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REVIEW ARTICLE

Emerging nanomaterials for antibacterial textile fabrication

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Abstract

In recent times, the search for innovative material to fabricate smart textiles has been increasing to satisfy the expectation and needs of the consumers, as the textile material plays a key role in the evolution of human culture. Further, the textile materials provide an excellent environment for the microbes to grow, because of their large surface area and ability to retain moisture. In addition, the growth of harmful bacteria on the textile material not only damages them but also leads to intolerable foul odour and significant danger to public health. In particular, the pathogenic bacteria present in the fabric surface can cause severe skin infections such as skin allergy and irritation via direct human contact and even can lead to heart problems and pneumonia in certain cases. Recently, nanoparticles and nanomaterials play a significant role in textile industries for developing functional smart textiles with self-cleaning, UV-protection, insect repellent, waterproof, anti-static, flame-resistant and antimicrobial-resistant properties. Thus, this review is an overview of various textile fibres that favour bacterial growth and potential antibacterial nanoparticles that can inhibit the growth of bacteria on fabric surfaces. In addition, the probable antibacterial mechanism of nanoparticles and the significance of the fabric surface modification and fabric finishes in improving the long-term antibacterial efficacy of nanoparticle-coated fabrics were also discussed.

Keywords Antibacterial agents · Nanoparticles · Cotton fabrics · Surface modification · Cationization

Introduction

Nanotechnology has emerged to be a significant field in various applications for manipulating science at the nano-regime to develop and produce products with exclusive properties (Jeevanandam et al. 2020a). In brief, nanotechnology can be defined as the science and engineering of designing, synthesizing and characterizing of nanomaterials with exceptional functional properties, compared to their bulk counterparts (Barhoum et al. 2020). Further, nanotechnology is not only emerging in single scientific discipline but also significant in interdisciplinary science, such as chemistry, physics, materials science and biology (Shrivastava and Dash 2009). Thus, synthesized nanomaterials are highly beneficial in various fields, including energy, electronics, environmental remediation, biomedicine and pharmaceuticals and functional textiles (Jeevanandam et al. 2018a). Among these applications, nanotechnology plays a significant role in textile industries for developing functional smart textiles with self-cleaning, UV-protection, insect repellent, waterproof, anti-static, flame-resistant and antimicrobial-resistant properties (Mahmud and Nabi 2017).

Textile is one of the few industries that has a profound demand all over the world. This industry plays a significant role in the world economy, by contributing to the industrial development, export earnings and employment generation (Tandon and Reddy 1990). The economy involved around the global textile industry was estimated to be around 920 billion US dollars in 2018, which is expected to increase to 1230 billion US dollars (4.4%) in 2023 (Walia 2019). Thus, it is essential to incorporate novel technologies to fabricate smart and advanced textile materials. Further, the innovative improvements in the textile industry are expected to allow the manufacturers to produce functional and smart textiles for the future (Cheung et al. 2018). It is noteworthy that textile materials that are utilized in everyday life provide an excellent environment for microorganisms, especially for bacteria to grow, due to their large surface area and profound ability to retain moisture. In addition, the growth of harmful bacteria on

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the textile material not only damages them but also leads to intolerable foul odour and significant danger to public health. In particular, the pathogenic bacteria present in the fabric surface can cause severe skin infections such as skin allergy and irritation via direct human contact and even can lead to heart problems and pneumonia in certain cases (Shalini and Anitha 2016). Hence, the development of functional textiles via nanoparticles has become the major focus of researchers, due to their high demand in recent years (Mahmud and Nabi 2017). Thus, this review is an overview of various textile fibres that favour bacterial growth and potential antibacterial nanoparticles that can inhibit the growth of bacteria on fabric surfaces. In addition, the probable antibacterial mechanism of nanoparticles and the significance of the fabric surface modification and fabric finishes in improving the long-term antibacterial efficacy of nanoparticle-coated fabrics were also discussed.

Types of textile fibres that favour bacterial growth

Fibres are the most common and essential raw material for textile fabric production and are primarily classified into natural and synthetic fibres as shown in Fig. 1. Generally, natural fibres are obtained from plants as cotton and from animals as wool and silk, whereas synthetic fibres are produced by modifying natural polymers via chemical processing such as cellulose viscose and cellulose acetate methods and are fabricated using synthetic polymers, namely nylon 6, poly (vinyl chloride) (PVC) and acrylic and polyester fibres (Pekhtasheva et al. 2012b; Pekhtasheva et al. 2012a).

Synthetic fibres

Synthetic fibres are conventionally prepared via polymerization approach, by utilizing chemical-based monomers. These polymeric synthetic fibres are fabricated into distinct varieties such as polyamide, polyester and acrylic fabrics with enhanced durability. However, these fibres are toxic to the environment due to the involvement of toxic chemicals as monomers in the polymerization process (Singh and Bhalla 2017). In addition, synthetic fibres can serve as a nutrient medium for microbial growth, as microbes can degrade the polymers and consume them as their nutrition. Chemical-based monomers may also be toxic to these microbes, which eventually control the growth of microbes in textiles produced using these fibres (Purwar and Joshi 2004).

Polyamides

Polyamides are macromolecular building blocks that are primarily composed of amide groups. Aliphatic polyamides, also

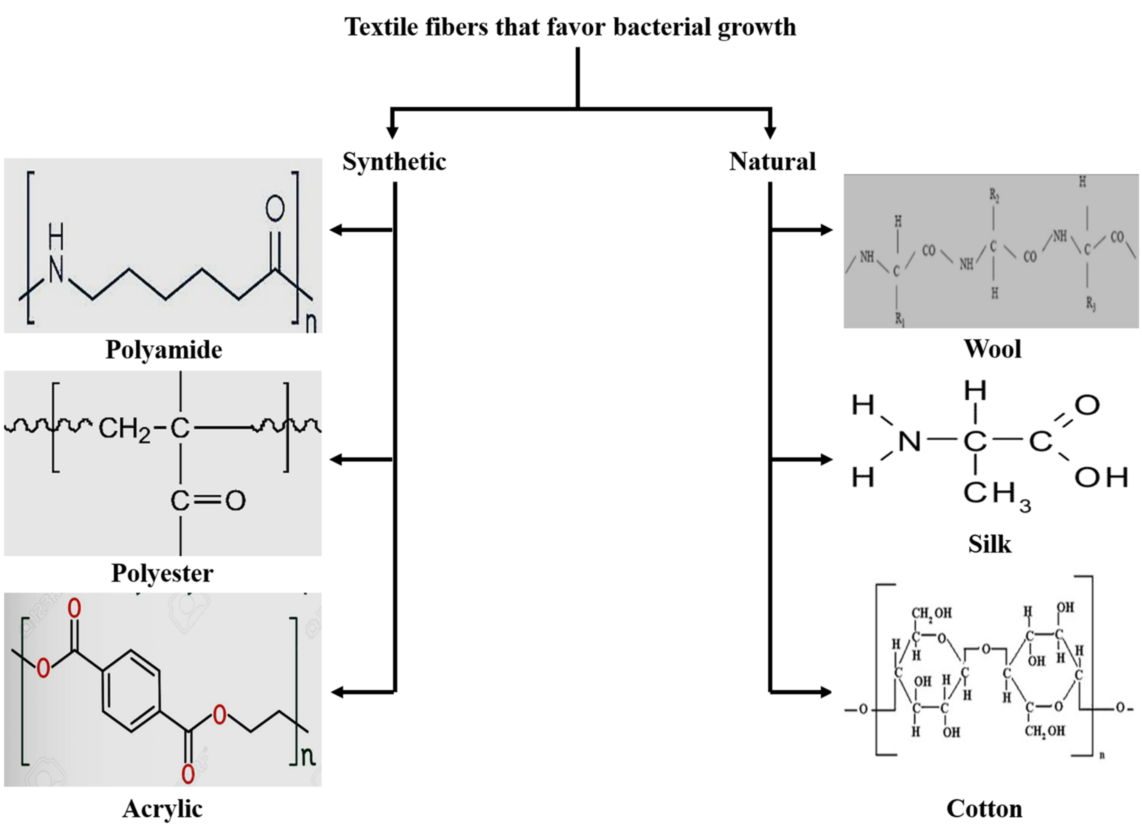


Fig. 1 Types of textile fabrics and their chemical structures

known as nylon 6, are the most significant polymer among polyamides. This type of polyamide possesses significant characteristics such as high strength, elasticity, abrasion resistance and dye ability, which makes them the most suitable material for clothing and home furnishing applications. Further, polyamides are highly resistant to microbial contamination, due to their extreme symmetrical molecular structure and strong intermolecular cohesive force of hydrogen bonds between the molecular chains (Elnagar et al. 2014), although several studies with various microbial strains revealed that microbes can grow in polyamides and contaminate and degrade them via oxidation or hydrolysis, which can cause depolymerization and damages in the fabric (Wu et al. 2015).

Polyester

Polyester is a synthetic fibre, which can be fabricated by the polymerization of ethylene terephthalate to form poly (ethylene terephthalate) (PET). Polyester-based fabrics possess excellent properties such as wrinkle resistance, high elasticity and pleat retention properties. Thus, this type of fabrics is extensively used as raincoats, pants, shirts, dress, children's wear and sportswear (Aoyama and Tanaka 2016). The strong hydrophobic properties of polyesters make them highly resistant to microbial contamination, due to the incapability of forming hydrogen bonds with other molecules. Even though polyester fabrics are highly resistant to microbes, the lubricants and spinning oils that are utilized during the finishing process of textiles provide sufficient nutrients for mild growth of the microorganisms on the polyester fabrics (Boryo 2013).

Acrylic

Acrylic fibre is a synthetic fibre composed of polymer (polyacrylonitrile) with an average molecular weight of 100,000 and 1900 monomer units. It consists of long chain synthetic polymer with 85% of the weight contributed by acrylonitrile units (El-Gabry et al. 2014). It is the third largest synthetically fabricated textile fibre in the world and holds a share of 20% of total synthetic fibre production. The acrylic fibre is an ideal fibre in textile industry to produce cloths to withstand harsh environmental conditions, due to their inherent properties such as resistance towards UV radiation, mildew and bacteria and excellent thermal insulating properties (Bajaj et al. 1996). However, the mould attack at high air relative humidity (90%) has been described in several literatures (Gutarowska et al. 2013), which is a limitation to utilize acrylic-based textile in humid conditions.

Natural fibres

Generally, natural fibres are obtained from plants, animals and mineral sources. The most widely used natural fibres in clothing and home furnishing applications are wool, which is obtained from sheep, and silk is obtained from insects, whereas cotton is obtained from plants. Biodegradability, non-carcinogenicity and cost-effectiveness are the significant properties of natural fibres to replace synthetic fibres that are toxic to the environment and humans. Moreover, higher mechanical strength and low weight of natural fibres attracted scientists and investors to utilize them in various textile-related applications (Konwar and Boruah 2018). However, it can be noted that the textile fabrics produced via natural fibres such as wool, silk and cotton are readily prone to microorganisms. The hydrophilic structure of natural fibres, which retains water, oxygen and nutrients, provides a suitable environment for the growth of the microorganisms and serves as a perfect substrate for pathogenic microbial transfer (Mohapatra and Malik 2015). Hence, the presence of pathogenic microbes on these natural fabrics leads to intolerable foul smell, loss of fabric strength, decolouration, allergic reactions and other skin-related infectious diseases in humans and animals (Badr 2018).

Wool

Wool is a natural fibre that is utilized by mankind as cloth and dresses, since ancient times. Natural wool is obtained from animals such as sheep and is composed of eighteen diverse amino acid groups, in which cysteine (13.1%), glutamate (11.1%) and serine (10.8%) are highly significant for textile applications (Ammayappan 2013). The extracted wool fibre from the animals is subjected to a thorough cleaning, which is composed of a single protein named keratin that contains 50% of carbon, 5–7% of hydrogen, 15–21% of nitrogen, 21–24% of oxygen, 2–5% of sulphur and other impurities. The keratin in wool existed in two distinct animal cell types such as cuticle and cortical cells, where the cuticle cells are overlapped by cortical cells. The wool absorbs the water through the cortex via the hydrophobic cuticle scales, which makes the core of the fibre to swell. This mechanical response from the wool fibre protects the animals from the environmental changes (Pekhtasheva et al. 2012a). Naturally originated wool has been extensively used to produce men's and women's outerwear, knitwear, underwear, socks, hand knitting yarns, blankets, upholstery, filled beddings, rugs and carpets, due to their diverse properties. Even though wool is from natural fibres, it is highly resistant to microbial attack, due to the existence of wax content in the natural fibre wool that prevents microbial contamination. Likewise, the presence of keratin in wool possesses certain resistance ability against microbial contamination due to their highly cross-linked structure with elevated sulphur content. Moreover, the surface of the wool is covered by the water-repelling membrane, which halts the penetration of microorganisms and enzymes into the fibre (Arshad et al. 2014).

Silk

Silk is a natural protein polymer, which is generally produced from insects such as silkworms, spiders, scorpions, mites and bees. In recent years, silk from silkworm (*Bombyx mori*) has been produced domestically, due to its enhanced biocompatibility, mechanical performance, ease of processing, tuneable degradation and sufficient supply. Further, it is noteworthy that silkworm-extracted silk has been used in the traditional textile industry for about a thousand years. Silk is primarily composed of two major protein components such as silk fibroin and sericin. Sericin is a glue-like protein that wraps around the fibroin, which is generally soluble and can be removed during the degumming process (Qi et al. 2017). Additionally, the silk has outstanding mechanical properties such as tensile strength, extensibility and toughness. Furthermore, natural silk fibre produced from silkworms is extensively utilized in advanced textile applications such as parachute cords, composite materials in aircrafts and protective clothing, due to its smooth texture and high mechanical strength with durability (Wang et al. 2014). The degummed silks are highly resistant to microbes as microorganisms assimilate sericin more easily than fibroin, due to microbial protease enzyme secretion. Hence, it is evident that degummed silk is highly resistant to microbial contamination, among other natural fibres (Bajpai et al. 2011a).

