



Review article

Recent advances in functionalization of nanotextiles: A strategy to combat harmful microorganisms and emerging pathogens in the 21st centuryO.N. Aguda^a, A. Lateef^{a,b,*}^a *Laboratory of Industrial Microbiology and Nanobiotechnology, Department of Pure and Applied Biology, PMB 4000, Ogbomosho, Nigeria*^b *Nanotechnology Research Group (NANO⁺), Ladoke Akintola University of Technology, PMB 4000, Ogbomosho, Nigeria*

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ABSTRACT

The textile industry can benefit from nanotechnology as new properties are conferred on functionalized nanotextiles beyond what a fabric can traditionally offer. These properties include extermination of microorganisms by nanotextiles to curtail their growth and dissemination in the environment and in healthcare facilities. The emergence and thriving of multi-drug resistance (MDR) phenomenon among microbes are threats to achieving good health and well-being (goal 3) of sustainable development goals (SDG) of UN. In addition, MDR strains emerge at a higher rate than the frequency of discovery and production of potent antimicrobial drugs. Therefore, there is need for innovative approach to tackle MDR. Among recent innovations is functionalization of textiles with metal nanoparticles to kill microorganisms. This paper explores strategies in nanotextile production to combat emerging diseases in the 21st century. We discussed different nanotextiles with proven antimicrobial activities, and their applications as air filters, sportswear, personal wears, nose masks, health care and medical fabrics. This compendium highlights frontiers of applications of antimicrobial nanotextiles that can extend multidisciplinary research endeavours towards achieving good health and well-being. Until now, there exists no review on exploitation of nanotextiles to combat MDR pathogens as included in this report.

1. Introduction

Nanotechnology, which is the art of developing, studying, and applying materials at the nanoscale (10^{-9} m) [1] has emerged as the hotbed of research activities and innovation of the 21st century with uncommon applications in virtually all facets of human endeavours. At the core of this innovation are nanoparticles which have sizes of 1–100 nm. Nanoparticles of different types have been exploited for numerous biomedical applications [2, 3, 4]. The use of nanomaterials has expanded the scope of nanotechnology in various disciplines of natural and applied sciences, engineering, agriculture, medicine, built environment and humanities [5, 6, 7]. Among nanomaterials that are used in different investigations, metal nanoparticles (MeNPs) are the most popular and versatile [8, 9]. MeNPs can be produced through two ways; namely top-down and bottom-up techniques. These can be executed by physical, chemical, and biological mechanisms [8, 9]. In top-down approach, larger molecules are broken down to smaller nanoparticles, while in bottom-up approach, atoms are engineered to form nanoparticles. Among the various methods of creating MeNPs, the biological synthesis continues to attract the interests of researchers. This is due to several

advantages of the process which include simplicity, high formation of nanoparticles, eco-friendliness and enhanced biocompatibility of MeNPs [10]. As a result, varieties of metabolites from plants, microorganisms and animals have been used extensively for the biosynthesis of MeNPs for diverse applications [11, 12, 13, 14, 15, 16, 17, 18, 19, 20].

Several uses of nanotechnology have resulted in the production of a large number of nano-functionalized materials, which have improved their conventional characteristics and functionalities. For instance, the bulk titanium dioxide (TiO_2) is utilized as sunscreen agent in the cosmetics sector. However, due to its poor stability when exposed to UV radiation for a long period, titanium dioxide nanoparticles (TiO_2 NPs) with proven UV-shielding capability have been found as suitable replacement to the bulk TiO_2 in cosmetics [21]. Also, paints of different kinds have been improved with MeNPs [22, 23, 24] to enhance their opacity as well as antimicrobial, waterproof, fireproof and adhesive properties. In food industries, nanotechnology has been used to improve taste, color, absorption and bioavailability of nutrients and health supplements. Also new food packaging materials with improved mechanical, and antimicrobial properties as well as nano-sensors for traceability and

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monitoring of the conditions of food during transport and storage have been produced through nanotechnology [25, 26, 27, 28, 29].

Nanomedicine is one of the most exciting sub-fields of nanotechnological research; owing to the possibilities that nanoscience may lead to solutions in the battle against multidrug-resistant bacteria, illnesses like cancer and atherosclerosis [30, 31, 32] as well as advances in regenerative medicine [33]. Nanoscale materials are now being increasingly developed, evaluated and used as diagnostic and therapeutic tools in medicine. They are employed in surgical and dental procedures, imaging, diagnostics, and drug delivery [33, 34, 35, 36]. These have aided medical professionals in treating various disorders. Most recently, nanotechnology played critical roles to curtail the spread of SARS-CoV-2 and its variants, in the development of diagnostic kits and vaccines against COVID-19 [37, 38, 39].

