Topical Review

Nanocomposites: Suitable Alternatives as Antimicrobial Agents

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Abstract
The exploration of nanocomposites has gained a strong research following over the last decade. These materials have been heavily exploited in several fields, with applications ranging from biosensors to biomedicine. Among these applications, great advances have been made in the field of microbiology, specifically as antimicrobial agents. This review aims to provide a comprehensive account of various nanocomposites that elucidate promising antimicrobial activity. The composition, physical and chemical properties, as well as antimicrobial performance of these nanocomposites are discussed in detail.

Keywords: antimicrobial agents, antibacterial, nanocomposites, nanomaterials

1. Introduction

1.1 Spread of Disease and Need for Antimicrobial Agents

Airborne and waterborne diseases, caused by the inhalation, ingestion or absorption of pathogenic microorganisms, pose a serious threat to human health. Quite naturally, such diseases have become the focal point of international relations as they present a significant burden to global health and healthcare expenditure.

Whilst morbidity and mortality rates of infectious diseases have dramatically declined since the 19th century, due to improvements in hygiene and sanitation, pathogenic microorganisms remain a serious threat to public health with 16 new infectious diseases having been identified in the last two decades (Fauci, *et al.*, 2005). The marked effects of these diseases are widespread, with significant impacts being made on societies, economies and political systems, particularly in developing countries. The unmet need for novel antimicrobial agents and treatments for combating infectious diseases has thus become crucial.

1.2 Current Antimicrobial Agents

A multiplicity of antimicrobial agents, such as peptides, antibiotics, antivirals, antiseptics, biocides, and disinfectants (including metal ions and quaternary ammonium compounds), has been heavily exploited in both domestic and industrial applications to prevent the proliferation of microorganisms (Allison, et al., 2007; Athanassiadis, *et al*., 2007; Aviv, Berdicevsky, and Zilberman, 2007; Bai, *et al*., 2008; Ball, *et al*., 2012; Jennings, *et al*., 2015; Liakos, *et al*., 2013; Ramstedt, *et al*., 2007; Silver, *et al*., 2006). However, these agents have several limitations, including: antimicrobial resistance, environmental pollution, labour-intensive processing methods, and high-cost.

Antimicrobial resistance, provoked by the continual use of antibiotics, antivirals, antiseptics and biocides, poses an ever-growing challenge in the search for viable antimicrobial treatments. *Staphylococcus aureus*, *Escherichia coli* and *Pseudomonas aeruginosa* are common multiple-drug resistant microorganisms that are responsible for numerous infections and typically require hospitalisation. It has been estimated that approximately 700,000 people die annually from drug resistant strains of common bacterial infections, human immunodeficiency virus, tuberculosis and malaria (U.K. Government, 2014). 29% of those deaths are caused by multi-drug resistant and extremely resistant tuberculosis (U.K. Government, 2014). The number of mortalities attributed to antimicrobial resistance is set to increase to 10 million in 2050, at a cumulative cost to global economic output of 100 trillion USD (U.K. Government, 2014). It is therefore evident that the medical and economical demand for developing new antimicrobial agents is critical.

As an alternative to conventional antimicrobial treatments, other antimicrobial agents such as peptides, metallic ions and quaternary ammonium compounds have been used. The discovery of novel, inexpensive and efficient antimicrobial agents has become the focus of foreign affairs and has gained strong scientific commitment. The desperate need for the development of such treatment methods has rapidly increased over recent years, as, despite extensive efforts in research and enormous investment of resources, the spread of antimicrobial resistance has outpaced the rate of treatment development. This has led to a paradigm shift towards the use of nanomaterials.

1.3 Nanocomposites

The application of material science and nanotechnology in medicine has shown remarkable potential for tackling various aspects of microbial infections. Many nanomaterials have been demonstrated to possess inherent antimicrobial properties that are rarely expressed in their bulk form, including silver nanoparticles, titanium oxide nanoparticles, tellurium nanoparticles, carbon nanotubes (CNTs) and their two-dimensional counterpart, graphene nanaoplatelets (GNPs) (Cheong *et al.*, 2017; Kumar, *et al.*, 2008; Matharu *et al.*, 2018a; Nepal *et al.*, 2008; Santos *et al.*, 2012; Wei *et al.*, 1994).

Nanocomposites are defined as solid multi-element materials with at least one of the elements having a dimension of less than 100 nanometres (Ajayan, Schadler, and Braun, 2004). Utilising nanocomposites enables the creation of novel materials with modifiable physical properties. This unique characteristic has attracted substantial interest from both scientists and engineers (various fields, such as biology, medicine, electronics and chemistry) in recent years. The incorporation of known antimicrobial nanoparticles into polymeric, ceramic or metallic matrices has given rise to a new generation of materials with improved properties/antibacterial activity. In some cases, the polymeric, ceramic or metallic matrices not only provide support for the nanoparticles but can also enhance antimicrobial performance and widen the potential applications of this material to meet various demands in the biomedical field, water treatment and food industry, among others.

1.4 Review Outline

In this article, a comprehensive review of the recent progress made in the use of nanocomposites for antimicrobial applications is provided. This paper will investigate the antimicrobial activity of various nanocomposites on pathogenic microorganisms; summarise the current understanding of the toxicity mechanisms of the discussed materials; as well as examine the methodologies used to perform these evaluations.

The principle aim of this article is to provide the reader with an overview of the antimicrobial activities of various nanocomposites. Such an understanding could aid in the development of strategies to mitigate potential adverse effects towards successful development of antimicrobial consumer and healthcare products.

In this review we adopt a more holistic philosophy on antimicrobial nanomaterials rather than focus on a category such as antimicrobial polymers or polymer-Ag nanocomposites (Huang *et al.*, 2016; Mei *et al.*, 2014).

1.5 Application of Antimicrobial Nanocomposites

Nanocomposites have shown tremendous importance in biomedical, water treatment, food industry, and textile applications.

1.5.1 Biomedical Industry

The safety of patients, healthcare workers and visitors are under continual threat from nosocomial infections. Such infections are typically induced by microbial biofilms that colonise the surfaces of medical devices such as syringes, catheters, infusion pumps, endotracheal tubes, and prosthetics (Klevens *et al.*, 2007). Device-associated infections are often polymicrobial, making them more challenging to treat. A crucial stage in the formation of biofilms is the initial irreversible attachment of free-floating microbes to the surface (Coad *et al.*, 2016). Once the infectious agents adhere, a biofilm develops through a combination of microbial replication and the production of a protective extracellular matrix. The adhesion and colonisation of pathogens on medical devices can be prevented through the use of antimicrobial coatings or the incorporation of antimicrobials into the materials. This results in the release of biocides into the biofilm or in contact killing (Desrousseaux *et al.*, 2013).

1.5.2 Water and Food Treatment Industry

Water and food hygiene is essential in preventing the transmission of a number of different infectious diseases and consequently has gained increasing awareness due to growing concerns regarding consumer health. The arrival of novel antimicrobial nanocomposites has come as a saviour to the water and food industry by reducing the threat to consumer health. In particular, substantial progress in water filtration technologies and food packaging has been achieved using these materials.

1.5.3 Textile Industry

Fabrics have proven to be an ideal substrate for microbial reproduction due to their large surface area and ability to retain moisture. Textiles frequently become contaminated, which can lead to undesired effects such as unpleasant odour and textile damage (James, Hyliands and Johnston, 2004; Leyden *et al.*, 1981; Munk *et al.*, 2001; Szostak-Kotowa, 2004). Some microbes are able to form strong bonds with the textile and create biofilms which are very difficult to remove. In addition, synthetic materials, such as polyesters and nylons, need to be laundered at cool temperatures with minimal agitation to prevent damage. This makes it harder to remove biofilms and thus supports the rapid development of malodour (McQueen *et al.*, 2007; McQueen *et al.*, 2014; Teufel *et al.*, 2010).

Furthermore, contaminated textiles can cause health complications in immunocompromised patients, hospital environments and can also encourage the spread of disease. For these reasons, many efforts have been made to develop antibacterial textiles. Antimicrobial coatings have previously been used, but raise environmental and health concerns, and also have a short life-span due to the frequent agitation of the textiles. Therefore, composite materials are highly desired in this application.

2 Silver Nanocomposites

Silver is a naturally occurring zero-valent transition metal that has been heavily exploited throughout millennia for antimicrobial treatments. The systemic use of silver dates back to ancient Greek civilisations (Melaiye, and Youngs, 2005; White 2001). Alexander III of Macedon reportedly treated and stored water in silver vials during long-haul expeditions (Alexander, 2009; Dhanalakshmi, *et al.*, 2013; Grier, 1968; Melaiye, and Youngs, 2005). This simple ideology has been translated into the 21st century where silver is used for storing and purifying water aboard the Apollo spacecraft, MIR space station and NASA space shuttle.

The medicinal applications of silver were first recorded by the Romans in 69 B.C.E., where silver nitrate was used to prevent the infection of burns and wounds (Alexander, 2009; Barillo and Marx, 2014; Hill, 1940). The use of silver and silver ions (Ag^{+1}) in both medical and environmental antimicrobial treatments continued to grow until the emergence of antibiotics in the 20th century. It wasn't until the 1960s when Moyer re-introduced the clinical use of silver ions. In this work Moyer used 0.5% silver nitrate in the treatment of severe human burns and put forth the claim that silver contains antibacterial properties against *S. aureus*, *E. coli* and *P. aeruginosa* (Moyer, 1965). This instigated the development of a multitude of silver-based composites. Although the antimicrobial mechanism of action has not been well investigated, it is thought that the antiviral and the antibacterial activities differ. Research has indicated that the antiviral activity is a result of the silver ions binding to the viral envelope glycoproteins, thereby inhibiting viral penetration into the host cell. Whilst the antibacterial mechanism is thought to involve the production of reactive oxygen species, membrane disruption and the interaction of silver ions with respiratory enzymes (**Figure 1**). However, there are still some controversies on the application of silver in clinical studies as high doses of silver ions may trigger intoxication.