Cotton

Cotton is the most abundant natural fibre that is cultivated from plant source, and it is said to be the pioneer for apparel and industrial applications. The cotton fibre consists of 88–95% of cellulose and a small quantity of pectin, wax, minerals and certain impurities. Further, cotton has excellent properties such as strength, softness, absorbency, dyeing, comfort and air permeability, which makes them an essential natural fibre in the textile industry. The cellulose in cotton is composed of 1, 4, β-D-glucan with 1, 4-glucosidic bonds and contains intermediate polymer chain sequences such as non-reducing and reducing end groups with glycosidic linkages (Uddin 2019). However, the hydrophilic nature and the existence of nutrients as well as moisture provide a suitable environment for the growth of harmful pathogenic microbes in cotton (Zhang et al. 2016).

It is noteworthy that the polymers present in these natural and synthetic fibres are responsible for microbial growth in fabrics, as they serve as a potential nutrient medium. The microbial attack of synthetic fibres involves adhesion of microbes on the fabric surface, penetration into the fibres and physical damage to fibres as well as chemical decomposition to the fabric via numerous metabolites secreted by microbes (Bajpai et al. 2011a). In addition, numerous studies have demonstrated that natural fibres are highly susceptible to microbial contamination, particularly cotton fabrics, compared to synthetic fibres. This microbe-mediated contamination of fabrics will be responsible for spreading infections either directly or by contact with environmental parameters. Further, the microbial attack on fabrics causes intolerable smell and deterioration and discolouration of textiles (Szostak-Kotowa 2004). Among microbes, bacteria commonly grow on the fabric, develop into colonies, damage the fibres and spread infections towards other living organisms, especially humans (if they are pathogenic), as the polymers in the fibres are highly beneficial as a nutrient substrate for their growth (Bajpai et al. 2011b; McQueen and Vaezafshar 2019). Hence, antibacterial fabrics are gaining much attention towards researchers in the field of textiles and apparels to mitigate the growth of bacteria, without compromising their mechanical strength and other exclusive properties.

Mechanism of bacterial growth in textile fabrics

The growth mechanism of bacteria in textile fabrics is essential to be known, to effectively inhibit their growth (Puvvada et al. 2019). Figure 2 shows the schematic representation of bacterial growth mechanism in textile fabrics. Generally, textiles, clothes and apparels are made up of synthetic or natural fibres, which are composed of polymers (Paderes et al. 2017). These polymers are formed by chemical or natural monomers, depending on the type of fibres, and serve as a potential substrate for the attachment of airborne bacteria and as a nutrient medium for their growth and development into colonies (Roy et al. 2019a). It can be noted that *Flavobacterium*, *Micrococcus* and *Pseudomonas*, especially *Pseudomonas aeruginosa*, are the most common textile affecting bacterial species (Sagar 1988; Gutarowska et al. 2016). Further, the absorption of sweat and atmospheric moist by the fibre will support the bacterial growth by providing perfect moisture condition (Varshney et al. 2020). Later, the bacterial growth by utilizing polymers as nutrients will lead to slower conversion of polymer to monomer in the fabric and release of metabolites from the bacteria (Gupta et al. 2017). Furthermore, the bacterial metabolites may also play a significant role in degrading the polymer in the fibre (Gupta et al. 2017). Hence, the synergistic effect of bacteria and its metabolites in degrading the fabric polymer will lead to damage in the cloth and the formation of bacterial colonies in large number (Lamba et al. 2017). When pathogenic bacteria undergo such mechanism, it may lead to skin irritation or infection in humans (Mondal and Saha 2019). It can be noted that natural fibres are highly prone to bacterial attack than synthetic fibres, as the polymers of natural fibres serve as a significant carbohydrate source for their growth, whereas chemical-based polymers are toxic to bacterial cells (Sarkar et al. 2003). Thus,

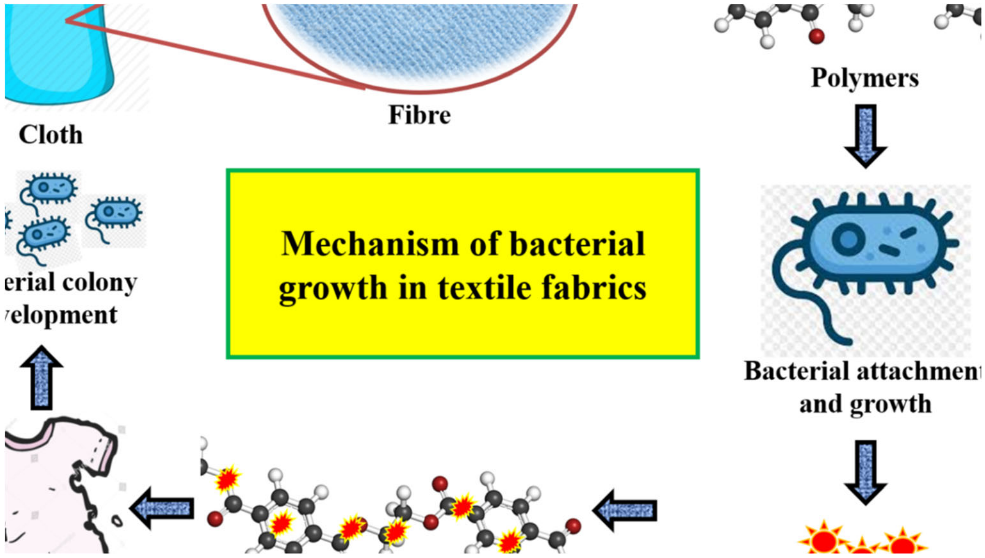


Fig. 2 Schematic representation of bacterial growth mechanism in textile fabrics

protection of fabric polymer from the bacterial cell attachment is crucial in avoiding their growth, and the presence of antibacterial agent in these polymers will inhibit their growth.

Antibacterial agents

The antibacterial agents are the compounds with the ability to prevent the growth of undesirable pathogenic bacterial strains, which can play a significant role in fabric discolouration, damage to the fibres and formation of unpleasant odour and can cause infectious skin diseases (Gokarneshan and Velumani 2017). The need for the antibacterial agents has increased in recent times, with the growing health awareness in public regarding the pathogens and resistance of bacteria towards various conventional antibacterial agents (Balu et al. 2020). These bacteriostatic agents are effectively used in several applications including medical devices, health care, water purification systems, hospitals, dental surgical equipment, food packaging and textiles (Shahidi and Wiener 2012). The use of antibacterial agents has been in practice for more than 2000 years. It is astonishing that the ancient Egyptians and Greeks used naturally derived plant extracts to treat infections (Savoia 2012). However, repeated usage of natural antibacterial agents has led to the development of resistance in pathogenic bacterial strains, which further led to the emergence of chemical disinfectants (Wright 2005). Even though chemical disinfectants are beneficial in inhibiting several bacterial strains, they are proven to be toxic to the environment as well as humans (Yang et al. 2014). Thus, researchers are on a quest to identify a superior antibacterial agent to inhibit bacterial growth, without resistance development and adverse toxicity towards humans as well as other organisms. Generally, antibacterial agents are categorized into chemical disinfectants and natural extracts as shown in Fig. 3.

Chemical disinfectants

Chemical disinfectants are the conventional antibacterial agents that are synthesized using synthetic chemical compounds. Quaternary ammonium compounds, N-halamines and triclosan, are the most common chemical disinfectants that are utilized for the inhibition of bacteria in various applications, especially in textile industries.

Quaternary ammonium compounds

Quaternary ammonium compounds (QACs) are the conventional chemical disinfectants that are used to inhibit the growth of microbes, particularly bacteria. These QACs are cationic surfactants or surface activating agents with a positive charge in the nitrogen site, which is attached to four distinct structural groups, whereas the anion bound to the nitrogen is usually a chlorine or bromine compound (Gerba 2015).

The antibacterial activity of QACs is primarily attributed to their cationic surfactant properties. The mode of QACs' antibacterial action depends on their interaction with bacterial cell membrane, which enables the disruption and leakage of the cell content. In fact, the antibacterial action of QACs is activated by the attraction between their positively charged ammonium group and the negatively charged bacterial cell membrane. Literatures suggested that the disruption and denaturation of bacterial proteins and enzymes by QACs are the reasons behind their enhanced antibacterial efficacy (Hegstad et al. 2010; Morais et al. 2016). Further, QACs also damage the bacterial DNA, which eventually prevents the loss of replication ability. Additionally, the hydrophobicity of QACs makes them effective against lipid and non-lipid-containing viruses and spores. Furthermore, these compounds are also proven to possess algae-static, bacteriostatic, tuberculostatic, spore-static and fungistatic properties, even at a low

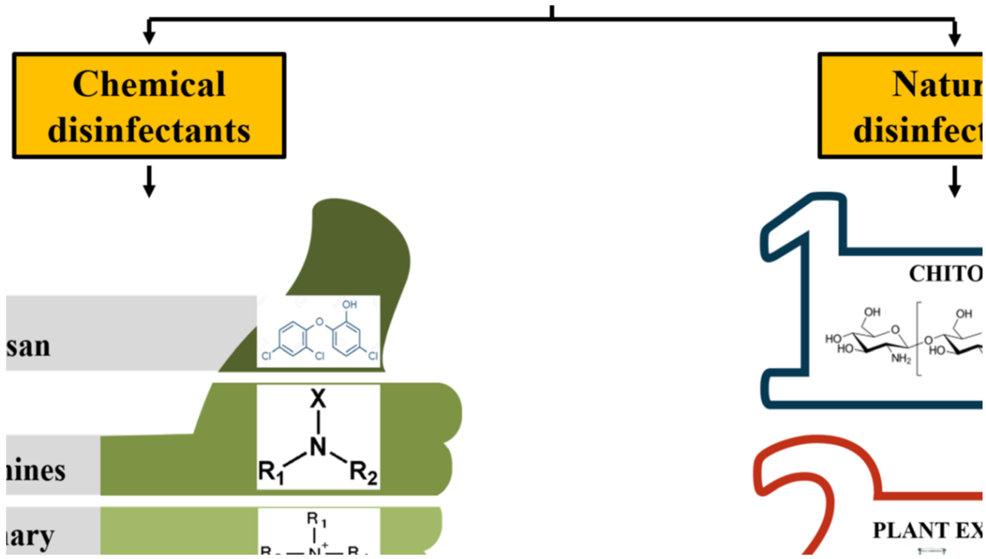


Fig. 3 Classification of chemical and natural antibacterial agents

concentration range of 0.5 to 5 mg/L (Gerba 2015; Simončič and Tomšič 2017). Even though all these studies revealed the antibacterial efficiency of QACs, increment in their concentration to elevate their antibacterial property may also lead to toxic effects in the environment and human cells (Zhang et al. 2015).

N-Halamines

N-Halamines are heterocycle organic compounds with one or few covalent nitrogen-halogen (chlorine, iodine or bromine) bonds that are formed via halogenation of imide, amide or amines. These N-halamines are extensively utilized as biocidal agents for several decades (Hui and Debiemme-Chouvy 2013). They are considered as the most effective antimicrobial agents due to their rapid inactivation efficiency against a broad microbial spectrum, such as gram-positive and gram-negative bacteria, yeasts, fungi and viruses. Additionally, they have long-term halogen stability with enhanced antimicrobial efficacy, due to their exclusive chemical structure (Dong et al. 2017). The most significant advantage of N-halamines is their effective inhibition of microbes via oxidative halogens and their repeated microbial inactivation ability after being recharged (Demir et al. 2017). The oxidized halogens can act via direct transfer of an active element to the biological receptor or by the dissociation of free halogen in an aqueous medium to recharge N-halamines and reform their antimicrobial efficacy (Hui and Debiemme-Chouvy 2013). Further, the antimicrobial properties of N-halamine, especially their antibacterial efficacy, may vary depending upon the electron withdrawing/electron donating groups in nitrogen-halogen bond (Ahmed et al. 2009). However, these compounds were also reported to be highly toxic to humans, which limits their usage in the production of large-scale antibacterial cotton fabrics (Ren et al. 2018).

Triclosan

Triclosan ($C_{12}H_{17}C_{13}O_2$; 2,4,4-trichloro-2-hydroxydiphenyl ether) exhibits biocidal effects against prokaryotic and eukaryotic cells and has been extensively utilized for personal hygiene and disinfectant purposes for decades (Kim et al. 2015). The major chemical interactions in triclosan occur via secondary bonds due to their nonpolar nature, which is available through the ether, oxygen and phenyl hydroxyl groups (Petersen 2016). Triclosan inhibits bacteria by halting the biosynthesis of fatty acid via blockage of lipid formation, such as phospholipid, lipopolysaccharide and lipoprotein synthesis. Moreover, it is noteworthy that triclosan also possesses the ability to inhibit the bacterial enzyme named enoyl-acyl carrier protein reductase (ECR), whereas it disrupts the cell membranes in the eukaryotes to exhibit potential antibacterial efficacy as well as toxicity (Orhan et al. 2007).