In recent times, the applications of nanotechnology have been extended to textiles, whereby fabrics are functionalized with nanoparticles to create smart textiles that have sensing, UV-shielding, electronic, thermoregulation and antimicrobial [40, 41, 42] properties among others. The increasing research activities in this area is worthy of evaluation towards improving performances in newly acquired properties of nanotextiles. Particularly, their antimicrobial actions against MDR and emerging pathogens that continually threaten the health of humans need to be evaluated. The cosmopolitan usage of textiles in personal products, industrial, sports, security, medical and military outfits among others showed that there is dire need to create new range of textiles to meet new challenges in their applications. Being made of biomaterials, fabrics are naturally susceptible to microbial attack that can promote their deterioration [43], thereby losing value and functionalities. This is because microorganisms can produce wide range of enzymes to degrade the components of textiles such as cellulose, hemicellulose, and keratin. They can also degrade additives that are added to textiles such as vanishes, dyes, adhesives and fillers to utilize them as nutrients for growth. Microorganisms also promote deterioration of synthetic fabrics such as polyester and nylon by attacking the additives that are added to the fabrics.

The microbial deterioration of fabrics gives rise to bad odours, loss of strength and discolouration [44]. The survival of microorganisms on textile materials can also endanger health of users of fabrics in various ways. For instance, the microorganisms growing on the fabric can cause skin infections and irritations. Additionally, sporulating fungi on the fabric can promote fungal respiratory infections and allergies. In the hospital settings, textiles that are used in various forms as uniforms by workers, nose masks, curtains and bedding can aggravate healthcare-associated infections because they can harbor and disseminate pathogens [45] that include methicillin resistant *Staphylococcus aureus* (MRSA) and vancomycin resistant enterococci (VRE) [46, 47].

These occurrences can threaten the achievability of good health and well-being (SDG 3) of sustainable development agenda 2030. To address the problems, the production of antimicrobial textiles has been an upward trend in the textile sector to curtail hospital-acquired infections and meet the demands for hygienic and athletic wears. The antimicrobial textile market was estimated at USD10.7 billion in 2021 and expected to grow at 6.5% to reach USD14.7 billion in 2026 [48]. Nevertheless, concerns on the use of antimicrobial textiles have been raised. These bother on biocompatibility, effectiveness and eco-friendliness of the antimicrobial textiles due to the use of organic and inorganic chemicals in their production. However, nanotechnology; particularly the green approach can represent a novel way to create more impactful, non-toxic and eco-friendly antimicrobial textiles [49]. In this article, we evaluated the current achievements in the functionalization of textiles with nanoparticles, with an emphasis on strategies to tackle harmful microorganisms, multi-drug resistant microorganisms (MDRs) and the emerging diseases of the 21st century.

2. Nanotextiles and their applications

Textiles are flexible materials that are made up of a network of natural and man-made fibers. They are made via weaving, crocheting and

knotting. Textiles are one of the world's most important goods of the consumer industries [50]. In 2019, Indian textile industry was valued at USD180 billion with projection of reaching USD223 billion in 2021. It also provided 105 million jobs in the country [51]. In 2014, China as the world largest manufacturer of textiles exported textiles worth USD120 billion, while EU (28) exported textiles of USD65 billion the same year [51]. The projected global market value of textiles was USD1.3 trillion in 2020 and it is expected to grow at annual rate of 4.4% within 2021–2028 [52]. The sector mostly consists of small and medium-sized firms that produce textiles for a range of uses. For instance, protective garments, car seat coverings, tarpaulin, fire fabrics and filter materials are examples of technical textiles. The ability of microorganisms to utilize biomaterials in natural fibres and additives of the fabrics (dyes, binders and fillers) makes textiles in their various forms to be susceptible to microbial attack, thereby leading to deterioration and loss of value in both aesthetics and functions.

Nanotextiles are fabric materials that have been functionalized with nanoparticles to give some benefits such as water resistance [53], odor and moisture removal [54], better elasticity and strength, and microbial resistance [55], fire retardancy [56] as well as UV absorption, drug delivery, electronic and biomedical capabilities among other innovative applications [57, 58]. It has been projected that nanotextiles will dominate advances in the textile industry due to the unique opportunities that they offer [57]. The textile industry has been added to the list of industries that have profited from nanotechnology in the recent time.