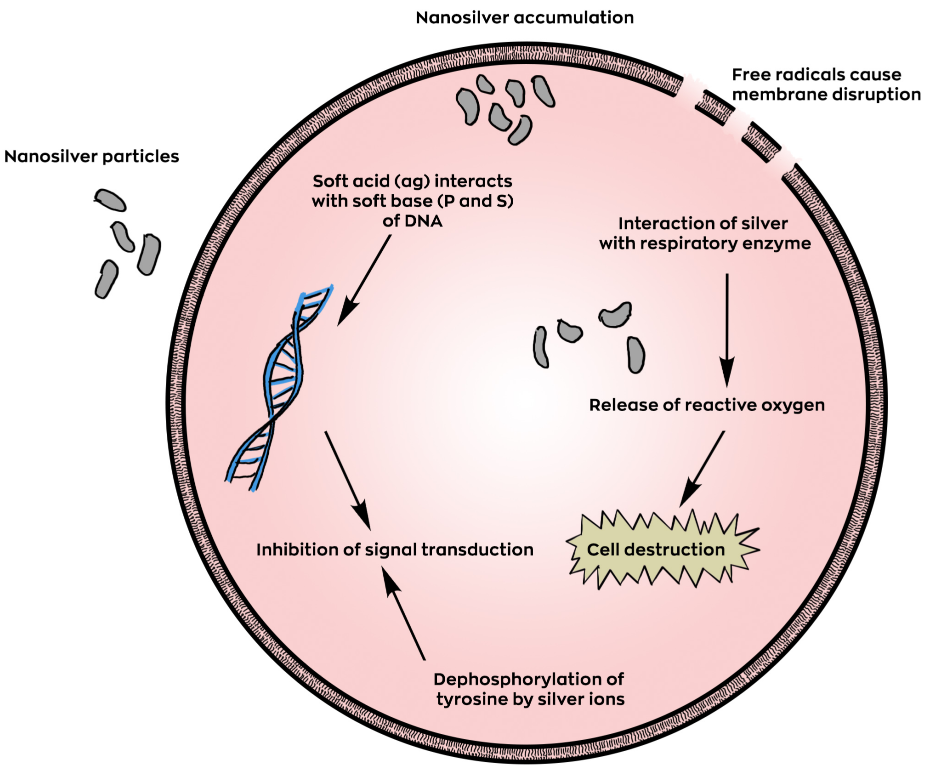

Figure 1: Schematic diagram summarising the various destructive modes of action of silver nanoparticles in bacteria.

Driven by the desire to establish a synergistic nanocomposite, countless researchers have endeavoured to synthesise silver based antimicrobial hybrids. The resulting materials have favourable properties for water treatment, wound dressing, packaging, food preservation and many other applications.

2.1 Silver – Chitosan

Chitosan is a naturally occurring linear cationic polysaccharide composed of randomly distributed N-acetyl-D-glucosamine and D-glucosamine sugars linked by ß-(1→4)glycosidic bonds (Tharanathan and Kittur, 2003). The ratio and distribution of these sugars often dictates its material properties, however in general chitosan is readily-available, physically stable, bioactive, biodegradable, biocompatible and easily processed (Singla and Chawla, 2001; Tharanathan and Kittur, 2003). Chitosan has also demonstrated unique antibacterial, antifungal and antiviral properties in both *in vivo* and *in vitro* interactions (Muzzarelli *et al*., 1990; No *et al*., 2002; Rabea, *et al*., 2003; Savard *et al*., 2002). These characteristics have led researchers to believe chitosan is either bactericidal or bacteriostatic, with recent literature suggesting that chitosan is bactericidal (Coma *et al*., 2002). For these reasons, chitosan has been used to preserve foods, treat damaged oral cavities and to provide antibacterial protection in wound dressings and ophthalmic gels (Felt *et al*., 1999; Jayakumar *et al*., 2011; No *et al*., 2007; Wieckiewicz *et al*., 2017).

Numerous studies have shown that the incorporation of silver nanoparticles into chitosan enhances the antimicrobial properties of the materials. Mesoporous § SBA-12 loaded chitosan films have shown significant antibacterial activity against *P. aeruginosa*, *Staphylococcus epidermidis* and *S. aureus* (Ambrogi, *et al.*, 2014). In this experiment, three chitosan films were loaded with increasing SBA-15 concentrations ranging from 5-15%. The results from this investigation showed that the incorporation of silver enhanced the antibacterial effect of chitosan against *S. epidermidis* and *S. aureus*. Whilst in the case of *P. aeruginosa* the silver particles were solely responsible for the antibacterial activity.

Silver nanoparticle/chitosan composites have also shown antiviral activity against H1N1 influenza A virus (Mehrbod, *et al.*, 2009; Mori *et al.*, 2013; Xiang, *et al.*, 2011). Mori and co-workers suspended 23.5 wt% of silver nanoparticles in a chitosan matrix in order to investigate its inhibitory activity against H1N1 influenza A virus. This study demonstrated that for all the three nanoparticle diameters tested (3.5 nm, 6.5 nm and 12.0 nm), antiviral activity increased as nanoparticle concentration increased. In addition, it was also observed that antiviral activity was size dependent, as antiviral activity was generally stronger when smaller silver nanoparticles were suspended in the composites (Mori *et al.*, 2013).

2.2 Silver – Silicon

Antibacterial ceramics have attracted significant attention in applications such as bone prosthetics, wastewater treatment, sanitary tile ware and glazing (Su and Xiong., 2007; Uzgur *et al.*, 2004; Wang *et al.*, 2011; Lv *et al.*, 2009). These ceramics predominately use silver as the antibacterial component.

The antibacterial activity of silver-silica nanocomposites against a variety of microorganisms (**Table 1**) has been documented in the recent literature (Egger *et al.*, 2009; Lv *et al.*, 2010). Egger and colleagues employed a ceramic composite composed of silver nanoparticles submerged in an amorphous silicon dioxide matrix, with particles located on the surface and also embedded within the matrix (Egger *et al.*, 2009). This research demonstrated that this novel material possessed antibacterial properties against both Gram-positive and Gram-negative bacteria at high concentrations when compared to conventional silver-based materials, such as silver nitrate and silver zeolite.

Lv *et al.*, further reported that silicon nanowires decorated with silver nanoparticles are also able to suppress bacterial growth. In this study *E. coli* DH5 and *B. subtilis* were cultured in Luria-Bertani liquid media containing silicon nanowires and silver coated silicon nanowires (Lv *et al.*, 2010). After two days of incubation, the suspension containing silicon nanowires became turbid suggesting bacterial proliferation took place, whilst the mixture containing silver coated silicon nanowires remained pellucid therefore indicating proliferation did not take place (Lv *et al.*, 2010). Bacterial growth was quantified by taking absorbance readings at an optical density of 600 nm. These results corroborated the observations made, as absorbance remained unchanged when 10% of silver coated nanowires were added to the cultures (Lv *et al.*, 2010).

2.3 Silver – Cotton

Cotton is a naturally occurring fibre composed mostly of cellulose, with its repeating unit being 1,4-glucopyranose (Son *et al.*, 2006). The use of cotton in the textile industry dates back to prehistoric times. The materials extreme popularity is a result of its advantageous properties, including its ability to absorb sweat and retain moisture. Unfortunately, this unique quality also makes cotton a suitable breeding ground for microorganisms. Numerous chemical agents and physical treatments have been used to inhibit microbial proliferation. Among these treatments, silver-cotton nanocomposites have demonstrated desirable killing properties.

In research conducted by Tarimala *et al.*, dodecanethiol-capped silver nanoparticles were incorporated in silica sol via the sol-gel process. The sol was then used to dope the surface of cotton. This study presented evidence that silver doped cotton exhibits antibacterial activity when incubated in a suspension of *E. coli* for 5 hours (Tarimala *et al.*, 2005). Fabric treated with the sol containing 15 mL of dodecanethiol-capped silver nanoparticles reported high antibacterial performance (Tarimala *et al.*, 2005). The treated cotton completely suppressed bacterial growth.

In another study, the antibacterial activity of cotton fibres decorated with silver nanoparticles showed enhanced antibacterial activity against *E. coli* when compared to pure silver particles. The nanocomposite fibres prevented microbial proliferation entirely, thus demonstrating strong antibacterial activity (Chen and Chiang., 2008).

Ravindra *et al.*, also concluded that the antibacterial efficiency of cotton fibres loaded with silver nanoparticles corresponded with the results of the previous two studies. In this investigation silver nanoparticles were loaded onto cotton fibres using a “green process”. Whereby only environmentally friendly materials and chemicals were used during the fabrication process, to reduce or eliminate the use or generation of hazardous substances in the design, manufacture and application of chemical products. Irrespective of the fabrication method, the fibres demonstrated similar antibacterial properties as an inhibition zone was observed when the fibres were tested against *E. coli* (Ravindra *et al*., 2010).

2.4 Silver – Polyurethane

Polyurethane is an organic polymer commonly used in a variety of industries including, building and construction, transportation, filtration, packaging, textiles and biomedical equipment.

Jain and Pradeep (2005) demonstrated that soaked polyurethane foams in silver nanoparticle solution exhibit antibacterial activity against *E. coli* ATCC 25922 and *E. coli* MTCC 1302. In this study, polyurethane foams were immersed in a silver nanoparticle solution overnight to allow the silver particles to saturate and cover the foam (Jain and Pradeep, 2005). The antibacterial activity of the foams was tested using three individual assays: test tube test, flow test and agar diffusion assay. In all three assays, no growth of both kinds of *E. coli* was detected after treatment with the polyurethane foam with nanoparticles, while growth was seen in the case of pure polyurethane (Jain and Pradeep, 2005). The results obtained here are in line with the WHO requirements for drinking water (Jain and Pradeep, 2005). It was also observed that the polyurethane foam coated with silver nanoparticles could be stored for extended periods of time without the loss of nanoparticles, therefore making it suitable for the commercial industry (Jain and Pradeep, 2005).