Limitations of chemical disinfectants

Despite having numerous positive aspects to utilize chemical disinfectants such as QACs, N-halamine and triclosan as potential antibacterial agents, they are not recommended for medical applications as they may lead to adverse side effects in the environment as well as humans. The inherent weakness of QACs is their ability to dislodge from the textiles, after washing cycles, as they do not have reactive functional groups in their structure to support strong chemical bond with the fabric. Thus, the dislodge of QACs after washing the fabric will result in bacterial inhibition decrement and poor wash durability (Simoncic and Tomsic 2010). Moreover, Melin et al. (2016) studied the toxicity assessment of quaternary ammonium using both female and male mice. The study investigated the gender-specific reproductive effects of alkyl dimethyl benzyl ammonium chloride (ADBAC) and didecyl dimethyl ammonium chloride (DDAC). The female reproduction of mice was assessed via ovulation, oocyte implantation and oestrous cycle, whereas the male reproductive system was assessed via sperm concentration, motility and viability. No significant difference was found in the *corpora lutea* upon exposure of ADBAC+DDAC for 2 weeks; however, alterations were observed after 8 weeks. It has been reported that the QAC exposure decreased the sperm concentration and mobility, but not sperm viability in males. Furthermore, the exposure of ADBAC+DDAC resulted in disturbances in both female and male mice. Finally, the exposure to QAC reduced breeding and fertility in mice via disturbance in ovulatory capacity and oestrous cycle in females. Thus, the results suggested that these findings are relevant to reveal the toxicity of ADBAC+DDAC, if an organism is in extensive exposure to these compounds (Melin et al. 2016). Likewise, the treatment of N-halamine may also result in increased adsorption of chlorine on the surface of the cotton fibre. This will result in unpleasant odour and discolouration of fabrics and is not recommended for textile industries (Dong et al. 2017). In the same way, the exposure of triclosan has been increasing every year, which elevated the risk assessment approaches associated with triclosan exposure. Due to the inclusion of triclosan in consumer products, it has been identified in the human breast milk, urine as well as serum and has raised concerns regarding human health outcomes. A review on toxicity assessment of triclosan reported that the exposure of triclosan may increase risk of cancer in humans (Dinwiddie et al. 2014). Hence, chemical disinfectants are not recommended for biomedical applications, and natural disinfectants are proposed to be a potential alternate to inhibit pathogenic microbes, especially bacteria that damage fabrics.

Natural disinfectants

The limitations of the synthetic antibacterial agents have led to the emergence of natural antibacterial agents, such as chitosan and plant extracts, for replacing conventional chemical disinfectants due to numerous significant progresses in the quest of developing novel and natural compounds with antibacterial activity.

Chitosan

The deacetylated amine group of chitin, which is an animal-derived polysaccharide, was reduced to 40–35% and is referred to as chitosan. The chitosan is classified into several types based on the degree of polymerization and molecular weight (Goy et al. 2009). Further, chitosan is widely known for its exclusive and superior antibacterial activity. The antibacterial efficacy of chitosan is due to the existence of charge groups in the polymer backbone and its interaction with the bacterial cell wall through ionic interactions. This eventually leads to leakage of intracellular electrolytes and causes bacterial cell death and inhibition of bacterial colony development. Also, the presence of charge in the chitosan chain is generated by the amine protonation in acidic medium or by structural modifications, which are reported to be essential for exhibiting antibacterial activity. However, studies have demonstrated that the antibacterial efficiency of chitosan is strongly dependent on its concentration (Goy et al. 2016). The excellent biocompatibility, high bioactivity, biodegradability, selective permeability, polyelectrolyte action, antimicrobial activity, ability to form gel and film, chelation ability and absorptive capacity have made the chitosan to be highly beneficial in various applications (Yadav et al. 2017; Huang et al. 2018). Among several applications, chitosan in textile industry is used for the fabrication of textile fibres such as cotton, silk, wool and polypropylene dyeing, durable press finishing, anti-static finishing, antibacterial finishing, de-odorizing finishing of fabrics, textile printing and medical textiles (Moattari et al. 2018).

Plant extracts

Plants were used as a source of antimicrobial agents, since ancient times (Cowan 1999). Plants with medicinal properties are recognized as potential natural antimicrobial agents and are considered as an alternate to the synthetic bacterial resistant antibiotics. The presence of phytochemicals and secondary metabolites in plant extracts is responsible for their medicinal properties. Plants with rich secondary metabolites such as flavonoids, terpenoids, alcohols, phenols, tannins and alkaloids are found to possess antimicrobial activity against various pathogenic microbes (Manandhar et al. 2019). Further, several studies reported that secondary metabolites produced from plants are the best biological entity to combat and eradicate infectious disease–causing bacteria (Al-Jumaili et al. 2018). The rich secondary metabolite contents in plants and plant parts are reported in several literatures to be an essential factor in deactivating the microbes, especially bacteria. The mechanism of antibacterial action of these secondary metabolites is complex and is still not clear. However, various studies have proposed that these secondary metabolites are hydrophobic in nature that allows them to accumulate and destruct the lipids of bacterial cell membrane. Further, the accumulated metabolites disturb the biological function of bacteria upon interaction with their cell membrane, cause failure in chemiosmotic control and damage the pore permeability of the membrane (Al-Jumaili et al. 2018). Additionally, the antibacterial action also depends on the chemical structure of each phytochemical compound of the secondary metabolites and varies depending on the interaction of bacteria with functional groups of phytochemicals (Wink 2015; Al-Jumaili et al. 2018; Andra et al. 2019b).

Limitations of natural disinfectants

The adverse toxic effects of synthetic antibacterial agents have led to the emergence of disinfectants from natural sources with high biocompatibility and bioactivity to be beneficial in biomedical applications. However, these natural antibacterial agents also possess certain limitations, particularly while utilizing them for textile applications. The use of chitosan on the surface of textile fabrics as an antibacterial finish provides strong bactericidal properties; however, chitosan is effective against bacteria only at high concentrations. This makes the deposition and accumulation of chitosan on fabric surface to form a thick layer or film, which reduces the air permeability of the fabric. Also, the fabrics become much stiffer than the normal fabric after coating chitosan on their surface. These drawbacks have limited the usage of chitosan in textile applications (A et al. 2018). Further, the natural antibacterial agents that are derived from plant extracts exhibit broad-spectrum antimicrobial activity. However, the main drawback of plant extract–treated fabrics is its failure to retain its durability, compared to synthetic antibacterial agent–coated fabrics. It is noteworthy that plant extract–coated fabrics can withstand only few numbers of wash cycles, which will later dislodge from the fabric and affect their antibacterial efficacy (Mohamed Ahmed et al. 2012). Thus, textile industries are in search for a superior antibacterial agent to be coated with fabrics without the limitations of chemical and natural disinfectants.

Nanoparticles as antibacterial disinfectants

The escalation of advancements in the field of nanotechnology has been the prime reason for the emergence of novel nanomaterials and nanoparticles with potential biological properties to be utilized in a wide range of biomedical applications. The potential use of nanoparticles in biomedical applications, especially as antimicrobial agents, has been under extensive research in recent times, and it has been considered as an alternate to conventional antimicrobials to overcome the multidrug resistance of microbes (Fernando et al. 2018). The resistance of bacteria towards antibiotics has been a great concern, which is attributed to the overuse and misuse of synthetic antibiotics as well as lack of new strategies for the development of antimicrobials to address the challenges. The bioactive properties such as antimicrobial, antiviral, antifungal, antioxidants and anti-inflammatory have made nanoparticles an extremely significant material for the development of novel nanodevices that can be used in biomedical and pharmaceutical applications (Vega-Jiménez et al. 2017; Khan et al. 2019). The high surface-to-volume ratio of nanoparticles enhances their interaction with the microbes and elevates their antimicrobial activity. Further, the antimicrobial activity of nanosized particles, such as metal, metal oxide, carbon-based nanoparticles and nanocomposites varies depending on the distinct nanoparticle types, their chemistry, particle size, morphology and surface charge as displayed in Fig. 4 (Fernando et al. 2018).

Metal nanoparticles

Nanosized metal particles such as gold, silver, platinum and copper nanoparticles are widely employed to exhibit antimicrobial activity, especially to inhibit bacterial growth. Further, these nanoparticles are embedded in textile fabrics in recent times, to eliminate the growth and spread of pathogenic bacterial strains via fabrics.

Gold nanoparticles

Gold is a precious metal, which plays a crucial role in the human history. The gold nanoparticles have a long history, since the ancient Roman period as it exhibits excellent optical properties and was initially used to make ruby-red opaque glass cup (McQueen and Vaezafshar 2019). Recently, several advancements in the field of nanotechnology have made nanosized gold to be employed in biomedical applications such as disease diagnosis and therapeutics. The gold nanoparticles have made a tremendous mark in the biomedical field by conjugating with various functionalization agents, which include polymers, surfactants, oligomers, DNA, dendrimers, drugs, RNA, protein and peptides (Lee et al. 2020). It has been extensively used as a bio-labelling, bioimaging or biosensing agent, due to its exclusive physical and optical properties (Elahi et al. 2018; Kotcherlakota et al. 2019). Further, nanosized gold particles are one of the most extensively used materials in drug delivery, as a potential carrier of vaccines and drugs to deliver them in the target sites (Das et al. 2011). Moreover, researchers have reported various shapes of gold nanoparticles such as triangular, spherical, rod and hexagonal nanoparticles, which play a predominant role in their biological applications (Gaware et al. 2012; Singh et al. 2018). However, the nanosized gold nanoparticles usually do not exhibit bacteriostatic or bactericidal activity, as it is known for their biocompatible nature with microbes. Hence, gold nanoparticles should be surface modified with functional groups or integrated with antibiotics to exhibit antibacterial activity against drug-resistant pathogens (Singh et al. 2018).

Li et al. (2014) studied the gold nanoparticles that are surface modified using different cationic functional groups of distinct chain length, nonaromatic and aromatic compounds to understand their potential antibacterial activity against multidrug-resistant bacteria. The monolayer-protected gold nanoparticles were able to completely inhibit the growth of 11 clinical multidrug-resistant bacteria, which include both gram-positive and gram-negative bacterial strains. However, the minimum inhibitory concentration (MIC) is differed by the

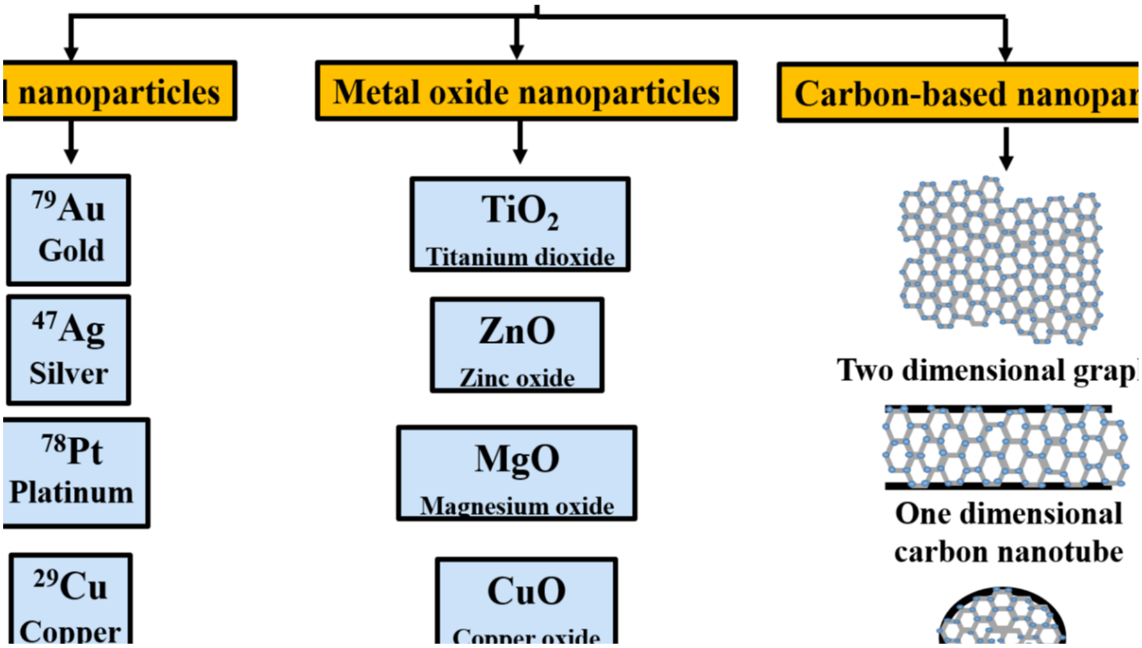


Fig. 4 Classification of antibacterial nanoparticles incorporated with textile fabrics

existence of carbon or hydrogen group as the cationic functional group in gold nanoparticles, which revealed the role of surface chemistry in enhancing the antibacterial activity of nanoparticles (Li et al. 2014). Likewise, Payne et al. (2016) synthesized a novel kanamycin-conjugated gold nanoparticle to study its potential against multidrug-resistant bacteria. The results demonstrated that kanamycin-conjugated gold nanoparticles exhibited strong inhibitory effect against both gram-positive and gram-negative bacteria, which also includes kanamycin-resistant bacteria. Also, the activity was demonstrated to be dose dependent, whereas the concentration of kanamycin-conjugated gold nanoparticle is very low to inhibit bacterial growth, compared to standalone kanamycin. This study has developed a novel method for coating antibiotic kanamycin on the surface of gold nanoparticles, to exhibit enhanced antibacterial efficacy against multidrug-resistant bacteria (Payne et al. 2016).

