureus, E.coli, MRSA, P.aeruginosa* **Antifungal:** *C.albicans*
Additional properties	UV-protection (UPF); Wound-healing; No cytotoxicity	Photocatalysis, UPF; dye degradation; No cytotoxicity; HAIs reduction	UPF; No cytotoxicity	Excellent photocatalysis,; Anti-cancer potential; No cytotoxicity

Table 5 Comparison between AgNPs, CuONPs, ZnONPs, TiO_2NPs in terms of synthesis methods, broad-spectrum antimicrobial activity and additional properties.

7.2 Comparison based on durability actions

It is extremely important for the synthesized nanoparticles to be able to retain their antimicrobial properties even after regular launderings. Moreover, it is important that the nanoparticles attach tightly to the textile fibers so that that are not leached away into the environment, harming the aquatic life mostly, among others. Considering these aspects, the durability-based comparison among the 4 above nanoparticles have been presented in **Table 6**.

Durability actions: Retainability of antimicrobial activity			
AgNPs	**CuONPs**	**ZnONPs**	**TiO_2NPs**
After 20-50 washings, 88-98% bacteriocidal	(N/A)	After 10 launderings, retains 33% NPs (with active enzyme treatment); No mass loss for $ZnCl_2$	(N/A)

Table 6 Durability-based comparison among AgNPs, CuONPs, ZnONPs, TiO_2NPs. (N/A: No usable data recorded).

7.3 Economic comparison

Based on the literature review, as well as the clear evidence infront of us, there is no ounce of doubt that the biosynthesis methods for any nanoparticle is considered as one of the most widely welcomed approaches. Reiterating the obvious reasons, the physical and chemical methods require large amounts of energy, high temperature, numerous chemicals, etc. On the other hand, the biosynthesis methods utilize all the natural products on Earth, such as extracts from plants, shrubs, fungi, algae, etc. These do not require the need for excess use of chemicals that are toxic and hazardous for life on Earth, thereby reducing additional health risks for the researchers and also for the aquatic community mainly.

The metals themselves are also mostly easily available and cost-effective, except for perhaps titanium, which is quite expensive itself and are also needed in large amounts for certain methods (Stan et al., 2016)

Chapter 8

Discussion

It is no secret that the involvement of nanobiotechnology and nanoparticles in health and hygiene has managed to revolutionize the face of the biomedical and textile industries. This paper was aimed to shed some light into the antimicrobial properties of fabrics coated by the 4 most commonly used metal and metal oxide nanoparticles, namely AgNPs, CuONPs, ZnONPs and TiO_2NPs. Taking into considerations their broad spectrum antimicrobial efficiency, along with having bonus properties of photocatalysis, UPF, dye degradation, non-toxicity to humans but highly toxic to microbes even at low concentrations, moreover, with reports of having been successful in reducing HAIs, it can be suggested that copper and copper oxide nanoparticles have a very high potential as impregnating materials for textiles. Copper is easily available, it is cost-efficient, and most importantly, among its diverse antimicrobial action, it has been proved in quite a handful of studies just how effective the CuONPs are in terms of their antiviral potentials. Copper has exceptional antiviral properties, which is extremely vital at present because of the ongoing SARS-CoV-2 pandemic. Even though there exists numerous scope of research into the viricidal effects of CuNPs and CuONPs on coronaviruses or surrogate coronaviruses, unfortunately, there is a lack of research studies in this context as of now. Additionally, a study conducted by Lazary et al. (2014) showed that CuO-impregnated linens and hospital textiles have been successful in reducing the incidence of HAIs, number of fever days, antibiotic consumption, GI infection, eye infection. Keeping all these beneficial points in mind, it can be suggested that copper and copper oxide nanoparticles might serve as a very strong candidate for inducing antimicrobial activity in fabrics..

Chapter 9

Conclusion

The importance of health and hygiene cannot be overlooked. It has now grabbed the biggest attention ever since the COVID-19 pandemic has emerged. In such trying times, the importance of having textiles and clothes with antimicrobial properties is imminent. Nanoparticles are doing wonders in a lot of variety of sectors, along with proving their worth in coating textiles and inducing antimicrobial properties in them. The findings covered in this study all point towards the positive aspect of utilizing nanoparticle-based fabric, and thus provide a ray of hope in the success of future studies in developing textiles that can protect people from the ongoing pandemic, along with various other diseases caused by infectious pathogens.

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