Hsu and colleagues (2010) have also shown the antibacterial properties of polyurethane films doped with various concentrations of silver nanoparticles (~ 5nm). The films were incubated in bacterial suspensions containing *B. subtilis*, *E. coli* and silver resistant *E. coli* for 12 hours. The polyurethane-silver nanocomposites showed much lower bacterial adhesion when compared to pure polyurethane films (Hsu, Tseng and Lin, 2010). For all strains tested, polyurethane films containing 30 ppm of silver nanoparticles showed the most potent antibacterial activity (Hsu, Tseng and Lin, 2010).

2.5 Silver – Epoxy Clay

Epoxy clay nanocomposites are heavily relied on in the construction industry due to its superior mechanical, structural and barrier properties. Several studies have verified that anchoring silver nanoparticles on epoxy clay reduces or eliminates microbial contamination. Roy *et al*., (2013) assessed the antibacterial activity of the composites using an agar diffusion assay against *S. aureus*, *B. subtilis*, *E. coli*, *P. aeruginosa* and *K. pneumoniae*. The nanocomposites were incubated for 24 hours at 37^{o}C. The results from this assay showed that the composite was antimicrobial against all strains tested but was most effective against *K. pneumoniae*, with a 20 mm inhibition zone being observed.

Mejía *et al.*, have also investigated the antibacterial activity of these nanocomposites against a *E. coli* cultures using an agar diffusion assay and reported the observation of an inhibitory halo around the nanocomposite containing silver (Mejía *et al.*, 2017). This result is in accordance with results obtained in other studies.

Although the agar diffusion assay has verified the antimicrobial properties of the silver epoxy composite, a more thorough analysis should be performed in order to understand the kinetics of antimicrobial activity and the long-term effects.

2.6 Silver – Polyester

Synthetic materials, such as polyester, are commonly used in textile fabrics. Such materials do not have resistance to pathogenic microorganisms, thus several researchers have incorporated silver nanoparticles into the material to control microbial colonisation and contamination. The antimicrobial properties of the nanocomposite have been evaluated, both quantitatively and qualitatively, against *S. aureus*, *K. pneumoniae* and *E. coli* cultures (Lee, Yeo and Jeong, 2003; Perelshtein *et al.*, 2008; Radetić *et al.*, 2008). In all studies, bacterial cultures were either significantly reduced (~ ≥84%) or completely eradicated after 1 hour of treatment with the silver-polyester composite.

Table 1 summarises the key points of a variety of studies on the different antibacterial features of nano-silver.

Table 1 Bactericidal and bacteriostatic activity of nano-scaled silver

Silver Form	Size Data	Hybrid Components	Microbial Strain	Key Features	References
SBA-15-Ag	200nm – 1μm	1.5% (w/w) chitosan dispersion in 0.5% (v/v) acetic acid and 0.1% (v/v) glycerol aqueous solution	*P. aeruginosa, S. epidermidis*, *S. aureus*		Ambrogi, *et al.*, 2014
Silver nanoparticles (synthesised from silver containing glass)	3.5nm – 12.9nm	Chitosan solution (10mg/mL), average molecular weight 54 kg/mol.	Human influenza A virus (H1N1)	Fifty-percent tissue culture infectious dose method.	Mori *et al.*, 2013
Silver 'seeds' formed by the reduction of silver nitrate	43 – 55 nm	Chitosan flakes (high molecular weight, >75% deacetylated)	Methicillin-resistant *S. aureus* UCLA 8076 and 1190R	Silver nanoparticles were encapsulated in chitosan.	Potara *et al.*, 2011
Silver nitrate	< 25 nm	Commercially available chitosan with low, medium and high molecular weights.	*S. aureus* ATCC 6538 and 9213	Chitosan films loaded with silver nanoparticles were used. Medium molecular weight chitosan-silver nanocomposites showed the most potent effect.	Regiel *et al.*, 2012
As-synthesised nanoparticles	10 nm	Ceraset® VL20 (KiON Corp)	*S. aureus* and *E. coli*		Bakumov *et al.*, 2007
Silver nanoparticles		Silicon Dioxide	*E. coli* ATCC 2732, *Klebsiella pneumonia* ATCC 4352, *Pseudomonas fluorescens* LME 2333, *Salmonella enterica* serovar Enteritidis D1, *Salmonella enterica*		Egger *et al.*, 2009

			serovar Typhimurium DB 7155, *Enterococcus faecalis* ATCC 19433, *Bacillus cereus* ATCC 14579, *Listeria monocytogenes* Scott A, *S. aureus* ATCC 10259, *Aspergillus niger* ATCC 9642		
Silver nanoparticles	3 – 15 nm	Silicon Nanowires	*E. coli* DH5, *Bacilius subtilis*	The silver coated silicon nanowires had stronger antibacterial affects against *E. coli*.	Lv *et al*., 2010
Silver bromide nanoparticles		Poly(4-vinyl-N-hexylpyridinium bromide)	*E. coli* and *B. cereus*	Poly(4-vinyl-N-hexylpyridinium bromide) is antibacterial towards both Gram positive and Gram negative bacterium	Sambhy *et al*., 2006
Silver Nitrate	40 – 150 nm	Cotton fibre-graft-GMA-IDA	*E. coli*		Chen and Chiang. 2008
Dodecanethiol-capped silver particles	1 – 5 nm	Cotton fabric	LBB735, a wild-type *E. coli* K12		Tarimala *et al*., 2005
Silver citrate		Polyurethane	*E. coli* ATCC 25922, *E. coli* MTCC 1302	No growth of both kinds of *E. coli* was detected after treatment with the polyurethane foam with nanoparticles.	Jain and Pradeep, 2005

Silver	~ 5 nm	Polyurethane.	*B. subtilis* ATCC 6633, *E. coli* JM109, *silver resistant E. coli* J53 (pMG101)	The polyurethane-silver nanocomposites showed much lower bacterial adhesion when compared to pure polyurethane films.	Hsu, Tseng and Lin, 2010.
Silver	5 – 20 nm	Epoxy clay	*S. aureus* ATCC 11632, *B. subtilis* ATCC 1174, *E. coli* MTCC40, *P. aeruginosa* MTCC 7814, *K. pneumoniae* ATCC 10031	The nanocomposite was effective against all strains tested but was most potent against *K. pneumoniae*.	Roy *et al.*, 2013.
Silver		Epoxy clay	*E. coli* K12 strain RP437	Agar diffusion assay was performed. Growth inhibition zone was observed.	Mejía *et al.*, 2017.
Nanosilver colloids	2 – 5 nm	Polyester fabric	*S. aureus ATCC 6538, K. pneumoniae ATCC 4352*	Agar diffusion assay was used. Specimens were incubated for 24 hours. 99.9% bacterial reduction observed for all strains.	Lee, Yeo and Jeong, 2003.
Silver	80 nm	Polyester fabric	*E. coli* strain 1313, *S. aureus* strain 195	Samples were incubated in bacterial suspensions at 37^{o}C and 170 strokes min^{-1} for 4 hours. Colony counting method was employed. 100% reduction in bacteria numbers was observed at 2 hours for all strains.	Perelshtein *et al.*, 2008.

Silver colloid	10 nm	Polyester fabric	*S. aureus* ATCC 25923, *E. coli* ATCC 25922.	Bacterial reductions ranged between 84.3 – 99.9%.	Radetić *et al*., 2008.
Silver nanoparticles	10 – 150 nm	Poly(ε-caprolactone)	*E. coli* (in house strain number 3891, Centre for Clinical Science & Technology, UCL), *P. aeruginosa* (strain 25-09071215-05)	The samples were incubated for 2 hours. An antibacterial rate of approximately 95% was observed with both strains tested.	Xu *et al*., 2016.

3. Titanium Dioxide Nanocomposites

Photocatalytic materials have a remarkable efficacy in provoking microbial death once illuminated by light (Kangwansupamonkon *et al.*, 2009). Titanium dioxide is amongst the most powerful photocatalytic materials; it shows high activity, great oxidizing power and long-term stability (Blake *et al.*, 1999; Maness *et al.*, 1999; Sato and Taya, 2000). However, mechanisms leading to microbial death are poorly understood in addition to its effect on microbes. When exposed to ultraviolet light at wavelengths less than 385 nm, titanium dioxide is able to generate strong oxidising powers (Huang *et al.*, 2000; Rincón, and Pulgarin, 2003; Schmidt *et al.*, 2005). The energy from the photon generates an electron hole pair on the titanium dioxide surface (Kubacka *et al.*, 2014). Hydroxyl radicals are then produced when hydroxide ions or water adsorbed onto the surface and react with the hole in the valence band (Kangwansupamonkon *et al.*, 2009). Superoxide ions can also be produced when the electron in the conduction band reduces O_2 (Kangwansupamonkon *et al.*, 2009). The hydroxyl radical and both holes become extremely reactive when in contact with organic compounds, causing the transformation into non-toxic materials (Kangwansupamonkon *et al.*, 2009).

Titanium dioxide has considerable benefits over alternative chemical and metallic antimicrobial materials. Titanium dioxide nanoparticles exhibit broad-spectrum biocidal activity toward many different microorganisms, Gram –negative and –positive bacteria, as well as fungi (Josset *et al.*, 2008; Wiener et al., 1999). Furthermore, titanium dioxide nanocomposites pose no threat to the environment and exert a non-contact biocidal action. Therefore, no release of potentially toxic nanoparticles (with unpredictable effects on human health) to the media is required to achieve disinfection (Cerrada *et al.*, 2008; Kubacka *et al.*, 2007; Luo *et al.*, 2009).