It is noteworthy that functionalization of antibiotic compound with gold nanoparticles was also being employed to enhance their antibacterial effect, while coating them in fabrics. Rai et al. (2010) synthesized antibiotic-mediated gold nanoparticles for potential antibacterial properties and evaluated their application as antibacterial coatings in textiles. The gold nanoparticles were synthesized using cefaclor antibiotic without using any other chemicals. The presence of amine group in the cefaclor acted as reducing and capping agent for the formation of nanosized gold that eliminates β-lactam of the antibiotic for efficient activity against microbes. The results demonstrated that cefaclor-reduced gold nanoparticles exhibited efficient antibacterial activity against both gram-positive *Staphylococcus aureus* and gram-negative *Escherichia coli*, compared to standalone cefaclor and gold nanoparticles. Further, the study reported that the cefaclor-reduced gold nanoparticles were coated over poly (ethyleneimine)-modified glass surface to obtain antibacterial finishing in glass, and their bactericidal activity was evaluated against *E. coli*. The nano-gold coating inhibited the *E. coli* at adverse conditions such as pH 3 (acidic) and pH 10 (alkaline). Furthermore, the results suggested that the antibacterial action is due to cefaclor that damages the peptidoglycan layer of bacteria and the holes created by gold nanoparticles in bacterial cell wall to increase cell wall permeability for elevating cell content leakage and eventually leads to cell death (Rai et al. 2010).

Silver nanoparticles

The ionic state of silver (Ag^+) is a common antimicrobial agent that is used to inhibit microbes for several years. The antimicrobial efficacy of ionic silver such as silver nitrate and silver sulfadiazine has made them an unavoidable entity in the commercial ointments for the treatment of wounds (Zheng et al. 2018). Recently, the nano-form of silver (Ag^0) has shown enhanced broad-spectrum antimicrobial properties against pathogenic microbes, especially against bacteria, compared to their bulk counterparts (Ahmed et al. 2016b). Szczepanowicz et al. (2010) prepared silver nanoparticles via chemical route using hydrazine, formalin and ascorbic acid. The resultant nanoparticles are reported to be in the size of 20 nm and demonstrated high antibacterial activity against both gram-positive and gram-negative bacteria (Szczepanowicz et al. 2010). Similarly, Thi et al. (2016)

studied the antibacterial activity of silver nanoparticles that are fabricated using sodium citrate as reducing agent. The antibacterial activity was evaluated in the wastewater shrimp pond, and the results suggested that nanosized silver particles possess high bactericidal efficacy against *E. coli* (Van Thi Thanh Ho and Thi 2016). Likewise, Guzmán et al. (2009) studied the antibacterial activity of nanosized silver against *E. coli*, *P. aeruginosa* and methicillin-resistant *S. aureus*. The effect of silver nanoparticles against microbes was studied by varying the concentration of silver precursor, stabilizing agent and reducing agent. The antibacterial assay results showed that smaller sized silver nanoparticles (9 and 11 nm) possess the greater size-dependent bactericidal efficacy (Guzmán et al. 2009).

It is noteworthy that silver nanoparticles can exhibit synergistic antibacterial effect, when they are combined with other natural and synthetic compounds (Durán et al. 2016). McShan et al. (2015) studied the synergistic antibacterial activity of silver nanoparticles against drug-resistant *Salmonella typhimurium* DT104 by combining them with inactive antibiotics such as tetracycline (polypeptide), neomycin (aminoglycoside) and penicillin (β-lactam). The study demonstrated that the combination of nanosized silver with inactive tetracycline and neomycin possesses the ability to synergistically inhibit the growth of bacteria, whereas no inhibition was observed for the penicillin-combined nanosized silver (McShan et al. 2015). In another study, Alkawareek et al. (2019) studied the synergistic antibacterial effect of silver nanoparticles along with hydrogen peroxide against *E. coli* and *S. aureus*. The results showed that there is only a slight decrease in the bacterial growth by using hydrogen peroxide or nano-silver alone, whereas the combination of these two agents completely eradicated both *E. coli* and *S. aureus*, even at low concentrations (Alkawareek et al. 2019). Likewise, Surwade et al. (2019) reported the antibacterial activity of ampicillin combined with silver nanoparticles against methicillin-resistant *Staphylococcus aureus* (MRSA). The results suggested that the presence of ampicillin at low concentration with silver nanoparticles is highly effective against MRSA. However, the ampicillin-overcoated silver nanoparticles at higher concentration prevent the direct interaction of nanoparticles with bacteria and reduced their antibacterial efficacy. This work suggested that the sub-lethal dose of silver nanoparticles with ampicillin was highly beneficial in inhibiting the growth of MRSA (Surwade et al. 2019).

Nanosized silver particles are extensively employed as a coating material on textile fabrics to provide an antibacterial finish, owing to their strong bactericidal properties for blocking the interaction between infectious pathogens and fabric (Bacciarelli-Ulacha et al. 2014). Figure 5 illustrates the alterations in the wool fibre surface, due to the incorporation of protease-silver nanoparticles, which also contributed for antibacterial property against *Klebsiella pneumoniae* and *S. aureus* (Memon et al. 2018). Recently, Zhang et al. (2014) studied the antibacterial properties of silk treated with silver nanoparticles. The in situ method of coating silver nanoparticles on the silk fabric was developed and evaluated for their antibacterial efficiency against *E. coli* and *S. aureus*. The results demonstrated that fabric finished with nanoparticles has shown excellent antibacterial activity against both bacteria. Moreover, the fabrics were assessed for their laundering durability for 50 washing cycles, and its results revealed that the antibacterial efficacy was retained up to 97.43% and 99.86% against *S. aureus* and *E. coli*, respectively (Zhang et al. 2014). In addition, Zhang et al. (2009) coated silver nanoparticles over cotton fabric surfaces to fabricate antibacterial finish, and the results indicated that cotton fabric with nanoparticles exhibited 99.01% of bacterial reduction ability against *S. aureus* and 99.26% of bacterial reduction efficacy against *E. coli*, where its antibacterial activity is retained for up to 20 wash cycles (Zhang et al. 2009).

Other metal nanoparticles

Apart from these common metal nanoparticles, platinum and copper are the other nanosized metals that are extensively under research to be included and coated over fabric surfaces to exhibit enhanced antibacterial property.

Platinum nanoparticles Platinum nanoparticles (PtNPs) have attracted much attention to be employed in biomedical applications, due to their wide range of exclusive properties. It is

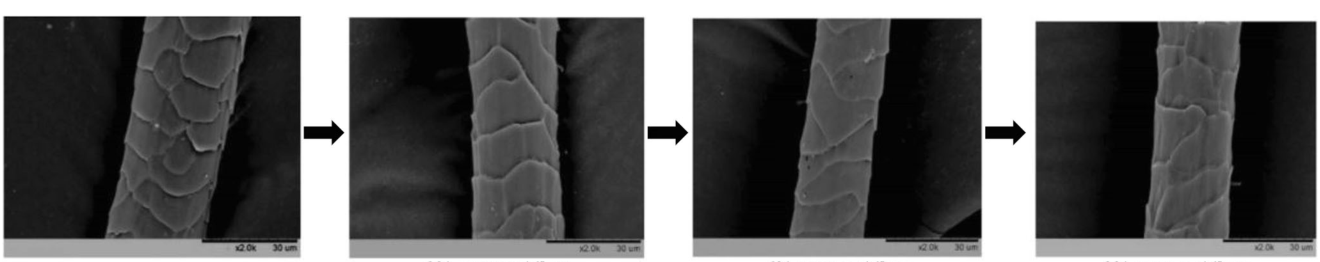


Fig. 5 Morphological transformation of wool fibre, due to the incorporation of protease-silver nanoparticles (Reproduced with permission from Memon et al., (2018))

the most expensive and rarest metal, which has high and unique corrosion resistance property to be incorporated in films to be extensively used in optical applications, enzyme immobilization and catalytic activities (Sharon et al. 2017). Recent studies indicated that PtNPs can exhibit antibacterial properties against numerous pathogenic microorganisms. Further, literatures reported that the increase in the bacterial inhibition by PtNPs is due to their increased production of reactive oxygen species (ROS). Thus, PtNPs have gained numerous significance in clinical applications as an antimicrobial agent (HASHIMOTO et al. 2017). Itohiya et al. (2019) studied the effect of PtNPs against dental pathogens such as *Streptococcus mutans*, *Enterococcus faecalis* and *Porphyromonas gingivalis*. Various concentrations of PtNPs (1, 5, 10 and 20 ppm) are allowed to interact with each inoculated bacteria for 10 min, and the existence of colonies was examined to determine the antibacterial effect. The results revealed that the colony formation was suppressed completely in all bacterial strains at a concentration greater than 5 ppm and the same trend was followed for all bacterial strains (Itohiya et al. 2019). Likewise, Ahmed et al. (2016) studied the in vivo antibacterial effect of PtNPs using adult zebra fish as the animal model to rescue zebra fish from bacterial infection. The zebra fish infected with *E. coli* and a fish-specific pathogen such as *Aeromonas hydrophila* were subjected to PtNP treatment. The results revealed that PtNPs exhibited dose-dependent antibacterial activity and completely rescued zebra fish from bacterial infection. This shows that PtNPs possess strong inhibitory effect against pathogenic microbes to be beneficial in antibacterial therapy (Ahmed et al. 2016a).

The application of PtNPs on textile fabrics has been tremendously increasing in recent times to provide the fabrics with antibacterial properties to prevent the wearer from infectious disease and pathogenic attack, considering the strong bactericidal properties of PtNPs. Zou et al. (2018) evaluated the antibacterial properties of in situ synthesized PtNPs on silk fabric to prove their exclusive bactericidal efficacy. The results proved that PtNP-treated silk fabrics exhibited 91% antibacterial activity, whereas the standalone silk fabric possesses no antibacterial effect (Zou et al. 2018). Further, Derakshan et al. (2018) coated cotton fabric with titanium dioxide (TiO_2)-platinum nanoparticles to provide superior antibacterial properties to cotton. The results revealed that the nanosized TiO_2-treated cotton fabric has shown antibacterial activity for about 68% and 37% against *E. coli* and *S. aureus*, respectively, compared to raw cotton fabric. However, the cotton fabric coated with platinum-TiO_2 nanocomposite has shown 100% synergistic antibacterial activity against both bacterial strains (Derakhshan et al. 2018a).

Copper nanoparticles Generally, copper is present in and required by animals as well as plants as a trance element, and it is used by mankind for more than 9000 years (Sistemática et al. 2016). It was observed that in the nineteenth century, workers from copper mines were immune to cholera, and copper was used for sterilizing wounds and water purification, in the early 2200 B.C. Thus, the antimicrobial properties of copper are proven to be beneficial to fight infectious disease caused by pathogenic microorganisms (Sistemática et al. 2016). The low cost, environmental safety and wide existence of copper in nature are the prime advantages in utilizing copper as an effective antibacterial agent to replace precious metals such as silver and platinum (Godymchuk et al. 2015). Moreover, copper is known for its ‘contact killing’ mechanism of antimicrobial action, due to its rapid killing of viruses, yeasts and bacteria upon interacting with the surface of metallic copper. This phenomenon is well known from the ancient times, and it is recognized as the first solid antibacterial material by the US Environmental Protection Agency (Grass et al. 2011). Recently, copper at the nanoscale regime has gained greater significance due to its enhanced physicochemical and exclusive functional properties. Such nanoparticles exhibit enhanced antibacterial behaviour against a wide range of pathogenic microbes, due to their high surface-to-volume ratio compared to their bulk counterparts (Chatterjee et al. 2014). The copper nanoparticles exhibited superior antibacterial activity against several microbes such as methicillin-resistant *Staphylococcus aureus*, *Bacillus subtilis*, *P. aeruginosa* and *Salmonella choleraesuis* and antifungal activity against *Candida albicans* (Usman et al. 2013).

The copper nanoparticles have been extensively used as a coating material on the fabrics to provide an antibacterial finish to the textiles, owing to their strong bactericidal properties. Namasivayam et al. (2013) fabricated copper nanoparticles via chemical approach and coated them over the cotton fabric surface to evaluate their antibacterial activity against bacterial strains that are isolated from post-operative patients such as *S. aureus*, *E. coli* and *P. aeruginosa*. The results revealed that the copper nanoparticles and the nanosized copper–treated fabrics exhibited superior antibacterial behaviour against all the tested pathogens (Karthick Raja Namasivayam et al. 2013). In another study, Eremenko et al. (2015) impregnated silver and bimetallic silver-copper nanoparticles over cotton fabric surfaces to evaluate their antibacterial properties against multidrug-resistant bacteria and fungi such as *E. coli*, *Enterobacter aerogenes*, *Proteus mirabilis*, *K. pneumoniae*, *S. aureus, E. faecalis* and *Candida albicans* yeasts. It can be noted that the nanoparticle-treated fabrics exhibited higher antibacterial properties against all the selected pathogens. Further, the bimetallic nanoparticles demonstrated enhanced antibacterial activity against *E. coli*, *K. pneumoniae*, *E. aerogenes*, *P. mirabilis*, *P. aeruginosa* and *S. aureus*, compared to silver-impregnated fabric (Eremenko et al. 2016). Thus, the above study confirmed the successful impregnation of copper nanoparticles on the surface of fabrics to provide an antibacterial finish and inhibit the growth of a wide range of bacterial strains.