More than thirty nations in the world have focused on the development of nanotechnology-based textile materials [59]. Nanotechnology is now being used in sportswear, with spacesuits being one of the most rapidly growing areas. Sharkskin suits based on plasma layer enhanced technology are the most common use of nanotechnology in textiles. Materials for quick evaporation of sweat, reflective textiles, insulation, and resilience fabrics for water-based activities are all included in the moisture management systems in sports. Smart surgical gloves and gowns that are made of nanotextiles are also employed in the healthcare business [59]. The value of technical textiles that are chiefly made up of nanotextiles was estimated at USD100 billion in 2010 [58] with highest annual rate of 4.1% for Asia. Nanotextiles have been described as the enablers of technological advances of the 4th industrial revolution, encompassing the internet of things (IoT) [60].

Nanotechnologies that are applied to textiles provide wider range of features with series of potentials for innovative applications in materials, products and services. Nanotechnologies can give new or increased functionalities by changing or improving characteristics of conventional fabrics. In Table 1, a survey of attributes of nanotextiles for diverse biomedical, environmental and industrial applications is presented. Through functionalization with nanomaterials, nanotextiles have shown antimicrobial, UV-blocking, anti-static, anti-wrinkling, hydrophobic, sensing, electrical, self-cleaning, catalytic and fire retardant activities. They also have improved strength and enhanced dyeability. Several nanoparticles such as Ag, Au, TiO₂, ZnO, Se, SiO₂, CuO, CdTe, and Pt among others have been employed using different techniques to functionalize varieties of textiles. The applications continue to expand on daily basis, thereby positioning nanotextiles as cosmopolitan utility for mankind in the 21st century and beyond.

3. Functionalization of textiles

Nanomaterials can be integrated into textiles through different processes that include coatings, treatments, fiber material composites and nanoscale fibers. Nanoengineered functional fabrics [55] are a new frontier in clothing technology that provides new and unique functionalities as wanted by users since the 18th century. Customers often demand for textiles having better color, form, texture, and usefulness [55]. In healthcare, medical monitoring of bodily functions and metabolism through integrated electrical devices that act as sensors in clothing has been achieved by functionalized textiles. Some of the methods for the

Table 1. A survey of applications of different types of nanotextiles and methods of functionalization.