The biocidal mechanism of action of titanium dioxide-based nanocomposites is not completely understood. However, it is known that an initial oxidative attack causes degradation of the cell wall and cytoplasmic membrane of the microorganism (Foster *et al.*, 2011; Kiwi *et al.*, 2005). The degradation leads to leakage of cellular contents, followed by cell lysis and complete mineralisation of the microorganism (Foster *et al.*, 2011; Kiwi *et al.*, 2005). It has also been reported that the production of reactive oxygen species such as hydroxyl radicals and hydrogen peroxide also interferes with Coenzyme A-dependent enzyme activities thus resulting in DNA damage (Matsunaga *et al.*, 1985).

3.1 Titanium Dioxide – Poly(N-vinylpyrrolidone) – Chitosan

Poly(N-vinylpyrrolidone) (PVP), a synthetic water-soluble polymer obtained by radical polymerisation in solution, displays unique desirable properties such as low toxicity, chemical stability and good biocompatibility (Liu *et al*., 2012). When subjected to ionising radiation, PVP undergoes crosslinking resulting in the formation of a PVP hydrogel having excellent transparency and biocompatibility (Archana *et al*., 2013). The development of PVP related hydrogels has gained strong scientific attention due to their potential applications in the biomedical industry, as contact lenses, a vitreous humour substitute, blood plasma expander, cell culture substrate, drug carrier for controlled-releasing of therapeutic drugs, wound dressing, temporary skin cover and much more (Altemeier *et al*., 1954; Yang *et al*., 2014; Zileinski and Acbischer, 1994). However, the hydrogel of PVP itself is of limited applicability because of its poor mechanical properties and its inability to prevent microbial growth. Therefore, many researchers have developed a series of PVP hydrogels with enhanced antimicrobial activity. For example, chitosan and titanium dioxide nanorods were incorporated into PVP to achieve excellent antimicrobial behaviour.

Archana *et al*., (2013) assessed the antimicrobial properties of this nanocomposite against both Gram-positive and Gram-negative bacteria using the agar disc diffusion method. It was reported that the antibacterial inhibition zone for chitosan-PVP-titanium dioxide against *E. coli*, *S. aureus*, *P. aeruginosa* and *B. subtilis* was measured as 30 mm, 32 mm, 38 mm and 28 mm, respectively. The inhibition zone against different microbial cultures proves that chitosan-PVP-titanium dioxide nanocomposites had an excellent antibacterial activity when compared to the control.

3.2 Titanium Dioxide – Polyvinyl Chloride

Biofilm formation on biomedical implants/devices poses a major threat to patient health and bears a financial burden on the healthcare system. It has been estimated that biomedical implants/devices are responsible for 1 – 30% of infections, with catheter associated urinary tract infections being the most prevalent (Suganya, Shanmugavelayutham and Rodriguez, 2017). A large majority of implants/devices in the biomedical industry are fabricated from polymeric materials, such as polyvinyl chloride (PVC), and serve as a perfect platform for bacterial adhesion and proliferation (Asadinezhad *et al*., 2012; Kennedy and Thorley, 2001).

Suganya and colleagues have demonstrated pre-functionalised PVC films grafted with titanium dioxide and PVP to have drastically improved antimicrobial properties towards *E. coli* (Suganya, Shanmugavelayutham and Rodriguez, 2017). The antibacterial activity of this nanocomposite was investigated by the agar diffusion method. PVC with titanium dioxide and PVP grafted films displayed inhibition zones ranging between of 4.5 and 8.0 mm, whilst pure PVC did not. It was also found that there was a positive correlation between the deposition rate of titanium dioxide and the antibacterial activity of the treated films, therefore indicating antimicrobial activity is dose dependent.

Light-activated titanium dioxide–PVC nanocomposites have also shown similar results. When exposed to 11.5 hours of ultraviolet radiation prior to bacterial testing, the nanocomposite shows minimal bacterial adhesion (1.5 $x10^4$ CFU/cm^2) when compared to pure PVC (1.3 $x10^5$ CFU/cm^2), therefore suggesting titanium dioxide-PVC nanocomposites inhibit bacterial adhesion and proliferation. In this instance, photoactivation of titanium dioxide nanoparticles increased the photocatalytic activity of the nanocomposite thus enhancing the materials' antibacterial activity (Lin *et al.*, 2008).

3.3 Titanium Dioxide – Cotton

The need for antimicrobial fabrics has been briefly mentioned in **section 2.3**. In addition to silver nanoparticles, photoactivated titanium dioxide nanoparticles have also been incorporated into textile fabrics. The use of photoactivated titanium dioxide nanoparticles benefits several applications, however the direct application of ultraviolet light on some materials can lead to degradation thus resulting in delamination. To alleviate this, titanium dioxide can be applied to textile fabrics, such as cotton. When exposed to both black light radiation and microbial suspensions for 24 hours, bacterial reduction ranges between 5.5% and 24.2% (Kangwansupamonkon *et al.*, 2009). This study, demonstrates that titanium dioxide coated cotton fabrics attain disinfecting properties yet carry no toxic properties towards human cells (Kangwansupamonkon *et al.*, 2009).

3.4 Titanium Dioxide – Polyurethane

Polyurethane is a well-known polymer used for various applications due to its excellent mechanical properties, as mentioned previously in this report. Zhang and colleagues prepared hydrophilic polyurethane/titanium dioxide complex films and evaluated the antimicrobial activities of the samples against *E. coli*, *C. albicans* and *Aspergillus niger*. The samples were incubated for 24 hours. The number of colonies in the suspension before and after incubation were counted and the bacterial reduction was calculated. The results showed a 100% reduction of bacterial cells after 24 hours of incubation with the titanium dioxide/polyurethane samples (Zhang *et al.*, 2008). Over 90% sterilisation of all bacterial strains was observed within 4 hours of incubation (Zhang *et al.*, 2008). The antimicrobial effect of the nanocomposite was much stronger on *E. coli* and *C. albicans* than *A. niger* (Zhang *et al.*, 2008). It was also observed that the longer the samples were stored prior to incubation, the stronger the antimicrobial properties, due to enhanced hydrophilicity (Zhang *et al.*, 2008).

Charpentier *et al*., (2012) later assessed the antimicrobial activity of nano-titania/polyurethane composite coatings they had prepared. In this study, titanium dioxide nanoparticles were homogenously dispersed in polyurethane coatings (Charpentier *et al.*, 2012). The antimicrobial activity of the specimens was evaluated by the photo-killing of *E. coli* under solar radiation (Charpentier *et al*., 2012). Here, a decrease in the number of *E. coli* colonies was observed after incubation with the composite (Charpentier *et al*., 2012). The results presented in this study demonstrate the bactericidal activities of this material as more than 99.5% of the bacteria were killed in one hour, whereas pure polyurethane only killed approximately 9% of the bacteria (Charpentier *et al.*, 2012).

Table 2 summarises some useful studies and data on the use of titanium dioxide-based nanocomposites as antimicrobial agents.

Table 2 Bactericidal and bacteriostatic activity of nano-scaled titanium dioxide nanocomposites

Titanium Dioxide Form	Size Data	Hybrid Components	Microbial Strain	Key Features	References
Titanium dioxide nanorods	25 – 35 nm	Chitosan and PVP	*E. coli*, *S. aureus, B. subtilis* and *P. aeruginosa*		Archana *et al.*, 2013
Titanium dioxide nanoparticles	40 – 60 nm	High density PVC resin and PVP	*E. coli*	PVC films grafted with titanium dioxide/PVP were used.	Suganya, Shanmugavelayutham and Rodriguez, 2017
Titanium dioxide film	20 nm	PVC	*E. coli*	Antibacterial properties light activated.	Lin *et al.*, 2008
Titanium dioxide nanoparticles	20 – 30 nm	Regenerated bacterial cellulose	*E. coli* (KCCM 12119)	Antibacterial activities were investigated by both optical density and colony forming unit methods.	Khan *et al.*, 2014
Titanium dioxide nanoparticle powder	<100 nm	Polylactide	*E. coli*, *Listeria monocytogenes*	Antibacterial activity was assessed through colony forming units	Li *et al.*, 2017
Titanium dioxide nanoparticles (KRONOClean 7050)	Not Available	Acrylic resin	*E. coli* CIP 53126	Photoactivated titanium dioxide was used. It is thought the antibacterial activity is a result of basic environmental conditions caused by the release of silicates	Verdier *et al.*, 2014
Titanium dioxide nanoparticles	390 nm	Cotton fabric	*S. aureus* (ATCC 6538), *E. coli* ATCC 25922, methicillin-resistant *S.*		Kangwansupamonkon *et al.*, 2009

			aureus (MRSA) DMST 20627, *Micrococcus luteus* ATCC 9341		
Titanium dioxide nanoparticles	~ 25 – 30 nm	Polyurethane	*E. coli, C. albicans, A. niger*	90% sterilisation of all bacterial strains was observed within 4 hours of incubation.	Zhang *et al.*, 2008
Titanium dioxide nanoparticles	25 nm	Polyurethane	*E. coli* DH	99.5% of the bacteria were killed in one hour.	Charpentier *et al.*, 2012

4. Zinc Oxide Nanocomposites

Zinc oxide is a synthetically produced inorganic compound that holds unique piezoelectric, optical, catalytic, semiconducting and photochemical qualities. These characteristics make zinc oxide a suitable material for various applications, including transparent electrodes, transistors and light emitting diodes. Zinc oxide nanoparticles have demonstrated a broad spectrum of activity against microorganisms, including Gram-negative and Gram-positive strains of bacteria as well as fungi (Brayner *et al.*, 2006; Buzea, Pacheco and Robbie, 2007; Jalal *et al.*, 2010; Jones *et al.*, 2008; Padmavathy and Vijayaraghavan, 2008; Zarrindokht Emami-Karvani, 2012).