Metal oxide nanoparticles

Nanosized oxides of metal particles such as titanium, zinc, magnesium, copper and iron are further used to coat with textile fabrics, apart from metal nanoparticles, to exhibit enhanced antibacterial activity. Metal oxide nanoparticles are highly stable in reaction conditions (Jeevanandam et al. 2016a), compared to metal nanoparticles, which makes them as a highly utilizable material to provide antimicrobial finishes to the fabrics, next to nanosized metals.

Titanium dioxide nanoparticles

Titanium dioxide (TiO_2) is a well-known material, specifically in industrial applications, due its interesting stability and optical and electrical properties, which generally occur in different variants such as rutile, anatase and brookite. Further, TiO_2 has been used in various applications that include environmental protection, civil engineering, medicine, agriculture, food and cosmetic industry. Moreover, nanosized titanium oxide particles are widely used in self-cleaning roof tiles, water and sewage treatment and gas combustion and are used as catalyst in organic synthesis and as an antimicrobial agent for decontamination in recent times, due to their enhanced catalytic properties (Baranowska-Wójcik et al. 2020). The anatase phase of TiO_2 is an extensively utilized material on photodegradation applications, compared to other two forms. Likewise, the anatase type absorbs the photons in the ultraviolet region to excite the valence electrons and generate electron-hole pairs (EHPs) that are recombined and absorbed on the surface of TiO_2 nanoparticles. The excited electrons and holes have high redox activities, which react with water and oxygen to produce reactive oxygen species (ROS) such as super oxide anions (O^{2-}) and hydroxyl radical (-OH) groups. This photocatalytic process of TiO_2 nanoparticles is under extensive research to inhibit the numerous microbes that contaminate environmental entities (Desai and Kowshik 2009). Pişkin et al. (2013) reported the antibacterial activity of TiO_2 nanoparticles against *E. coli*, *S. aureus*, *P. aeruginosa*, *C. albicans* and *B. subtilis*. The results demonstrated that nanosized TiO_2 were highly toxic to *E. coli* (zone of inhibition (ZoI) – 31 mm), followed by *S. aureus* (ZoI – 29 mm), *C. albicans* (ZoI – 25 mm), *P. aeruginosa* (ZoI – 15 mm) and *B. subtilis* (ZoI – 15 mm). Moreover, the results also suggested that TiO_2 nanoparticles have potent antibacterial effect against broad-spectrum microbes (Pişkin et al.). Likewise, Zimbone et al. (2015) recently synthesized TiO_2 nanoparticles and studied their antibacterial efficacy against *E. coli*. It is worthy to note that the nano-TiO_2 exhibited greater antibacterial activity, which was attributed to the electron-hole pair recombination-mediated ROS formation mechanism (Zimbone et al. 2015).

TiO_2 nanoparticles have also been used in textile industry, due to their antimicrobial, self-cleaning, UV-light protection, mothproofing and flame retardancy properties (Derakhshan et al. 2018b). Recently, Zhang et al. (2019) fabricated TiO_2 nanoparticles via two-step sol-gel and hydrothermal method, to coat them over the cotton fabric surface, and studied their efficacy against common bacterial strains. The results revealed that the TiO_2-treated cotton fabrics showed excellent antibacterial activity against both *E. coli* and *S. aureus* (Zhang et al. 2019). Likewise, Perelshtein et al. (2012) demonstrated excellent antibacterial properties against *E. coli* and *S. aureus* by coating TiO_2 nanoparticles on the surface of cotton fabrics (Perelshtein et al. 2012). In another study, Sarathi et al. (2009) prepared TiO_2 nanoparticles using urea as a reaction medium and coated them on the surface of 100% cotton and 45/55% polyester/cotton fabrics. The nanoparticle-treated fabrics were evaluated for potential antibacterial property against gram-positive *S. aureus* and gram-negative *K. pneumoniae*. The results demonstrated that the nanoparticle-treated fabrics exhibited excellent antibacterial activity with 85% and 64% of efficacy for 100% cotton and 93% and 73% of efficiency for 45/55% polyester/cotton fabrics against *S. aureus* and *K. pneumoniae* bacteria, respectively (Sarathi and Thilagavathi 2009). However, Prorokova et al. (2018) reported that TiO_2-treated polyester fabric does not exhibit any antimicrobial properties, whereas the silver-doped TiO_2 nanoparticles with higher photocatalytic activity provided antimicrobial efficacy to the fabric in suppressing the growth of the microbes. The study stated that the silver metal as dopant has elevated the photochemical activity of TiO_2 to exhibit microbial growth inhibition property in polyester fabric (Prorokova et al. 2018).

Zinc oxide nanoparticles

Zinc oxide (ZnO) is the most promising metal oxide that can be fabricated into a diverse range of nanostructures such as nanotubes, nanobelts, nanowires, nanorods and other complex structures. Generally, it possesses unique properties to be beneficial as semiconductors in optics and can be fabricated as piezoelectric materials. The excellent and exclusive properties of ZnO nanoparticles are widely used in numerous applications such as nano-electronics or nano-optical devices, cosmetic products, energy storage and nanosensors (Vaseem et al. 2010; Kołodziejczak-Radzimska and Jesionowski 2014). The wide band gap (3.3eV) and large excitonic binding energy have made nanosized ZnO the most versatile material to be utilized for both scientific and industrial applications (Sabir et al. 2014). ZnO usually appears as a white powder and is insoluble in water and widely applied as additives in numerous materials including ceramic, glass, cement, rubber in car tyres, lubricants, paints, ointments, adhesives, plastics, sealants, pigments, foods, batteries, ferrites and fire retardants (Sabir et al. 2014). The usage of ZnO has been increased extensively in recent times, due to its superior UV absorption properties, especially in products such as sunscreen and cosmetics. Apart from the above-mentioned applications, it has also gained interest in biomedical applications as it shows toxic effects against cancer cells and broad-spectrum microbes (Malaikozhundan 2018).

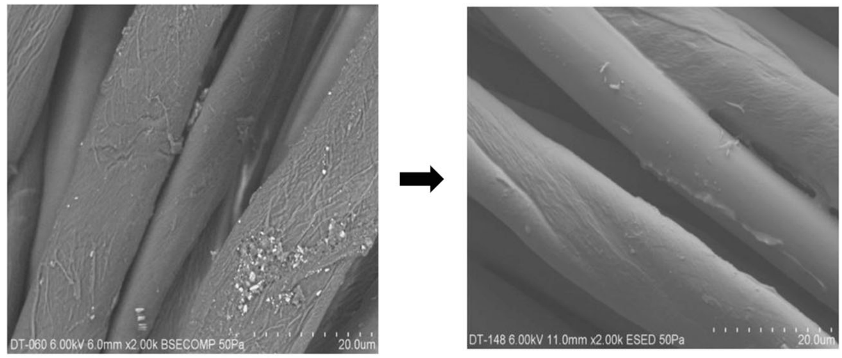
Emami-Karvani et al. (2011) reported the antibacterial activity of ZnO nanoparticles against gram-positive and gram-negative *S. aureus* and *E. coli*, as conventional antibiotics are a great concern, which fail to control bacterial resistance. The results demonstrated that the resultant ZnO nanoparticles possess excellent size-dependent antibacterial activity against both microbes. Further, it can be noted that the resultant ZnO nanoparticles are more toxic to *S. aureus* than *E. coli* (Emami-Karvani and Chehrazi 2011). Similarly, Akbar et al. (2019) reported the antibacterial efficiency of nanosized ZnO particles against foodborne pathogens, namely *Salmonella typhimurium* and *Staphylococcus aureus*. The results demonstrated that the nanosized ZnO possesses time-dependent bactericidal effect cells, where the complete inhibition of bacterial strains occurred at 8 h for *S. typhimurium* and 12 h for *S. aureus* (Akbar et al. 2019). Moreover, ZnO nanoparticles with enhanced antibacterial property were coated on textile fabrics as an antimicrobial finish to inhibit pathogenic bacterial growth in fabrics. Singh et al. (2012) studied the antibacterial efficacy of ZnO nanoparticle-coated cotton fabrics against gram-positive *S. aureus* and gram-negative *E. coli* bacterial strains. The results demonstrated that the nanoparticle-coated cotton fabrics exhibit significant antibacterial activity against both bacterial strains. However, it is noteworthy that the nanoparticle-treated fabrics exhibited slightly higher activity against *S. aureus* than *E. coli* (Singh et al. 2012). Likewise, Perelshtein et al. (2009) deposited ZnO nanoparticles on the surface of cotton bandages via in situ sonochemical method and reported their antibacterial properties. The results demonstrated that ZnO-coated cotton bandage at a low concentration of 0.75% exhibited excellent antibacterial activity against *E. coli* and *S. aureus*. The time-dependent activity revealed that the ZnO-coated cotton bandages are capable of inhibiting 100% of *E. coli* bacteria at 2 h of contact period, whereas 99.93% of *S. aureus* were inhibited at 3 h of contact period (Petkova et al. 2016). The morphological changes in the cotton/polyester (65/35%) fabric due to the incorporation of zinc oxide-chitosan nanocomposite have been illustrated in Fig. 6, which has also exhibited antibacterial activity against gram-negative *E. coli* and gram-positive *Micrococcus luteus* bacterial strains (Farouk et al. 2012).

Magnesium oxide nanoparticles

Magnesium oxide (MgO) nanoparticles are among the widely used inorganic metal oxide nanoparticles in numerous fields, due to their excellent functional properties such as high thermal stability, low heat capacity, chemical inertness and optical transparency (Andra et al. 2019a). MgO at nanoscale generally exhibits unique optical, electrical, thermal, chemical, mechanical and magnetic properties. It has been used as catalysts, in wastewater remediation, and as refractory materials, due to their versatility in exhibiting properties (Camtakan et al. 2012). It has also been used as a gas absorption material to clean air that is polluted with toxic gases such as nitrogen dioxide (NO_2) and sulphur dioxide (SO_2), which pose tremendous threat to human health as well as the ecosystem (Duong et al. 2019).

Despite numerous applications, MgO nanoparticles are widely employed in biological applications for heat burns and cancer therapy and are used as an antimicrobial agent (Suresh et al. 2013; Jeevanandam et al. 2018b). Recent evidences have shown that the nanosized MgO particles are extensively utilized for their exclusive antimicrobial properties due to the concern about multidrug-resistant pathogens. Several researchers have reported the broad-spectrum activity of MgO nanoparticles against bacteria, fungi and a few viruses (Cai et al. 2018). Thus, nano-MgO has been used as a curative agent against disease-causing pathogenic bacteria, owing to its strong bactericidal properties. Jeevanandam et al. (2019) fabricated MgO nanoparticles using the leaf extracts of *Amaranthus tricolor*, *Amaranthus blitum* and *Andrographis paniculata* and evaluated their antibacterial activity against *E. coli* as a food-borne pathogen model. The result revealed that the ~78-nm-sized spherical MgO nanoparticles synthesized via *A. blitum* possess enhanced antibacterial efficacy. Further, Cai et al. (2018) studied the antibacterial activity of commercial MgO nanoparticles against agricultural bacteria, namely *Ralstonia solanacearum*, which is a soil-borne pathogen that can infect numerous plant species around the world. The results demonstrated that MgO nanoparticles exhibited the superior, concentration-dependent, antibacterial property against *R. solanacearum* bacteria via intimate contact at an MIC value of 250 μg/ml, which is lower compared to bulk MgO. In addition, the transmission electron micrograph (TEM) results showed physical injury of bacterial cells upon interaction with MgO nanoparticles, which has led to the destruction of cell membrane, leakage of cell content and finally cell death. Hence, the results suggested that the nanosized MgO possesses the ability to inhibit the bacterial plant pathogens (Cai et al. 2018).

Recently, nano-MgO is also being used as a coating material on textiles to provide an antimicrobial finish to the fabric. There are numerous reports on treating the MgO nanoparticles



Untreated cotton/polyester fabric

ZnO nanoparticle-chitosan coated cotton/polyester fabric

Fig. 6 Morphological transformation of cotton/polyester fabric due to coating of ZnO nanoparticle-chitosan (Reproduced with permission from Farouk et al., (2012))

on both synthetic and natural fabrics (Ponnuvelu et al. 2016). Suresh et al. (2013) fabricated the MgO nanoparticles via wet chemical method using the magnesium nitrate and sodium hydroxide as the precursors and starch as the stabilizing agent. The synthesized nanoparticles were evaluated for their antibacterial activity against *E. coli* and *S. aureus*. The results demonstrated that the zone of inhibition indicated the antibacterial activity of MgO nanoparticles was higher for *S. aureus* than *E. coli*. The findings of the study suggested that the fabrication of MgO nanoparticles via a simple and cost-effective approach will possess the ability to exhibit strong antibacterial property in textile fabrics (Suresh et al. 2013).

Copper oxide nanoparticles

Copper oxide (CuO) nanoparticles are the smart transition metal oxide among other metal oxide nanoparticles with a band gap of 2 eV. It possesses interesting features such as good electrochemical activity, high specific surface area, proper redox potential and excellent stability in solutions (Verma and Kumar 2019). Generally, these CuO nanoparticles exist in the form of Cu, Cu_2O or CuO and has been applied in diverse applications such as microcircuits, microelectronics, sensors, nanofluids, coatings, supercapacitors, near-infrared filters, paints, catalysis and emission devices (Andra et al. 2018; Eltarahony et al. 2018). It is worthy to note that nanosized CuO powder is soluble in dilute acids and insoluble in water and slowly dissolves in alcohol and ammonium solutions. Moreover, the CuO at the nanoscale has superior chemical and physical properties, such as quantum size effect, volume effect, magnetic quantum tunnelling, chemical reactivity, optical absorption and thermal stability. Recently, the CuO nanoparticles have attracted greater attention among researchers to be beneficial for various applications and has become one of the extensively used transition metal oxides (Singh et al. 2016). Further, the CuO nanoparticles possess various optical, electrical, magnetic and mechanical properties, which can be exhibited by controlling their size and morphology (Grigore et al. 2016).