Exploration of zinc oxide as a suitable material to prohibit microbial attachment, growth and proliferation began in the 1950s (Espitia *et al.*, 2012). However, exploitation of zinc oxide as an antimicrobial commenced in the late 1990s, following research conducted by Sawai and colleagues that demonstrated zinc oxide had antibacterial properties (Sawai, 2003; Sawai *et al.*, 1997; Sawai *et al.*, 1998).

At present, zinc oxide is regarded as “generally recognized as safe” (GRAS) by the American Food and Drug Administration, it has also shown no toxicity towards human cells as it is non-allergenic, non-irritating and non-comedogenic (Colon, Ward and Webster, 2006). For these reasons, it has been heavily relied upon in the food packaging industry to prevent the spread of foodborne diseases, as well as in topical treatments for superficial cutaneous irritations.

Formulations incorporating nanoscale zinc oxide have shown enhanced antimicrobial activities. A critical point for addressing the bactericidal and bacteriostatic capabilities of zinc oxide-based nanocomposites concerns the mechanism by which cell viability is lost and cell death occurs. As with many nanomaterials the exact mechanism is being debated, however a few theories have been proposed, including: physical penetration of zinc oxide nanoparticles into the microbial cell wall, resulting in cell wall rupture followed by the leakage of cellular contents; cellular internalisation of zinc ions; electrostatic interactions between the nanoparticles and the negatively charged cell membrane facilitates nanoparticle attachment; and photocatalytic activity such as, the formation of reactive oxygen species (in particular hydrogen peroxide) under ultraviolet light illumination (Adams, Lyon and Alvarez, 2006; Brayner *et al.*, 2006; Brunner *et al.*, 2006; Jalal *et al.*, 2010; Kasemets *et al.*, 2009; Li, Zhu and Lin., 2011; Lipovsky *et al.*, 2011; Sawai *et al.*, 1998; Sirelkhatim *et al.*, 2015; Zhang *et al.*, 2006).

4.1 Zinc Oxide – Fortified Cold Cream

Novel organic dermatological and cosmetic formulations to combat various skin concerns have of significant current interest. Chemical preservatives are typically used to increase the shelf life of these products, however due to the increased desire for organic products, zinc oxide presents itself as a suitable alternative (Pasquet et al., 2015). Incorporation of zinc oxide in cosmetic formulations, does not only increase the shelf life of the product through the prevention of microbial colonisation but also by improving the stability of the active ingredients.

Fortified cold cream was blended with zinc oxide nanoparticles at two different concentrations (1% and 2%) and the antimicrobial action of the formulations were studied using *Candida* species over a period of 7 days and the disc diffusion method (S. *et al.*, 2017). The presence of zinc oxide significantly enhanced the antifungal properties of the cream, whilst allowing it to retain its other properties. When compared to commercially available products, the nano-cream formulation displayed improved fungal resistance. It has been proposed that the antifungal activity of zinc oxide is a result of the nanoparticles causing hyphal deformation, thus preventing the development of conidiophores and consequently hyphal death (He *et al.*, 2010).

4.2 Zinc Oxide - Halloysite

Modifying halloysite nanotubes with zinc oxide nanoparticles has proven to be a successful method to enhance antibacterial activity. Halloysite is a naturally occurring nanosized tubular clay mineral (aluminosilicate) that has many important uses in different industries (Yuan, Tan and Annabi-Bergaya, 2015). Shu and colleagues loaded zinc oxide nanoparticles onto the surface of halloysite and assessed the antibacterial properties of the nanocomposite with respect to Gram-negative bacteria using *E. coli* as the model bacterium (Shu *et al.*, 2017). The nanocomposite along with the bacterial culture were incubated for 4 hours at 37^{o}C (Shu *et al.*, 2017). Incorporation of zinc oxide onto halloysite drastically improved the materials antibacterial activity by 88% (the nanocomposite exhibited 12% cell viability whilst pure halloysite showed 100% cell viability) (Shu *et al.*, 2017). The antibacterial mechanism of this novel nanocomposite is thought to involve both the physical interactions between zinc oxide and the bacteria, as well as the chemical reactions. Zinc oxide nanoparticles penetrate the cell membrane and consequently disrupt cell membrane integrity and increase permeability. Zinc oxide nanoparticles infiltrate the cell and initiate the production of reactive oxygen species which in turn damage the cells' DNA leading to cell death.

4.3 Zinc Oxide – Cellulose

Synthesis of zinc oxide – cellulose nanocomposites in form of filaments, papers and foams has attracted significant research interest (Fu *et al.*, 2014; Martins *et al.*, 2013; Wang *et al.*, 2014). The antimicrobial efficacy of this nanocomposite has shown to be dependent on the concentration of zinc oxide nanoparticles in the composition. Studies have demonstrated that as the amount of zinc oxide increases, the antibacterial activity also increases (Yu *et al.*, 2014; Zhao *et al.*, 2017). Quantitative analysis of the minimum inhibitory concentration (MIC) of zinc oxide–cellulose nanocomposites revealed that the MIC for *S. aureus* is 0.44 mg/mL^{-1}, whilst for *E. coli* it is 0.63 mg/mL^{-1}(Zhao *et al.*, 2017).

In a study carried out by Martins *et al.* (2013), a 2-log reduction was achieved when zinc oxide–nanofibrillated cellulose was incubated with *Klebsiella pneumoniae* for 24 hours at 30^{o}C with no light. During this study, the nanocomposite was incubated with *S. aureus*, *B. cereus* and *K. pneumoniae* for 4 hours with light illumination or 24 hours with no light. *K. pneumoniae* demonstrated the maximum log reduction, followed by *S. aureus* (maximum reduction: 1.75-log) *and B. cereus* (maximum reduction: 1.5-log).

The studies reported here suggest the increased antimicrobial activity of zinc oxide-incorporated cellulose materials arise from the infiltration of the zinc oxide component with a resulting high bactericidal effect.

4.4 Zinc Oxide – Polyurethane

The production and evaluation of antimicrobial activity of zinc oxide – polyurethane nanocomposites have been reported by numerous researchers. Zinc oxide – polyurethane nanofibers produced by electrospinning were achieved by Lee (2009). The biocidal activity of these fibres was assessed by measuring the bacterial reductions of *S. aureus* and *K. pneumoniae,* in accordance with the ASTM E 2149-01 standardised test. The fibres had the most potent effect against *S. aureus*, with 99.9% bacterial reductions being observed at concentrations of 1 and 5 wt% of zinc oxide. Whilst 60.0% and 98.7% bacterial reductions were noted for *K. pneumoniae* at zinc oxide concentrations of 1 and 5 wt%, respectively. On the basis of these results, it can be said that antibacterial activity is dose dependent.

An 84% bacterial reduction of *B. subtilis* has also been observed and reported by Li *et al.*, (2009). In this study polyurethane coatings were reinforced with 4 wt% of zinc oxide nanoparticles (~ 27 nm) (Li *et al.*, 2009). The samples were incubated for 24 hours with bacteria after which the bacterial reduction was calculated. This reduction is less when compared to the reduction observed with *E. coli* and *K. pneumoniae* but is thought to be due to the generation of free radicals (Li *et al*., 2009).

A variety of materials, ranging from naturally occurring ceramics to synthetic polymers, have been compounded with zinc oxide nanoparticles as potential new antimicrobial agents. Some of these formulations are shown in **Table 3**.

Table 3 Bactericidal and bacteriostatic activity of nano-scaled zinc oxide nanocomposites.

Zinc Oxide Form	Size Data	Hybrid Components	Microbial Strain	Key Features	References
Zinc oxide	10 – 12 nm	Fortified cold cream (composed of bees wax, liquid paraffin, borax, Milli-Q water)	*Candida species*	Disc diffusion method was used. 2% demonstrated enhanced antifungal properties compared to commercially available products.	S. *et al.*, 2017
Zinc oxide	10 – 15 nm	Lanthanum	*S. aureus*, *Proteus mirabilis*, *Salmonella typhii* and *B. subtilis*	Disc diffusion method was used.	Manikandan *et al.*, 2017
Zinc oxide	8 nm	Halloysite nanotubes	*E. coli* Dh5	Antibacterial activity was determined using the plate count method. A 12% cell viability was exhibited, when compared to the control which was 100%.	Shu *et al.*, 2017
Zinc oxide	10 – 30 nm	Cellulose	*S. aureus, E. coli*	Disc diffusion method was used.	Zhao *et al.*, 2017
Zinc oxide	41 nm	Nanofibrillated cellulose	*S. aureus, B. cereus, K. pneumoniae*	Maximum 2-log reduction was achieved.	Martins *et al.*, 2013
Zinc oxide	24 – 71 nm	Polyurethane	*S. aureus* ATCC 6538, *K. pneumoniae* ATCC 4352	>90% bacterial reduction was observed with composites containing 5 wt% zinc oxide.	Lee, 2009

Zinc oxide	27 nm	Polyurethane	*E. coli, B. subtilis*	At 4 wt% 90% and 84% bacterial reductions were observed for *E. coli* and *B. subtilis*, respectively.	Li *et al.*, 2009

5 Copper Nanocomposites

Copper and its alloys are naturally occurring antimicrobial agents that have been used by human civilisations since the 5th millennium B.C. (Grass, Rensing and Solioz, 2010). The earliest recording of copper being employed as an antimicrobial agent can be found in Edwin Smith Papyrus (written in 1501 B.C.), where the application of copper to disinfect thoracic injuries and drinking water is described. Ancient civilisations continued to take advantage of copper and its compounds in medicinal preparations to treat ailments such as; intestinal parasites and ear infections and for general hygiene.

During the 19th Century, a new realisation of coppers' antimicrobial potency arose from the observation that copper miners seemed to possess cholera immunity throughout the 1832 and subsequent outbreaks and pandemics (Dollwet and Sorenson, 1985). The use of copper and its alloys as antimicrobial agents in both micro- and nano-scale formulations continued until the arrival of commercially available antibiotics in 1932.