Among other applications, intensive research focuses on the biological applications of the nanosized CuO as it possesses strong biocidal properties to be utilized in the field of biomedicine (Grigore et al. 2016). In addition, Ahamed et al. (2014) prepared CuO nanoparticles via the co-precipitation approach and studied their antibacterial efficacy against various bacterial strains such as *E. coli*, *P. aeruginosa*, *K. pneumoniae*, *E. faecalis*, *Shigella flexneri*, *S. typhimurium*, *Proteus vulgaris* and *S. aureus*. The results demonstrated that the synthesized CuO nanoparticles exhibited excellent antibacterial activity against all the selected pathogens. However, it can be noted that the CuO nanoparticles are highly toxic against *E. coli* and *E. faecalis* and are less toxic towards *K. pneumoniae*. These findings have suggested that the CuO nanoparticles possess the ability to exhibit broad-spectrum antibacterial activity (Ahamed et al. 2014). Further, nano-CuO has also been widely used in water filtrations as disinfectants, due to its strong antibacterial properties (Liu et al. 2013). Likewise, Amiri et al. (2017) reported superior antibacterial activity of CuO nanoparticles against certain oral bacterial strains such as *S. mutans*, *Lactobacillus casei* and *Lactobacillus acidophilus* as well as fungal species, namely *C. albicans* (Amiri et al. 2017).

In recent times, the surface coating of CuO nanoparticles on textile fabrics has increased tremendously to provide functional antibacterial properties to the fabric as it can help in mitigating transmission of contact diseases via fabrics (Majumder and Neogi 2016). Hasan (2018) synthesized the nanosized CuO via the chemical route and immobilized them over the surface of 100% woven cotton fabrics using the pad-dry-cure method. The results showed that the CuO nanoparticle–treated fabric exhibited higher antibacterial activity against both *E. coli* and *S. aureus*, whereas the bulk CuO–treated fabric does not show any activity. Further, the wash durability results emphasized that the activity of nanoparticle-treated fabrics before wash exhibited 86.28% and 94.05% for *E. coli* and *S. aureus*, respectively. Furthermore, the inhibition of bacteria decreased gradually upon increasing the washing cycle, and no reduction in the bacterial growth is observed at 25th wash. The findings of the study suggested that the CuO nanoparticles are physically adsorbed on the fabric surface that is leached during washing cycles and leads to a decrement in the antibacterial efficacy of the fabric (Hasan 2018a).

Other metal oxide nanoparticles

Apart from the metal oxide nanoparticles mentioned in the previous sections, there are other nanosized oxides of metal particles such as iron and cerium oxide that are identified to be beneficial to immobilize over the fabric surface to inhibit the growth of pathogenic bacterial strains. Rastgoo et al. (2016) reported a novel ultrasound and sonosynthesis-mediated deposition of magnetite iron oxide nanoparticles on the surface of cotton or polyester fabric to exhibit antimicrobial activity with exclusive magnetic property. The results demonstrated that the magnetic nanoparticle–coated fabric exhibited 95% of antibacterial activity against *S. aureus* and 99% of antifungal efficacy against *Candida albicans* with photocatalytic, sonocatalytic and enhanced mechanical property (Rastgoo et al. 2016). Similarly, Harifi and Montazer et al. (2014) revealed that magnetic iron–based magnetite and haematite nanoparticles that are coated over polyester fabric surface possess enhanced antibacterial efficacy against *S. aureus* along with catalytic sono-Fenton activity to be beneficial in the discolouration of toxic dyes present in the fabric (Harifi and Montazer 2014). Likewise, cotton fabrics coated with nickel oxide nanoparticles via sodium alginate as a cross-linker were proven to possess enhanced antibacterial activity against *E. coli* and *S. aureus* with excellent wash durability up to 25 cycles (Suresh et al. 2014). In addition, green and biosynthesized metal oxide nanoparticles were also extensively employed to be coated with fabric surfaces for exhibiting enhanced antibacterial activity (Das and Rebecca 2017).

Carbon-based nanoparticles

Carbon-based nanoparticles such as two-dimensional graphene, one-dimensional carbon nanotubes (CNTs) and zero-dimensional carbon dots as well as fullerenes are recent nanoparticle-based candidates that are under extensive research to coat with textile fabrics to inhibit pathogenic bacterial growth.

Graphene nanoparticles

Generally, graphene and its oxides were combined with either metal or metal oxide nanoparticles to be embedded in the cotton fabrics. Ghosh et al. (2019) reported that reduced graphene oxide-silver nanoparticle composites can be fabricated and decorated on the surface of conductive cotton fabric to exhibit antibacterial property. The results showed that the nanocomposite-coated fabrics possess exclusive antibacterial activity against *E. coli* along with efficient electromagnetic interference shielding property (Ghosh et al. 2019). Likewise, Karimi et al. (2015) decorated the surface of cotton fabrics with titanium dioxide nanoparticles and graphene oxide nanosheets to provide an antibacterial finish to the fabric. The study confirmed that the nanoparticle-coated cotton fabric possesses efficient antibacterial efficacy against *E. coli* and *S. aureus* along with ultraviolet ray blocking activity (Karimi et al. 2016). Similarly, Nazari (2019) recently fabricated zinc oxide–reduced graphene oxide nanocomposite synthesized using pomegranate juice extract to immobilize them on the surface of cotton fabric. The study demonstrated that the nanocomposite-coated cotton fabric possesses enhanced antibacterial property against *E. coli* and *S. aureus* as well as an improved photocatalytic activity to degrade toxic methylene blue dye (Nazari 2019). Contrarily, Hu et al. (2019) recently embedded graphene oxide over cotton fabric by modifying its surface with cross-linking iron ions. These graphene-coated fabrics exhibited excellent antibacterial activity against *S. aureus* and *E. coli* along with superior mechanical, thermal and washing durability properties (Hu et al. 2019).

Carbon nanotubes

Carbon nanotubes (CNTs) are one-dimensional, hollow rod-shaped carbon nanostructures that are widely used in the electronic industry as well as in several biomedical applications (Jia and Wei 2019). The ability to functionalize the terminal ends of CNTs with antibiotics and the possibility to embed nanosized antibacterial agents in their hollow structures make them a potential nanomaterial to incorporate antibacterial finishes in textile fabrics, in addition to their standalone antibacterial properties (Alimohammadi et al. 2018a). Mojtahed et al. (2015) fabricated carboxylated CNTs via plasma pretreatment to elevate their adsorption property for coating them on the surface of cotton fabrics. The results revealed that the increased absorption of CNTs towards cotton fabrics has led to an improvement on their antibacterial efficacy against *S. aureus* bacterial strain (Mojtahed et al. 2016). Further, Chen et al. (2016) utilized layer-by-layer assembly technique to coat polyhexamethylene guanidine phosphate (PHMGP) and CNT-potassium alginate on the surface of the cotton fabric. These CNT-coated fabrics exhibited enhanced thermal stability, flame resistance by promoting the formation of char, burning time decrement and afterglow elimination during combustion. Additionally, these cotton fabrics are proven to possess a superior bilayer growth number–dependent antibacterial efficacy against *E. coli* (Chen et al. 2016). Similar to graphene, CNTs were also incorporated with other metal-based and polymeric nanoparticles to form nanocomposites to increase their strong bond formation efficiency with textile fabrics for unveiling their exclusive antibacterial property. Kumar et al. (2019) decorated pristine-functionalized single-walled CNTs with silver nanoparticles via acidic treatment as well as microwave irradiation approach and immobilize them on the surface of the cotton fabric using dip-dry-curing process. The resultant silver-CNT nanocomposite–coated cotton fabric exhibited enhanced antibacterial efficacy against *E. coli* and *S. aureus* with durability up to 20 wash cycles (Kumar et al. 2019). Likewise, Alimohammadi et al. (2018) fabricated a novel CNT functionalized with polyvinylpyrrolidone (PVP) to form nanocomposite and coated them on the surface of cotton fabric under ultraviolet ray irradiation via the pad-dry-cure approach. The resultant cotton fabric exhibited enhanced thermal stability with reduced flammability along with the ability to inhibit the *S. aureus* and *E. coli* bacterial colonies on the fabric surface (Alimohammadi et al. 2018b).

Carbon dots

Carbon dots and fullerenes (C60) are the zero-dimensional carbon nanostructures that are electronically confined in all the directions (Peng et al. 2017b). These dimensionless nanostructures are highly beneficial in the biomedical field, especially in bioimaging and drug delivery applications (Moussa 2018; Anwar et al. 2019). It is possible to encapsulate conventional antibiotics in the void spaces of carbon dots and fullerenes to deliver them in the targeted pathogenic bacterial cells to increase their antibacterial efficacy (Zhilenkov et al. 2017; Jijie et al. 2018). In addition, standalone carbon dots and fullerenes were also proven to exhibit antibacterial activity against various pathogenic bacterial strains (Li et al. 2018; Zhang et al. 2018). Moreover, these dimensionless nanostructures are sensitive to visible light, which elevates their antibacterial activity by acting as a photocatalyst upon light irradiation (Ouyang et al. 2017; Xie et al. 2018). In recent times, carbon dots are immobilized on the surface of textile fabrics to protect them from ultraviolet rays (Zuo et al. 2019). However, there are no reports on immobilization of zero-dimensional nanostructures on the surface of cotton fabrics to exhibit antibacterial property. However, it is possible to improve their involvement in the textile industry for antibacterial finishes as carbon dots possess enhanced antibacterial efficacy. Even though carbon-based nanoparticles are employed to provide antibacterial finishes to the fabrics, their toxicity towards humans remains as a major limitation to utilize them to inhibit bacterial colonies that exist in the fabric surfaces. Thus, metal-based nanoparticles are extensively employed for antibacterial finishes in textile applications, due to their long-term stability and non-/less toxic nature towards humans.

Novel nanocomposites

Recently, nanocomposites are gaining applicational significance in various fields due to their ability to exhibit positive properties of two or more materials by reducing their negative properties (Jeevanandam et al. 2019). In textile applications, these nanocomposites are extensively under research to elevate the antibacterial properties of fabrics with multifunctional attributes as well as to reduce potential toxicity towards other organisms (Paramasivan et al. 2018). Gao et al. (2019) demonstrated that silicone quaternary ammonium salts can be bound with silver and zinc oxide to form nanocomposite for exhibiting antibacterial activity. The results revealed that the chemical structure of the nanocomposite is stable after coating it on the cotton fabric surface with excellent antibacterial efficacy against *S. aureus* and *E. coli*, along with hydrophilicity, air permeability, softness and durability until 10 washing cycles (Gao et al. 2020). Likewise, Attarchi et al. (2018) fabricated a novel silver-titanium dioxide-beta cyclodextrin nanocomposite for coating on the surface of cellulose fabric. The nanocomposite-coated fabric was stated to possess enhanced antibacterial efficacy against *S. aureus*, along with self-healing ability to degrade toxic methylene blue dye, enhanced chrome ion adsorption, elevated tensile strength and crease recovery angle (Attarchi et al. 2018). In addition, copper oxide-poly ethylene glycol (Khani and Talebian 2017), copper oxide-titanium dioxide (Ibrahim et al. 2019) and hydroxyapatite-silver nanoparticles (Ferreira et al. 2019) are the other nanocomposites that are coated on the textile fabric surface to inhibit bacterial strains, which show that nanocomposites possess the ability to replace conventional nanoparticle–based antibacterial textile finishes in the future. All these studies showed that nanoparticle-coated fabrics exhibited improved antibacterial properties along with enhanced mechanical properties. However, the antibacterial mechanism and efficacy of nanoparticle-coated fabric differ among *S. aureus* and *E. coli* bacterial strains, as suggested in various literatures, where the former is a gram-positive and the latent is a gram-negative model of a bacterial strain. This diversification in their antibacterial property can be primarily attributed to the cell wall structure of both bacterial strains and the method of synthesis approach used for fabrication of nanoparticles. Table 1 presents the summary of various nanoparticles that are incorporated with textile fabrics, especially in cotton fabrics, to provide antibacterial finishes.