More recently, composites containing copper nanoparticles have come back into attention, with numerous research studies investigating this material as an antimicrobial agent. Two major advantages of copper-based antimicrobial materials are its multi-toxicity and that they are the only metal touch surface registered as an antimicrobial material by the U.S. Environmental Protection Agency.

Although the detailed destructive mechanism of antibacterial action for these materials is inadequately understood, it is thought this attack is multifaceted. The release of soluble copper ions has been proposed to be the chief cytotoxic mechanism (Chatterjee, Chakraborty and Basu, 2014; Wu *et al.*, 2009). The biocidal effect of these ions involves them interacting either directly with the cellular membrane or intracellulary to produce reactive oxygen species (**Figure 2**). Other hypothetical reported mechanisms include the accumulation and dissolution of nanoparticles in the bacterial membrane changing its permeability, with subsequent release of intracellular biomolecules and dissipation of the proton motive force across the plasma membrane (Amro *et al.*, 2000; Azam, *et al.*, 2012; Jiang, Mashayekhi and Xing, 2009).

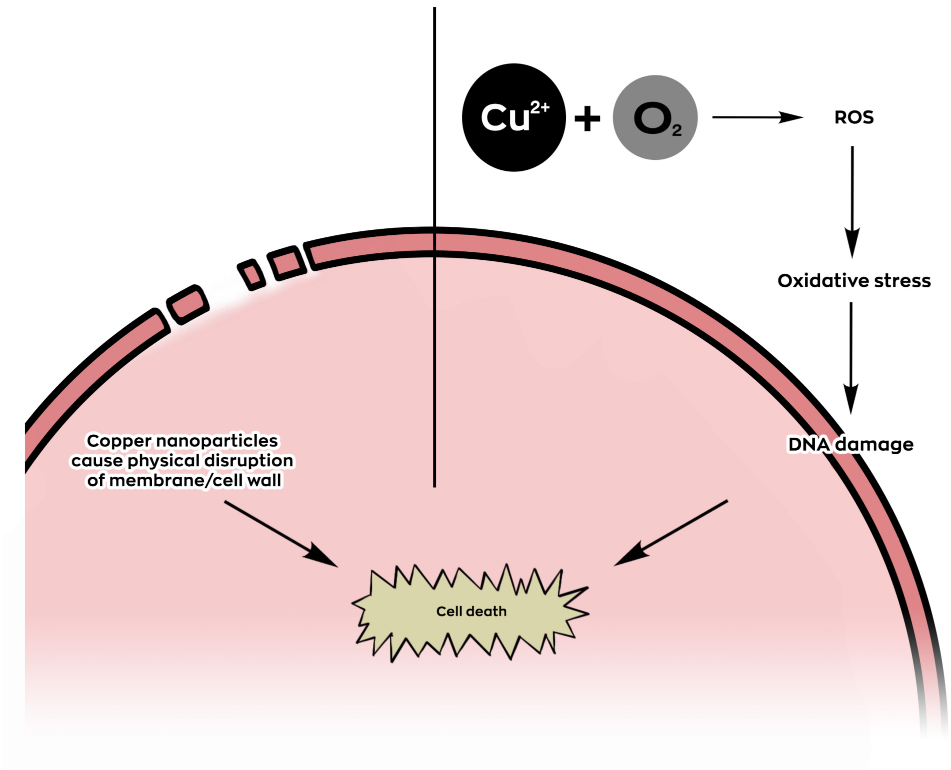

Figure 2: Predicted mechanisms of antibacterial activity of copper nanoparticles.

5.1 Copper – Cellulose

Polymer based nanocomposites with antimicrobial activity offer an interesting alternative to attenuate the persisting concern of bacterial resistance. Compounding copper with cellulose to improve its sterilisation capabilities has proven successful.

In a study carried out by Pinto and colleagues (2013), copper/cellulose nanocomposites were prepared using both vegetable and bacterial cellulose fibre matrices. The nanocomposites (100 mg of vegetable cellulose based nanocomposite and 50 g of bacterial cellulose based nanocomposite in 25 mL) were incubated with both Gram-negative (*K. pneumoniae*) and Gram-positive bacteria (*S. aureus*) for 24 hours at 23^{o}C with vigorous shaking (Pinto *et al.*, 2013). The antimicrobial studies revealed that the copper nanocomposites had antibacterial action for both types of bacteria, though with a more pronounced effect in respect to Gram-negative bacteria (Pinto *et al.*, 2013). A maximum 5.5-log reduction (complete killing) was observed with both vegetable and bacterial cellulose based nanocomposites against *K. pneumoniae* (Pinto *et al.*, 2013). Results also demonstrated that antibacterial activity is directly related to copper content (Pinto *et al.*, 2013). As the concentration of copper increased from 0.93 to 4.95 w/w%, a 2-log bacterial reduction was observed in both types of cellulose and bacteria (Pinto *et al.*, 2013). This is the result of increased copper ions being released from the nanocomposite and thus increasing the production of reactive oxygen species (Pinto *et al.*, 2013). However, when the copper content was increased further to 5.17 w/w%, the nanocomposite did not yield a higher log-reduction, this is most likely due to reduced surface reactivity of the nanoparticles thus leading to lower amounts of soluble and oxidised copper species.

5.2 Copper – Chitosan

The potential of chitosan as a powerful chelating agent makes it a perfect matrix to support metallic nanoparticles. In the presence of acetic acid, chitosan reacts with the hydrogen ions to produce protonated chitosan, thus increasing the electrostatic attraction between the positively charged ammonium cations on chitosan and the negatively charged copper ions. This in turn decreases copper agglomeration resulting in a more stable nanoparticle dispersion.

Various studies have shown that copper nanoparticles without chitosan have extensive aggregation and low antimicrobial results compared to nanoparticles with chitosan (Ancona *et al.*, 2014). Mallick *et al.* (2012) fabricated copper/cellulose nanocomposites, with a copper concentration of 21.5 μg/mL. Bactericidal activity was measured by incubating the nanocomposite with both Gram-negative (*E. coli*) and Gram-positive (*B. cereus*) bacteria at 37^{o}C. Bacterial reproduction was monitored by optical density. The results from this study showed that in the presence of the nanocomposite bacterial growth was inhibited, and that the nanocomposite exhibited higher antibacterial activity at much lower doses in comparison to the raw materials (Mallick *et al.*, 2012). Electron microscopy and flow cytometry analysis revealed that the nanocomposite was attached to the bacterial cell wall, causing irreversible physical damage to the membrane thus leading to the leakage of intracellular constituents and consequently cell death (Mallick *et al.*, 2012).

In another study by Cárdenas and colleagues (2009), copper/chitosan nanocomposite films were prepared by the solution casting method. The antimicrobial properties of the films against *S. aureus* and *Salmonella enterica* were investigated. Incorporation of copper nanoparticles into the chitosan matrix improved the materials' ability to deform and disintegrate the microbial cell wall and, in turn, reduce microbial concentration (Cárdenas *et al.*, 2009).

Copper/chitosan hybrid nanoparticles manufactured through "green synthesis" showed effective antimicrobial activity against both Gram-negative (*E. coli*, *Salmonella paratyphi*) and Gram-positive (*Bacillus*) bacteria (Manikandan and Sathiyabama, 2015). The ability of the nanocomposite to inhibit bacterial growth was investigated using the agar diffusion method. A greater zone of inhibition was observed for the Gram-negative bacteria, when compared to the Gram-positive bacteria (Manikandan and Sathiyabama, 2015). This was attributed to the structural differences in the bacterial cell wall. Zero-valent copper nanoparticles immobilised in a chitosan matrix have also shown antibacterial tendencies towards *S. epidermidis*, *E. coli*, and *B. cereus* (Said-Galiev *et al*., 2011).

5.3 Copper – Polypropylene

Polypropylene is one of the most frequently used thermoplastic polyolefin. This polymer has uses in a wide variety of applications, including packaging, textiles, stationary and automotive components. The unique properties of polypropylene directly correspond to the type and amount of crystalline and amorphous regions formed in the polymer chains (Karian 2003). However, in general, polypropylene is known for its outstanding processability, translucency, physical and thermal properties.

Espańa-Sánchez and colleagues (2014) have demonstrated that treating copper/polypropylene nanocomposites with argon surface plasma significantly improves the antimicrobial properties of the composite against *S. aureus* and *P. aeruginosa*. During this study copper/polypropylene composites were incubated along with the bacterial suspensions for a total of 6 hours at 37^{o}C. Bacterial colony forming units were enumerated using the colony counting method. It was found that the incorporation of copper into polypropylene enhanced the antimicrobial activity of the polymer by over 400% after 3 hours of exposure. The antibacterial activity observed in this study has been attributed to the increased surface roughness of the nanocomposite, and therefore the increased surface area for the bacteria to interact with.

Copper/polypropylene nanocomposites prepared by melt mixing have demonstrated unprecedented abilities to inhibit microbial growth and colonisation. Palza *et al*. (2010) have reported that incubating this composite (with a copper nanoparticle concentration of 1 v/v%) with *E. coli* for a minimum of 4 hours at 37^{o}C kills 99.9% of the living population. Increasing the copper concentration to 10 v/v% in the nanocomposite requires 50% less time to see similar antibacterial activity (Palza *et al*., 2010). It was suggested that the antibacterial activity of this composite is the result of copper ion release into the surrounding environment, therefore encouraging the production of reactive oxygen species.

5.4 Copper Oxide – Polyurethane

100% antimicrobial efficiency has been achieved and reported with copper-polyurethane composite materials. Ungur and Hruza prepared polyurethane nanofibers loaded with various concentrations of copper dioxide nanoparticles.

The composite fibres were incubated with *E. coli* and *S. gallinarum* for a maximum of 24 hours according to the Cornell test (ASTM E2149). Antibacterial efficiency ranged between 96.8 and 100% for *E. coli*, and 62.7 and 99.6% for *S. gallinarum*. For both bacterial strains, antibacterial activity grew as the copper oxide concentration increased from 5 wt% to 12 wt%. It was also noted that the nanocomposite fibres were more potent towards Gram-negative bacteria than Gram-positive bacteria.

Key studies highlighting and demonstrating the antimicrobial activity of copper nanocomposites are discussed in **Table 4**.

Table 4 Bactericidal activity of nano-scaled copper nanocomposites.

Copper Form	Size Data	Hybrid Components	Microbial Strain	Key Features	References
Copper	90 – 220 nm	Cellulose	*K. pneumoniae ATCC 4352 (DSM 789), S. aureus ATCC 6538 (DSM799)*	Contact time was 24 hours with shaking. Colony counting method was used.	Pinto *et al.*, 2013
Copper	4 – 12 nm	Chitosan	*GFP-expressing E. coli, B cereus*	The minimum inhibition concentration was determined using the agar diffusion test. Concentrations ranging between 21.5 and 27.29 µg/mL were identified.	Mallick *et al.*, 2012
Colloidal copper	9 – 13 nm	Chitosan	*S. aureus* ATCC 25923, *Salmonella enterica* serovar Typhimurium	Colony counting method was employed. Cell wall deformation was observed using transmission electron microscopy.	Cárdenas *et al.*, 2009
Copper	1 – 40 nm	Chitosan	*S. epidermidis, E. coli, B. cereus*		Said-Galiev *et al.*, 2011
Copper	25 nm	Polypropylene	*S. aureus*, *P. aeruginosa*		España-Sánchez *et al.*, 2014
Copper	5 nm	Polypropylene	*E. coli*	Colony counting method used. After 4 hours incubation, a bacterial reduction of 99.9% was observed.	Palza *et al.*, 2010
Copper oxide	~ 50 nm	Polyurethane	*E. coli, S. gallinarum*	The Cornell test (ASTM E2149) was employed.	Ungur and Hruza, 2017

				Bacterial reductions ranged from 62.7% to 100%.	

6. Iron Oxide Nanocomposites

Thus far, the biocidal and biostatic activity of various metal and metal oxide nanopowders have been discussed. However, it is important to mention, that despite their antimicrobial properties, increased exposure to these nanomaterials can carry dangerous environmental and health implications. Although these approaches are deemed advantageous, as they are able to surpass bacterial resistance mechanisms, they also exhibit deleterious characteristics. Side effects of these substances include, acute respiratory irritation, caustic injury of the upper gastrointestinal tract or subcutaneous tissue, psychological disorders, cardiovascular morbidity/mortality, neuronal translocation and argyria (Gwinn and Vallyathan, 2006; Samberg, Oldenburg and Monteiro-Riviere, 2009). Furthermore, increased concentrations of metallic ions, such as silver ions (colloids), in the bloodstream of childbearing women has been linked to the development of congenital craniofacial abnormalities in their offspring (Samberg, Oldenburg and Monteiro-Riviere, 2009). To overcome this major drawback, studies have reported iron oxide nanoparticles to be a plausible replacement for the inhibition of microbial growth (Arakha, *et al.*, 2015; Ismail *et al.*, 2015; Prucek, *et al.*, 2011; Thukkaram, *et al.*, 2014). Iron oxide nanoparticles, including magnetite (Fe_3O_4), maghemite (γ-Fe_2O_3), hematite (α-Fe_2O_3) and goethite (FeO(OH)), have showcased impeccable biocompatibility, chemical stability and magnetic behaviour, making them suitable for a range of applications in the biomedical field. The antimicrobial findings in relation to these iron oxide nanoparticles have made the substitution of metallic oxide components possible in the composites aforementioned in this review.

Iron oxide (magnetite)/chitosan nanocomposites were synthetically prepared by coating iron oxide nanoparticles (prepared by the co-precipitation method) with chitosan, thus allowing the nanoparticles to carry a positive charge (Arakha *et al.*, 2015; Nehra *et al.*, 2017). The growth kinetics of *B. subtilis*, *E. coli*, *C. albicans*, *Aspergillus niger* and *Fusarium solani* were studied in the presence of different concentrations of iron oxide in the nanocomposite. The magnitude of the antibacterial activity of the hybrid material was increased compared to the pure chitosan sample. The propensity of iron oxide (magnetite)/chitosan nanocomposites to induce microbial resistance is dependent on the amount of iron oxide present. Arakha *et al.* (2015) showed that the cell viability remained at approximately 30% for both *B. subtilis* and *E. coli* cell cultures at an iron oxide concentration of 50μM. Nehra *et al.* (2017) employed the agar diffusion method and reported mean diameter inhibition zones ranging between 14.5 to 18.5 mm for all microorganisms tested, with *B. subtilis* having the largest inhibition zones. The destructive mechanism has been attributed to the attraction between the nanoparticle and the cellular membrane. This interaction encourages the production of reactive oxygen species at the interface and consequently cell death (**Figure 3**).

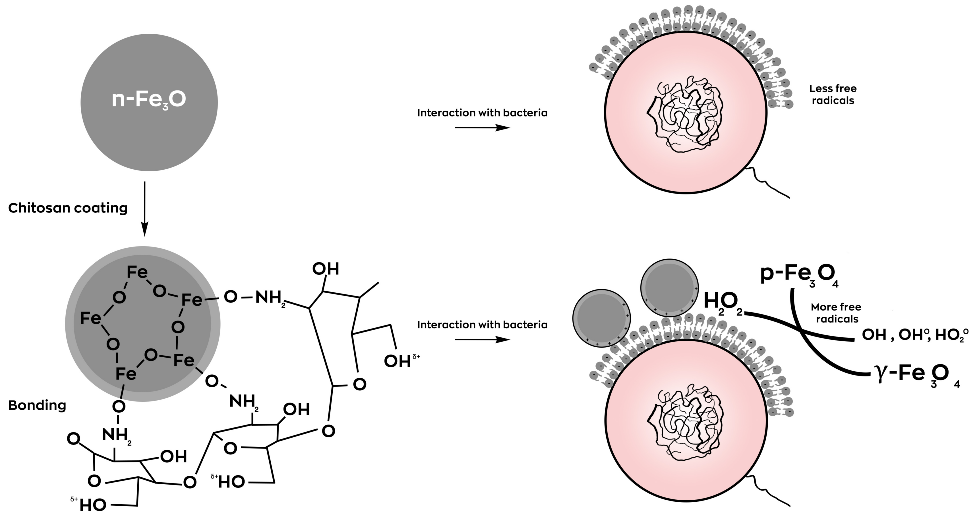

Figure 3: Proposed schematic model elucidating the detailed mechanism of iron nanoparticles against bacterial cells.

7. Carbon Based Nanocomposites

Carbon-based nanomaterials, such as fullerenes, nanotubes (CNTs), graphene sheets, graphite, carbon nanohorns, quantum dots, nanodiamonds, graphene oxide and its derivatives, are one of the most recently developed biocidal nanomaterials. Several theories have been discussed in previous literature regarding the mechanism involved in the materials' antimicrobial properties. One of these hypotheses states that these materials are able to induce oxidative stress by reactive oxygen species and lipid peroxidation. It has also been proposed that carbon-based nanomaterials are able to cause cell death by direct penetration into the cell wall, thus causing leakage of intracellular content (Hu *et al*., 2010). Kotchey *et al*. (2011) have suggested that the biocidal activity of carbon-based nanomaterials is a result of the membrane disintegration caused by the superoxide anion generated by carbon. In addition, Akhavan and Ghaderi (2010; 2012) have proposed that carbon-based nanomaterials are able to trap bacteria in agglomerates, thus isolating them from necessary nutrients needed for survival. Lastly, it has been reported that carbon-based biocidal activity is the result of the material extracting large amounts of phosopholipids from the cell membrane due to strong dispersion interactions between graphene and lipid molecules (Tu *et al*., 2013).

With the rapid development of nanocomposites, a great variety of carbon-based nanocomposites have been explored. Most of them have been proven to possess antibacterial activity.

7.1 Graphene Oxide – Molybdenum Disulfide

Graphene oxide is a water-dispersible compound formed by the oxidation of graphite. Its structural arrangement consists of carbon atoms arranged in a hexagonal lattice with carboxylic, phenol, hydroxyl and epoxide groups on its edges and basal planes (**Figure 4**) (Compton and Nguyen, 2010; Park and Ruoff, 2009). On the basis of its aqueous stability, low production cost and amphiphilic behaviour, graphene oxide is a promising material as a building block for graphene-based nanomaterials and their various applications.

Recent studies have shown graphene oxide/molybdenum disulphide nanocomposites to have exceptional antibacterial activity against *E. coli* K12. During this investigation, the nanocomposite was incubated with the cell suspension for 3 hours at 30°C (Kim *et al.*, 2017). Cell viability was quantified by counting the number of colony forming units present in the suspension (Kim *et al.*, 2017). When in contact with the nanocomposite, bacterial cells underwent physical cell membrane disruption and direct oxidation of intracellular components (Kim *et al.*, 2017). After 3 hours of incubation approximately 60% of bacterial cells died, thus demonstrating the capacities of the nanocomposite as an antibacterial agent (Kim *et al.*, 2017).

7.2 Graphene – poly(N-vinylcarbazole)

Graphene is the two-dimensional counterpart of carbon that consists of a single layer of carbon atoms arranged in honeycomb structure (**Figure 4**). Dispersing graphene into a polymer matrix not only improves the material biocidal properties but also its processability and mechanical properties. The use of a π-electron-rich polymers, such as poly(N-vinylcarbazole), results in a more stable dispersion due to its ability to form π-stacking with the graphene sheets (Santos *et al.*, 2012).