Effect of nanoparticle synthesis in their antibacterial property

Generally, synthesis approaches play a crucial role in determining the uniqueness of nanoparticles to be used in desired

Table 1 Nanoparticles incorporated with textile (cotton) fabric for antibacterial finishes

Nanoparticles	Antibacterial activity	Reference
Metal nanoparticles		
Cefaclor-coated gold nanoparticles in cotton fabric	Enhanced activity against *E. coli* and *S. aureus* even at pH 3 and 9	(Rai et al. 2010)
Silver nanoparticles in silk fabric	97.4% of activity against *E. coli* and 99.8% of activity against *S. aureus*, even after 50 wash cycles	(Zhang et al. 2014)
Silver nanoparticles in cotton fabric	99.2% of activity against *E. coli* and 99.01% of activity against *S. aureus*, even after 20 wash cycles	(Zhang et al. 2009)
Platinum nanoparticles in silk fabric	91% of antibacterial activity against *E. coli*	(Zou et al. 2018)
Titanium dioxide-platinum nanoparticles in cotton fabric	68% of activity against *E. coli* and 37% of activity against *S. aureus*	(Derakhshan et al. 2018a)
Copper nanoparticles in cotton fabric	Enhanced activity against *S. aureus*, *E. coli* and *P. aeruginosa*	(Karthick Raja Namasivayam et al. 2013)
Bimetallic silver-copper nanoparticles in cotton	Enhanced activity against *E. coli*, *Enterobacter aerogenes*, *Proteus mirabilis*, *Klebsiella pneumoniae*, *S. aureus*, *E. faecalis*	(Eremenko et al. 2016)
Metal oxide nanoparticles		
TiO_2 nanoparticles in cotton	Enhanced activity against *E. coli* and *S. aureus*	(Zhang et al. 2019)
TiO_2 nanoparticles in cotton	Enhanced activity against *E. coli* and *S. aureus*	(Perelshtein et al. 2012)
TiO_2 nanoparticles in 100% cotton and 45/55% polyester/cotton fabric	Enhanced activity against *K. pneumoniae* and *S. aureus*	(Sarathi and Thilagavathi 2009)
TiO_2 nanoparticles in polyester fabric	Silver-doped TiO_2 nanoparticles possess enhanced antibacterial activity via light irradiation	(Prorokova et al. 2018)
ZnO nanoparticle in cotton	Enhanced activity against *E. coli* and *S. aureus*	(Singh et al. 2012)
ZnO nanoparticle in cotton bandages	100% activity against *E. coli* and 99.3% of activity against *S. aureus* after 2 and 3 h of contact period, respectively	(Petkova et al. 2016)
Hexagonal MgO nanoflakes in medical textiles	Enhanced activity against *B. subtilis* and *E. coli*	(Ponnuvelu et al. 2016)
CuO nanoparticles in cotton fabric	Enhanced activity against *E. coli* and *S. aureus*	(Majumder and Neogi 2016)
CuO nanoparticles in cotton fabric	Enhanced activity against *E. coli* and *S. aureus* with 86.28% and 94.05% of activity, respectively, up to 25 wash cycles	(Hasan 2018a)
Iron oxide nanoparticles in cotton fabric	95% of antibacterial activity against *S. aureus*	(Rastgoo et al. 2016)
Iron-based magnetite and haematite nanoparticles in polyester fabric	Enhanced activity against *S. aureus*	(Harifi and Montazer 2014)
Nickel oxide nanoparticles in cotton fabrics	Enhanced activity against *E. coli* and *S. aureus* with wash durability up to 25 cycles	(Suresh et al. 2014)
Carbon-based nanoparticles		
Graphene oxide-silver nanoparticle in cotton	Antibacterial activity against *E. coli* with electromagnetic interference shielding property	(Ghosh et al. 2019)
Titanium dioxide nanoparticles and graphene oxide nanosheets in cotton	Enhanced activity against *E. coli* and *S. aureus* with ultraviolet ray blocking activity	(Karimi et al. 2016)
Zinc oxide–reduced graphene oxide nanocomposite in cotton	Enhanced activity against *E. coli* and *S. aureus* with photocatalytic activity to degrade methylene blue dye	(Nazari 2019)
Graphene oxide nanoparticles in cotton	Enhanced activity against *E. coli* and *S. aureus* with wash durability	(Hu et al. 2019)
Carboxylated CNTs in cotton	Enhanced activity against *S. aureus*	(Mojtahed et al. 2016)
PHMGP and CNT-potassium alginate in cotton	Enhanced activity against *E. coli* with thermal stability and flame resistance	(Chen et al. 2016)
Pristine-functionalized single-walled CNTs-silver nanoparticles in cotton	Enhanced activity against *E. coli* and *S. aureus* with wash durability up to 20 cycles	(Kumar et al. 2019)
PVP-CNTs in cotton	Enhanced activity against *E. coli* and *S. aureus* with thermal stability	(Alimohammadi et al. 2018b)
Nanocomposites		
Silicone quaternary ammonium salts-silver-zinc oxide in cotton	Enhanced activity against *E. coli* and *S. aureus* with durability up to 10 washing cycles and hydrophilicity	(Gao et al. 2020)
Silver-titanium dioxide-beta cyclodextrin in cellulose fabric	Enhanced activity against *S. aureus* with self-healing ability to degrade methylene blue dye	(Attarchi et al. 2018)
Copper oxide-polyethylene glycol in cotton		(Khani and Talebian 2017)

Table 1 (continued)

Nanoparticles	Antibacterial activity	Reference
	Enhanced activity against *E. coli* and *S. aureus* in dark condition for wound healing applications	
Copper oxide-titanium dioxide in medical textile gowns	Enhanced activity against *E. coli*, *Klebsiella pneumoniae*, *Saccharomyces* sp. and *S. aureus* under sunlight	(Ibrahim et al. 2019)
Hydroxyapatite-silver nanoparticles in cotton fabrics	Enhanced activity against *E. coli* and *S. aureus*	(Ferreira et al. 2019)

applications. The size, morphology, topology and surface charge of nanoparticles are determined by the synthesis approaches, which eventually affect their properties. There are three major synthesis approaches such as physical, chemical and biological methods for the fabrication of nanoparticles. Each of these synthesis approaches possesses several advantages and limitations in exhibiting biological properties among nanoparticles, especially in determining its usage in inhibiting pathogenic bacterial strains (Jeevanandam et al. 2016b). It is noteworthy that the synthesis approach–mediated antibacterial properties of nanoparticles are a critical factor in determining their bactericidal efficiency, while coating them on the surface of textile fabrics (Suwan et al. 2018). For instance, physical approach to synthesize nanoparticles such as laser ablation (Zhang et al. 2017), ball milling (Wang et al. 2017) and physical vapour deposition (Han et al. 2018) will help to yield monodispersed nanoparticles with desired size and morphology. Even though nanoparticles from these methods possess antibacterial activity (Khashan et al. 2016; Baláž et al. 2017; Jäger et al. 2019), the cost involved and complex process in the synthesis approach are the challenges to be faced, while using them for textile applications. Likewise, chemical approaches such as sol-gel, precipitation and hydrothermal synthesis are the most common methods used to fabricate nanoparticles (Caramazana et al. 2018; Rajesh et al. 2019; Parashar et al. 2020). This method is beneficial in yielding nanoparticles with stability and desired morphology and size along with the ability to alter its surface charge, which is beneficial in biomedical applications, especially in their antibacterial activity (Jeevanandam et al. 2020b). However, the dispersity of nanoparticles and its cytotoxicity towards human cells, due to the usage of toxic chemicals for synthesis (Khan et al. 2019), are the challenging factors that cannot be altered via chemical approach, which affects their efficiency in utilizing them as a large-scale commercial antibacterial agent to develop bactericidal fabrics. Recently, green or biosynthesis approaches are gaining numerous applicational importance to fabricate nanoparticles that are environmentally friendly and nontoxic to humans (Kaur 2018). Biological organisms such as bacteria (Mukherjee and Nethi 2019), fungi (Siddiqi and Husen 2016), algae (LewisOscar et al. 2016) and plants (Benelli 2016) as well as their extracts were widely employed to fabricate nontoxic nanoparticles to be beneficial in biomedical applications. Thus, biosynthesized nanoparticles are used as effective bactericidal agents in recent times to coat them on the textile fabric surface as antibacterial finishes to inhibit pathogenic bacteria (Vasantharaj et al. 2019). However, lack of stability and formation of an ineffective feeble bond between the fabric and nanoparticles are the limitations of biosynthesized nanostructures to be included in textile applications (Ovais et al. 2018). Thus, the fabrics should be subjected to additional processes such as cationization to create effective bondage between fabric and nanoparticle, which will be useful to exhibit enhanced antibacterial efficacy, even after several washing cycles.

Mode of antibacterial mechanism exhibited by nanoparticles

Antibacterial mechanism of nanoparticles is still not clear, and the research is still under progress to elucidate their mode of action. The bactericidal mechanisms of nanoparticles that are proposed in recent times are (i) bacterial cell wall and membrane damage, (ii) penetration into bacteria and (iii) oxidative stress (Roy et al. 2019b). In addition, it has been reported that the bacterial cell membrane possesses the negative surface charge, due to the presence of carboxyl, phosphate and amino groups, and hence, the positively charged nanoparticles generally bind to the cell membranes via electrostatic interaction (Yun'an Qing et al. 2018; Sánchez-López et al. 2020). Later, the nanoparticles can easily penetrate and internalize into the bacterial membrane to interact with bacterial biomolecules such as protein, lipids and DNA. The interaction of nanoparticles with cell organelles will lead to cell damage and finally leads to cell death (Yun'an Qing et al. 2018). Further, nanoparticles produce reactive oxygen species (ROS) such as superoxide radical (O^{-}), hydroxyl radical (OH-), hydrogen peroxide (H_2O_2), and singlet oxygen (O_2) to induce oxidative stress in the bacterial cells. The ions released by the dissociation of nanoparticles produce ROS, which hinders the proliferation of bacteria or damages their cells or cell organelles. Furthermore, the size, shape, morphology, topology and surface charge of the nanoparticles are also the significant factors that influence their mode of action against bacteria (Parham et al. 2016; Slavin et al. 2017). Yan et al. (2018) studied the interaction of silver nanoparticles with *P. aeruginosa* and elucidated the antibacterial mechanism using comprehensive characterization. The results revealed that the interaction between nanoparticle and the cell membrane and the production of ROS are the primary pathways for their effective antibacterial mechanism (Yan et al. 2018). Similarly, Concha-Guerrero et al. (2014) studied the antibacterial mechanism of CuO nanoparticles using 11 bacterial strains and reported the interaction of nanoparticles with bacteria through TEM analysis. The results demonstrated that the CuO nanoparticles possess effective antibacterial activity via cavity and hole formation and degradation of membranes and blebs, which leads to cellular collapse and lysis in bacteria. It was proposed that these toxic effects of nanoparticles are due to the ionic interaction with bacteria along with production of ROS and oxidation-reduction reactions in bacteria (Concha-Guerrero et al. 2014). Further, Azam et al. (2012) reported the size-dependent antibacterial activity of 20–28-nm-sized CuO nanoparticles against both gram-negative and gram-positive bacteria. The results revealed that the smaller-sized CuO nanoparticles possess effective antimicrobial activity with very less MIC and minimum bactericidal concentration (MBC) values. This study suggested that the mode of antibacterial action is also dependent on the size of nanoparticles, other than the formation of oxidative stress and ROS generation (Azam et al. 2012). It can be noted that the similar mechanism of antibacterial action as mentioned above will be followed by the nanoparticles coated in textile fabrics, and Fig. 7 presents the summary of the probable antibacterial mechanisms that are proposed to be exhibited by nanoparticles.

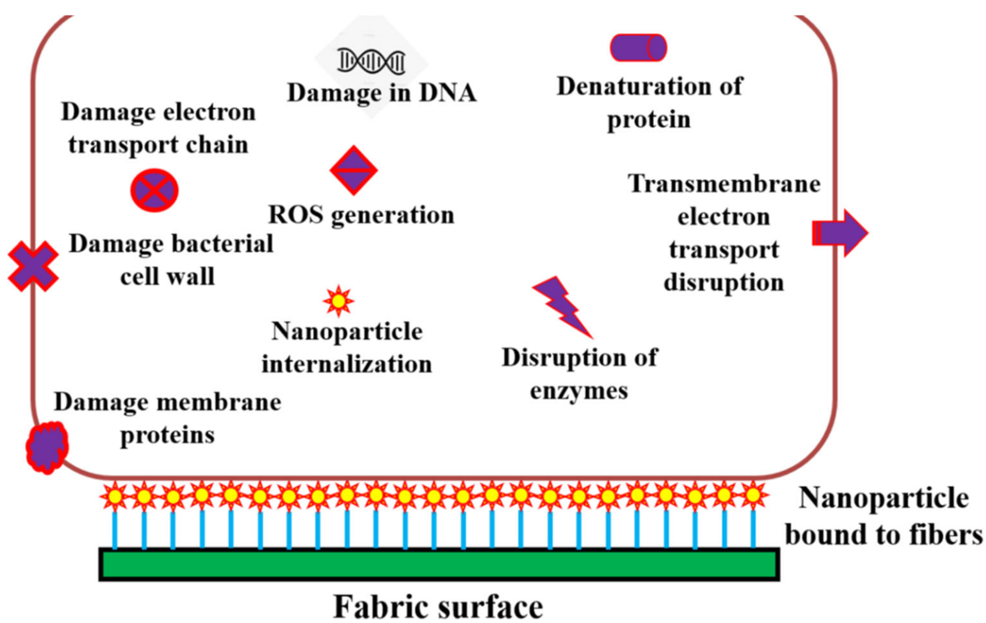


Fig. 7 Mode of antibacterial mechanism exhibited by nanoparticles in the fabric surface

Incorporation of antibacterial nanoparticles in textile fabrics

The recent advancements in the field of nanomaterial architectonics have led to the emergence of several novel antibacterial nanoparticles to be beneficial in several applications, apart from medical and pharmaceutical sciences. In recent times, the benefits of antibacterial nanoparticles are utilized in paints, textiles, medical equipment and even in socks to avoid bacteria-mediated infections among humans (Mashitah et al. 2016). In textiles, the application of antibacterial nanoparticles is widespread from medical, commercial and casual textile fabrics for protecting the cloths from damage and controlling the spread of pathogenic bacteria and their associated infections towards humans (Perelshtein et al. 2016b). Thus, the incorporation of nanoparticles on the surface of textile fabrics is highly beneficial in utilizing them as a potential agent to avoid the spread of pathogenic bacteria (Perkas et al. 2018). However, nanoparticles do not possess the ability to bind and form effective bonds with textile fabrics, due to the lack of functional sites, which will lead to dislodge after a few wash cycles. Hence, processes such as functionalization of nanoparticles or surface modification of textiles are required to embed nanoparticles on the fabric surface. Even though functionalization process provides active sites for bond formation with fabrics, their bonds are not strong and stable for long-term applications (Wagener et al. 2016). Conversely, the surface-modified textiles are potential for allowing the introduction of novel, interesting and multi-functionalities in textiles without affecting their physicochemical properties. Recently, the surface modification of fabrics has been increased to chemically incorporate the nanoparticles on the fabric surface to prevent their dislodgement during washing and to produce durable antibacterial fabrics (Nadi et al. 2018). Plasma technique, laser treatment and cationization are the common approaches that have recently been used for the surface modification of fabrics.