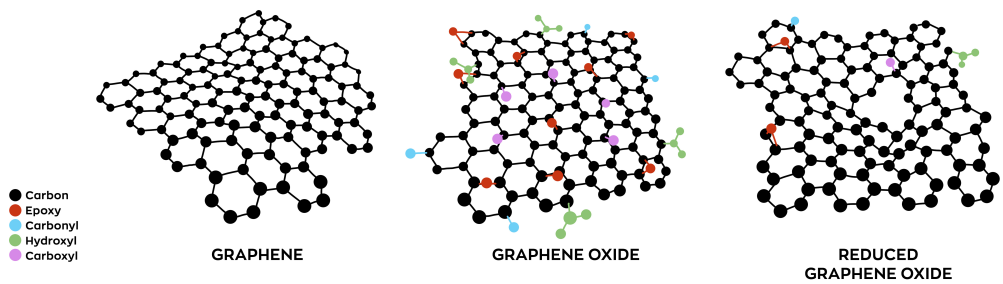

Figure 4: schematic chemical structures of graphene, graphene oxide and reduced graphene oxide.

When studying the effect of graphene/poly(N-vinylcarbazole) nanocomposites on *E. coli* and *B. subtilis* growth, it was noted that exposure to the nanocomposite resulted in a high cell inactivation (approximately 90% and

100% for *E. coli* and *B. subtilis*, respectively) (Santos *et al*., 2012). Cell toxicity was higher with the nanocomposite, as opposed to pure graphene. This result suggests that the antibacterial performance of graphene is largely dependent on its dispersion.

7.3 Reduced Graphene Oxide – Polyacrylamide

One major limitation of graphene oxide is its propensity to aggregate due to its large aspect ratio and strong π-π interactions between the layers. This prevents a homogenous dispersion of the material in solvents and matrices, which limits its suitably in several applications. One strategy which can be used to overcome this is reducing graphene oxide further to form reduced graphene oxide.

Incorporating reduced graphene oxide into a polyacrylamide matrix has proven to increase the biocidal activity of the material. In this research *Pseudomonas*, *S. aureus* and *C. albicans* were exposed to the nanocomposite for 24 hours at 37^{o}C (Mahdavi, Rahmani and Shahverdi, 2016). Larger inhibition zones were observed with *S. aureus*, followed by *Pseudomonas* and *C. albicans*. The antibacterial activity of freshly prepared nanocomposites and one year old samples were tested, the results were identical to each other, therefore indicating the materials stability (Mahdavi, Rahmani and Shahverdi, 2016).

7.4 Graphene Nanoplatelets – Poly(methyl methacrylate)

Graphene nanoplatelets (GNPs) are the two-dimensional counterpart of carbon nanotubes. The molecular configuration of GNP involves a single layer of sp^2 hybridized carbon atoms arranged in a regular hexagonal lattice, therefore doubling the exposed surface area when compared to single-walled carbon nanotubes (Georgakilas *et al*., 2015; Li *et al*., 2014; Pumera *et al*., 2010; Tkachev, Buslaeva, and Gubin, 2010). Each atom is attached to three neighbouring carbon atoms in the x-y plane by sigma bonds (Scida *et al*., 2011). The atoms also have a weakly delocalised π-electron cloud that is orientated in the z-axis (Scida *et al*., 2011). These electron clouds are responsible for the materials superior electrical conductivity, adjustable band gap, room temperature quantum Hall effect, and the π-plasmon resonance (Greshnov, 2014; Luo *et al*., 2013; Novoselov *et al*., 2007). Due to the materials novelty, the antibacterial properties of GNP have not been studied in depth.

Matharu *et al*. (2018b) have compounded varying quantities of GNPs with PMMA and processed this composite using pressurised gyration to form continuous fibres. The GNP/PMMA fibres were incubated in *E. coli* and *P. aeruginosa* cell suspensions for 24 hours at 37^{o}C and 150 rpm. The results collated from this investigation indicated that the antibacterial properties of the fibres were dose dependent. At low GNP concentrations (2 and 4 wt%), the fibres encouraged bacterial growth (Matharu *et al.*, 2018b). Whilst at higher concentrations, such as 8 wt% GNP, the fibres had antimicrobial activity with cell inactivation percentages of 85 ±5% and 95 ±2% for *E. coli* and *P. aeruginosa*, respectively (Matharu *et al.*, 2018b). The bacterial proliferation observed with lower GNP concentration fibres may be attributed to GNP serving as a nutrient source for microbial growth (Frias, Ribas, and Lucena, 2001; van der Kooij, Visser, and Hijnen, 1982). The antibacterial activity of the fibres with a high GNP concentration is thought be the result of GNP-induced oxidative stress, as well as, membrane destruction and microbial encapsulation.

7.5 Carbon Nanotubes – Silicone

Microbial contamination of silicon-based medical devices (such as catheters and dialysis tubing) is a major concern in the treatment of hospitalised or chronically ill individuals. Carbon nanotube composite films that possess antibacterial properties have been reported by Narayan *et al*. These novel materials were formed by pulsed laser ablation of carbon and bombardment of nitrogen ions from a Kaufman ion source (Narayan, Berry, and Brigmon, 2005). The carbon nanotube composite film was placed in direct contact with a lawn of *S. aureus* and incubated for 24 hours in ambient air at 35^{o}C. After incubation, it was noted that *S. aureus* did not grow over the nanocomposite film, however it did grow over the silicone surface, therefore suggesting the nanocomposite film prevented microbial growth (Narayan, Berry, and Brigmon, 2005). The antimicrobial activity of this material has been attributed to the physical interaction between nanotubes and bacterial cell walls (Lee et al., 2004). It is believed that nanotubes penetrate the lipid bilayer of microbial cells and allow release of intracellular contents through artificial pores.

Carbon-based nanocomposites can be considered controversial materials, as traditionally carbon is known to support bacterial growth. However, with the right concentrations, carbon-based nanocomposites can be tailored to suit their desired applications. All the carbon-based composite related studies discussed in this review have been summarised in **Table 5**.

Table 5: Bactericidal activity of nano-scaled carbon-based nanocomposites

Carbon Form	Size Data	Hybrid Components	Microbial Strain	Key Features	References
Graphene Oxide	1.2 nm	Molybdenum Disulfide	*E. coli K12*	Contact time was 3 hours. 60% loss of cell viability observed	Kim *et al.*, 2017
Graphene	1.8 nm (height) x 10 – 20 μm (length)	poly(N-vinylcarbazole)	*E. coli* MG 1655, *Bacillus subtilis* 102	Approximately 90% and 100% cell inactivation for *E. coli* and *B. subtilis*, respectively.	Santos *et al.*, 2012
Reduced graphene oxide		Polyacrylamide	*Pseudomoas, S. aureus, Canidida. albicans*	Agar diffusion method was used.	Mahdavi, Rahmani and Shahverdi, 2016
Graphene nanoplatelets	Width: 110 nm Length: 170 nm	Poly(methyl methacrylate)	*E. coli K12* and *P. aeruginosa NTCC 12903*	At low GNP concentrations, bacterial growth was observed. At high GNP concentrations, bacterial reduction was observed.	Matharu *et al.*, 2018b
Carbon nanotubes		Silicon	*S. aureus*	The disk diffusion test was performed. Composite inhibited microbial growth.	Narayan, Berry, and Brigmon, 2005

Table 6: Comparison of the bactericidal of activity of silver nanoparticles compounded in different materials against *E. coli*.

Antimicrobial Agent	**Size Data**	**Hybrid Component**	**Microbial Strain**	**Key Features**	**Reference**
Silver citrate		Polyurethane	*E. coli* ATCC 25922, *E. coli* MTCC 1302	No growth of both kinds of *E. coli* was detected after treatment with the polyurethane foam with nanoparticles.	Jain and Pradeep, 2005
Titanium dioxide nanoparticles	25 nm	Polyurethane	*E. coli* DH	99.5% of the bacteria were killed in one hour.	Charpentier *et al.*, 2012
Zinc oxide	27 nm	Polyurethane	*E. coli*	At 4 wt% 90% bacterial reductions were observed for *E. coli*.	Li *et al.*, 2009
Copper oxide	~ 50 nm	Polyurethane	*E. coli*	The Cornell test (ASTM E2149) was employed. 100% bacterial reduction was achieved at a copper oxide concentration of 5 wt%.	Ungur and Hruza, 2017

A fair and honourable comparison between the different antimicrobial agents is difficult to achieve due to the variety of hybrid components used, and the different experimental set-ups adopted by the researchers. However, a humble attempt to compare the antimicrobial properties of the different active agents has been displayed in **Table 6**. Here, the same hybrid component and microbial strain has been used. Where possible, similar assays were also used.

8. Concluding Remarks

At present, there have been numerous published studies relating to the antimicrobial activity of nanocomposites. The nanocomposites presented in this review exhibit broad-spectrum biocidal activity, subsequently motivating its use in a large number of industrial and biomedical applications as well as a growing list of consumer products. There is no doubt that the multidisciplinary efforts of researchers to discover novel antimicrobial nanocomposites is one of the most scientifically promising advancements in composite materials and has a tremendous societal and health impact. The rapid development of these newly manufactured materials to prevent microbial growth and colonisation is assisting in resolving the current global health crisis regarding antimicrobial resistance.

Research in this field has generated wider knowledge on three main subjects: (1) possible mechanisms of antimicrobial action, (2) the most commonly used composite systems and how they influence antimicrobial activity of the resulting material and (3) potential applications in accordance with the additional features of these nanocomposites.

Despite the revolutionary success of antimicrobial nanocomposites, there are still numerous challenges that must be tackled and considered in order to unleash their full performance. For example, although several cytotoxic mechanisms of action have been proposed, little knowledge is known on the exact mechanism and long-term toxicity of the materials. This prevents the materials from becoming commercially available products. In spite of this, the excellent antibacterial properties of the nanocomposites reported here against a broad spectrum of microbes, together with their unique material properties make them an outside alternative to conventional biocides.

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