Plasma treatment

Plasma is a combination of particles, including positive ions, electrons, free radicals, ultraviolet radiation and neutral species that are generated by a gas or vapour in electromagnetic or electric fields. When the material surface is exposed to free radicals, electrons readily activate the surface and combine with the excited gas species to provide chemically reactive groups that are covalently bonded to the substrate surface (Bhat et al. 2011). The effect of plasma treatment on the structure of cotton to fabricate functional textiles has been reported in numerous recent literatures. Zhou et al. (2016) developed a regeneratable antibacterial cotton fabric via plasma treatment with dimethylhydantoin. The results demonstrated the aid of plasma treatment in the incorporation of antibacterial agent to the fabric surface, followed by chlorination, to provide durability and stability to the fabric (Zhou et al. 2016). Similarly, Ribeiro et al. (2018) studied the efficiency of silver nanoparticles coated on dielectric discharge barrier (DBD) plasma–treated fabrics and reported their antimicrobial studies. DBD is a dry environmentally friendly technique that modifies the surface of the textiles without conventional chemicals. Further, the DBD plasma–modified fabrics have shown enhanced absorption of nanoparticles with the ability to release them in a controlled fashion (Ribeiro et al. 2018). Although plasma treatment of textile fabric provides unique opportunities for the surface modification to impart durable, functional antibacterial nanoparticle finish, they also have certain limitations such as requirement of high-cost equipment and the similar usage of flow rate, gas pressure and input power, which may not produce the same level of essential reactive species to functionalize and modify the surface of the fabric (Sarmadi 2013).

LASER treatment

Surface modification using light amplification by stimulated emission of radiation (LASER) is the key to the easy and efficient approach to the surface of the fabric, where the ablation and chemical or physical alteration can occur depending on the level of power supply (Shahidi et al. 2013). The major advantages of laser are its high speed to modify structures and its easiness in handling, which makes it a potential entity in the textile industry for the decolouration of denims, cutting fabrics and control of wool shrinkage in labs (Rouette et al. 1995; Nayak and Padhye 2016). Nourbakhsh et al. (2012) developed silver nanoparticle–coated fabrics after modifying the surface of cotton fabric via laser treatment. The CO_2 laser was used for the surface modification of cotton and is coated with methylene blue dye to investigate the existence of carboxyl group on the fabric's surface. The silver nanoparticles were coated on laser-treated and laser-untreated fabrics to evaluate their antibacterial activity and durability. The results demonstrated that the colour difference of the fabric increased at a higher energy level of LASER treatment, and further increase in laser power affected the dye absorption. The silver content in laser-untreated and laser-treated fabrics that were analysed using mass spectroscopy revealed that the untreated cotton possesses 0.024% of silver, which was decreased to 0.009% after repeated washing. Contrarily, the laser-treated samples possess a high concentration of silver content (0.047%), after applying higher laser energy level (100 W/1000 cm/s), which was decreased to 0.028% after repeated washes. The antimicrobial results showed that laser-treated silver-coated fabric reduced 99.25% and 97.1% of bacterial growth, whereas the laser-untreated silver-coated fabric showed 39.9% and 23.3% of bacterial growth against *E. coli* and *S. aureus*, respectively. This study suggested that, not only laser treatment, the increase in the laser energy level can also increase the absorption of silver nanoparticles on the fabric to improve their antibacterial efficacy (Nourbakhsh and Ashjaran 2012).Recently, Peng et al. (2018) demonstrated the efficiency of a CO_2 laser for the pretreatment of polyester fabric to coat copper films on the fabric surface. These fabrics were then evaluated for their hydrophobicity, heat generation and electrical conductivity. The results revealed that the copper film coated on polyester fabric after laser treatment possesses excellent electrical conductivity, high contact angle, heat generation and UV-blocking properties. Further, the laser-treated fabric showed enhanced adhesion strength, compared to laser-untreated fabrics. This study suggested that the laser treatment can be used as a potential approach for the pretreatment of cotton fabrics (Peng et al. 2017a). Even though the laser provides a unique pretreatment process for the surface modification of fabrics, there are certain demerits that limit its usage in the textile industry. It is worthy to note that the mechanical properties of the fabric can be affected due to variations in laser intensity level, treatment time and pixel time. It has been reported that the laser treatment has led to the appearance of grooves and microcracks on the laser-treated fabrics, which can be noticeable on the fabric surface after increasing the treatment time and pixel time. Thus, it is evident that the laser treatment not only affects the mechanical properties but also the structure of the fabric. Moreover, an increase in the fabric stiffness was demonstrated to be improved after treating 100% of woven cotton fabric with laser (Hung et al. 2017). However, the exposure to laser in fabrics also lowers its rigidity, which makes it difficult to cut the fabric due to distortion and leads to difficulties in the tailoring and sewing process of textiles.

Cationization process

Cationization is a common method for the modification of fabric substrate to impart the functional cationic groups to coat antibacterial agents. This modification has primarily focused on improving the dyeability of cotton with the reactive dyes than other textile fibres. The presence of cationic groups in the cotton fabric chemically forms ionic bond with the reactive dyes, thus reducing salt consumption and resulting in the increased dye exhaustion and colour yield of the fabric (Nallathambi and Rengaswami 2016). Cationic treatment of cotton is highly advantageous in the textile industry, as it can dye in less time with less energy to reduce environmental impact by achieving higher colour yields and fastness properties. Thus, the pretreatment of cotton with cationic agents is essential for novel fabric–based applications to provide excellent finishes in textile industry (Acharya et al. 2014). Several studies have reported the improved affinity of anionic dyes towards cationic cotton fabric by modifying the cotton surface via cationization process by introducing cationic sites on the cotton surface (Chattopadhyay 2001; Acharya et al. 2014; Arivithamani and Dev 2017b). It is essential to treat textile fabric with various cationic groups, such as cationic monomer, polymers and biopolymers, for the modification of cotton surface to impart positively charged cationic sites (Blackburn and Burkinshaw 2002). In addition, epichlorohydrin, dendrimers, poly-(4-vinylpyridine) quaternary ammonium compounds, glycidyltrimethyl ammonium chloride (Glytac), chlorotriazine, choline chloride, N-methylolacrylamide and biopolymers such as chitosan and keratin have been reported to be beneficial as cationic agents for cotton surface modification to incorporate antibacterial nanoparticles (Arivithamani and Dev 2017a). However, the polymer cationic groups are not suggested for textile application, as they can cause irritation to the eyes, skin and respiratory organs and may result in dizziness, shortness of breathing, vomiting and nausea. Although the biopolymers as cationic agents have the ability to reduce salt usage in the reactive dyeing process, their usage has been limited in the textile industry as these polymers are expensive and will increase the production cost of textile fabric. Also, large concentration of cationic agents must be applied on the cotton surface, due to the low substantive stability of cationic monomer towards cotton in certain reaction conditions. Further, the presence of amine in the monomers with low molecular weight is toxic in nature, which restrains their application in textiles (Roy Choudhury 2014).

Apart from surface modification, finishing of fabrics after incorporating nanoparticle with fabric material is also highly significant to exhibit antibacterial activity with efficiency. Dip coating, pad-dry-cure and sonication approaches are the three common methods used for the fabric finishing processes. Dip coating is a simple and versatile method for the coating of nanoparticles on the cotton fabrics, due to its higher controllability and large-scale production ability (Wu et al. 2017). Recently, Kumar (2016) simply immersed the fabric in the *Acalypha indica*–synthesized silver nanoparticle solution and placed in a rotating shaker at 100 rpm for a period of 1 h at room temperature, which was later allowed to dry at 60°C. The coated samples exhibited superior antibacterial activity against gram-negative bacteria *E. coli* (Kumar). However, the major drawback of the dip coating method is the controlling of the thickness and non-uniformity in the fabric finish (Balamurugan et al. 2017). Similarly, the pad-dry-cure method is the most widely used coating technique that ensures the attachment of nanoparticles on the fabric by adjusting the factors such as pressure, speed and curing temperature (Gokarneshan 2018). Recently, Hassan (2018) developed an antibacterial cotton fabric using copper oxide nanoparticles by immersing the cotton samples in a solution of CuO (2%) as well as acrylic binder (1%) and passing through the padding mangle by maintaining 100% of wet-pickup ability. Later, the samples were then cured for 3 min at 140°C, followed by rinsing and drying process. The results revealed that the CuO nanoparticle–coated fabrics possess enhanced antibacterial activity against gram-positive and gram-negative bacteria until 25 wash cycles (Hasan 2018b). Even though the padding technique provides a uniform nanoparticle coating on the surface of fabrics, it is not recommended for textile applications as it requires excess binder, which eventually increases the production cost.

Among the fabric finishing techniques, sonication is an effective method for the deposition and insertion of nanoparticles on the fabric surface. The sonochemical coating method guarantees better adherence of the deposited nanoparticles at high speed (>500 m/s), in which the nanoparticles are embedded in the substrate by the microjets via a collapse of acoustic bubble near the surface. Hence, the ultrasonic waves spread the nanoparticles on the fabric surface, thus resulting in uniform and thick coating of nanoparticles (Perelshtein et al. 2016a). Perelshtein et al. (2008) successfully coated the silver nanoparticles in nylon, polyester and cotton fabrics via sonochemical method and reported an excellent antibacterial activity against gram-positive and gram-negative bacteria (Perelshtein et al. 2008). Further, Firdhouse et al. (2013) fabricated antibacterial perspiration pads and cotton cloth using green-synthesized silver nanoparticles. *Amaranthus dubius*–synthesized silver nanoparticles were coated on both fabrics via dip coating and sonochemical method and exhibited excellent antibacterial efficiency against *Corynebacterium* sp. The results revealed that the antibacterial activity against the bacterial strain is superior for sonication-coated samples, compared to dip-coated fabric samples (Firdhouse and Lalitha 2013). In another study, CuO nanoparticles are successfully coated on the cotton fabric surface using the sonochemical coating technique. The resulting fabrics demonstrated excellent antimicrobial efficiency for up to 65 wash cycles; however, the activity was decreased drastically with increased washing cycles (Perelshtein et al. 2013). Both surface modifications of fabric finishing strategies are used to coat the antibacterial nanoparticles strongly on the surface of the textile fabrics to provide durability during the laundering process. These pre- and post-treatments of fabrics are required to effectively bind the nanoparticles, which will reduce their dislodgement during washing processes and maintain their antibacterial efficacy for long-term. In addition, dislodgement of nanoparticles during washing process will lead to an increment in the existence of nanoparticles in the environment, which may eventually lead to environmental toxicity and biomagnification affecting various living organisms in the ecological food chain (Kulthong et al. 2010). Thus, maintenance of laundering durability is still a challenge for the antimicrobial agent–treated fabrics, particularly for the nanoparticle-treated textiles. Several researchers have successfully coated nanoparticles on fabric surface via physical contact, which is reported to be leached out from the fabric during the washing process (Mitrano et al. 2015). The leached nanoparticles from textile fabrics into the air, water and landfill must be taken into serious concern as they can directly or indirectly affect the humans via inhalation and indigestion and through skin contact from the fabric (Almeida and Ramos 2017). Hence, selection of significant nanoparticle fabrication approach, surface modification and fabric finishing methods for enhanced laundering durability is essential to provide and maintain the long-term antibacterial efficacy in nanoparticle-coated fabrics.

Conclusion

Textile is a unique industry, which always evolves according to the trend of fashion in the particular decade among people and the available advanced equipment or material to produce fabrics. Currently, smart textiles are the trend among consumers that can modify according to the surrounding or used as a sensor for patients to regularly monitor their disease complications. The emergence of nanotechnology has altered the perspective of material used in various industries, and it has been receiving extensive positivity in the textile industry for the fabrication of smart textiles. The antimicrobial, especially the antibacterial, activity of nanoparticles is gaining much significance in inhibiting bacterial growth on the fabric surface to avoid the spread of pathogenic bacteria and to protect the cloth from bacteria-mediated damages. Surface modification and fabric finishing approaches are beneficial to effectively coat the antibacterial nanoparticles on the fabric surface, which eventually reduces their dislodgement into the environment and maintains long-term antibacterial efficacy. Recently, antibacterial nanoparticles are widely proposed to be useful in medical textiles, gloves, bandages and socks to mitigate bacterial growth. Moreover, biosensing nanoparticles can also be incorporated into the fabric using similar methods that are utilized for embedding antibacterial nanoparticles, to monitor disease conditions, which will be beneficial for patients. Thus, smart textiles with antibacterial efficacy and disease monitoring ability will be beneficial in the future of medical textile industries, to control bacteria-mediated infection and monitor disease conditions in patients.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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