Types of Fabric	Functionalization (Nanomaterials)	Methods of functionalization	Attributes	Potential applications	References
Cotton and silk	Silver nanoparticles	Pad-Dry-Cure	Antibacterial and antifungal	Biomedical	[73]
Cotton	Zinc oxide nanoparticles	Pad-Dry-Cure	Antibacterial, UV-protection, tensile strength and crease resistance	Biomedical, industrial and crease recovery	[87]
Silk, cotton and bamboo	Nano-emulsions	Padding (continuous) process and batch (exhaust) process	Antibacterial, antifungal, tensile strength, air and permeability	Biomedical	[88]
Cotton	Silica-silver-carbon-based hybrid nanoparticles	Pad-Dry-Cure	Antifungal	Increase in self-life	[89]
Cotton	Titanium dioxide -silicon dioxide/Chitosan	Dip-spin-coating	Antifungal	Biomedical and industrial	[90]
Cotton	<i>Tragacanthin</i> gum/nanosilver hydrogel	Pad-Dry-Cure	Antibacterial and water absorption	Biomedical and industrial	[91]
Cotton	Polyaniline derivatives/nanosilver	Immersion	Antibacterial, electrical conductivity and colorimetric sensory effects	Biomedical, Geo-textile, Antistatic	[92]
Cotton	Silver nanoparticles	Immersion	Dielectric, wave-absorbing, shielding and conductive properties	Biomedical and industrial	[93]
Cotton	Silver nanoparticles	Pad-Dry-Cure	Antibacterial	Biomedical	[94]
Cotton	Zinc oxide and silicon dioxide nanocomposite	Layer-by-layer	Hydrophobic, UV-protection, and breathability	Industrial	[95]
Cotton	Polyvinylsilsesquixane and titanium dioxide nanoparticles	Pad-Dry-Cure	UV-blocking and hydrophobicity	Industrial	[61]
Wool	Silica, titania, and silver nanoparticles	Electrostatic self-assembly	Antibacterial, hydrophilicity and self-cleaning	Biomedical and industrial	[96]
Wool	Selenium nanoparticles	Immersion	Dyeing, antibacterial and UV-blocking properties	Biomedical and industrial	[97]
Wool, Cotton	Zinc oxide, titanium dioxide, and copper oxide nanoparticles	Pad-Dry-Cure	Antibacterial, antifungal, UV-blocking, and self-cleaning	Biomedical and industrial	[98]
Cotton, Entretela, and Polylactic acid-PLA	Titanium oxide nanoparticles		Degradation of crude oil and Rhodamine B	Environmental and industrial	[99]
Wool	Zinc nanoparticles and silver nanoparticles	Pad-Dry-Cure	Antibacterial, antifungal, antistatic, and self-cleaning	Biomedical and industrial	[100]
Wool	Silver nanoparticles	Immersion	Dyeability, antibacterial, hydrophobicity, antistatic and improved UV absorption	Biomedical and industrial	[101]
Wool	Bio-nano-mordant	Sonochemical method	Dyeability and antibacterial	Biomedical and industrial	[102]
Silk	Nano-silica	Immersion	Hydrophobicity, UV resistance, wrinkle resistance, and self-cleaning	Industrial	[103]
Polyester	Tin-sulfide nanomaterials, Tin-sulfide/Titanium dioxide nanocomposites	Layer-by-Layer	Photocatalytic, solar light activated self-decontaminating textile, and chemical warfare agents protection	Optics	[104]
Nylon	Titanium dioxide and zinc oxide nanoparticles	Layer-by-Layer	Antibacterial, UV- protection and stain-proof	Biomedical and industrial	[105]
Polyester	Nano composites (Propyltriethoxysilane, betadex sulfobutyl ether sodium, and butanedioic acid)	Layer-by-Layer	Anti-droplet and flame retardancy	Industrial	[106]
Polymer	Poly (lactic acid) Nanofiber	Emulsion Electrospinning	Antibacterial	Biomedical and industrial	[107]
Polymer	Polycaprolactone/Zinc oxide nanoparticles nanofibers	Electrospinning	Photocatalytic and corrosion resistance	Environmental and industrial	[108]
Polymer	Nanofibre composites	Electrospinning	Sensor	Industrial	[109]
Polymer	Poly (lactic acid) nanofibres	Electrospinning	Hydrophobicity, breathability, antibacterial, and antiviral	Biomedical and industrial	[110]
Silk	Lanthanide nanocrystal (Ytterbium, Gadolinium, and Erbium doped Sodium Yttrium Fluoride- NaYF ₄ : Yb, Gd, Er)	Electrospinning	Imaging	Imaging and tissue engineering	[111]
Silk	Gold nanoparticles	Electrospinning	Wound dressing and healing	Biomedical, tissue engineering	[112]
Silk	Cobalt ferrite/Iron (III) oxide nanoparticles	Electrospinning	Scaffolds	Tissue Engineering	[113]
Silk	Gold nanoparticles	Layer-by-Layer	Ammonia	Environmental and industrial	[114]

(continued on next page)

Table 1 (continued)

Types of Fabric	Functionalization (Nanomaterials)	Methods of functionalization	Attributes	Potential applications	References
Silk	Cadmium telluride	Layer-by-Layer	Immunoglobulin detector	Biomedical Biosensor	[115]
Silk	Platinum nanoparticles	Immersion	Antibacterial, catalysis and dyeability	Biomedical and industrial	[116]
Silk	Copper oxide nanoparticles	Immersion	Depollution	Environmental and industrial	[117]
Cotton	Silver nanoparticles	Immersion	Anti-viral	Biomedical and personal wear	[199]

functionalization of textiles are discussed and also schematically presented in Figure 1.

3.1. Vapor deposition method

Both chemical and physical vapour deposition methods can be used to functionalize textiles. Vapour deposition is the process of depositing a substance onto a substrate using the gaseous phase of the material being deposited. The deposition can be achieved by condensation, chemical reaction, or dropping of small particles on surfaces of materials. Cheng *et al.* [61] demonstrated a technique to produce hydrophobic fabric using films that were developed from poly (3,4-(hydroxymethyl)ethylenedioxy-thiophene) (PHMEDOT). The films were used alongside FeCl₃ that acted as oxidant to modify commercial textile in producing the

hydrophobic fabric. Thus, it is established that commercial textiles can be easily transformed via deposition of polymers into hydrophobic or hydrophilic fabrics. Coating of fabrics through vapour deposition is advantageous than conventional use of silane (SiH₄), as the functionalized fabrics are more resistant to mechanical and solvent cleaning. In certain cases, vapour coating can enhance some functionalities of modified fabric that cannot be achieved by solution phase functionalization technique. For instance, wettability of fabric can be created through vapour deposition and not by solution-based technique. Through vapour deposition, extreme hydrophobic textiles can be produced. The modified textiles which are reusable have large-volume for oil–water separation and can find applications as filters or absorbents [61].

Similarly, physical vapour deposition methods such as sputtering, evaporation and ion implantation have been exploited to deposit thin

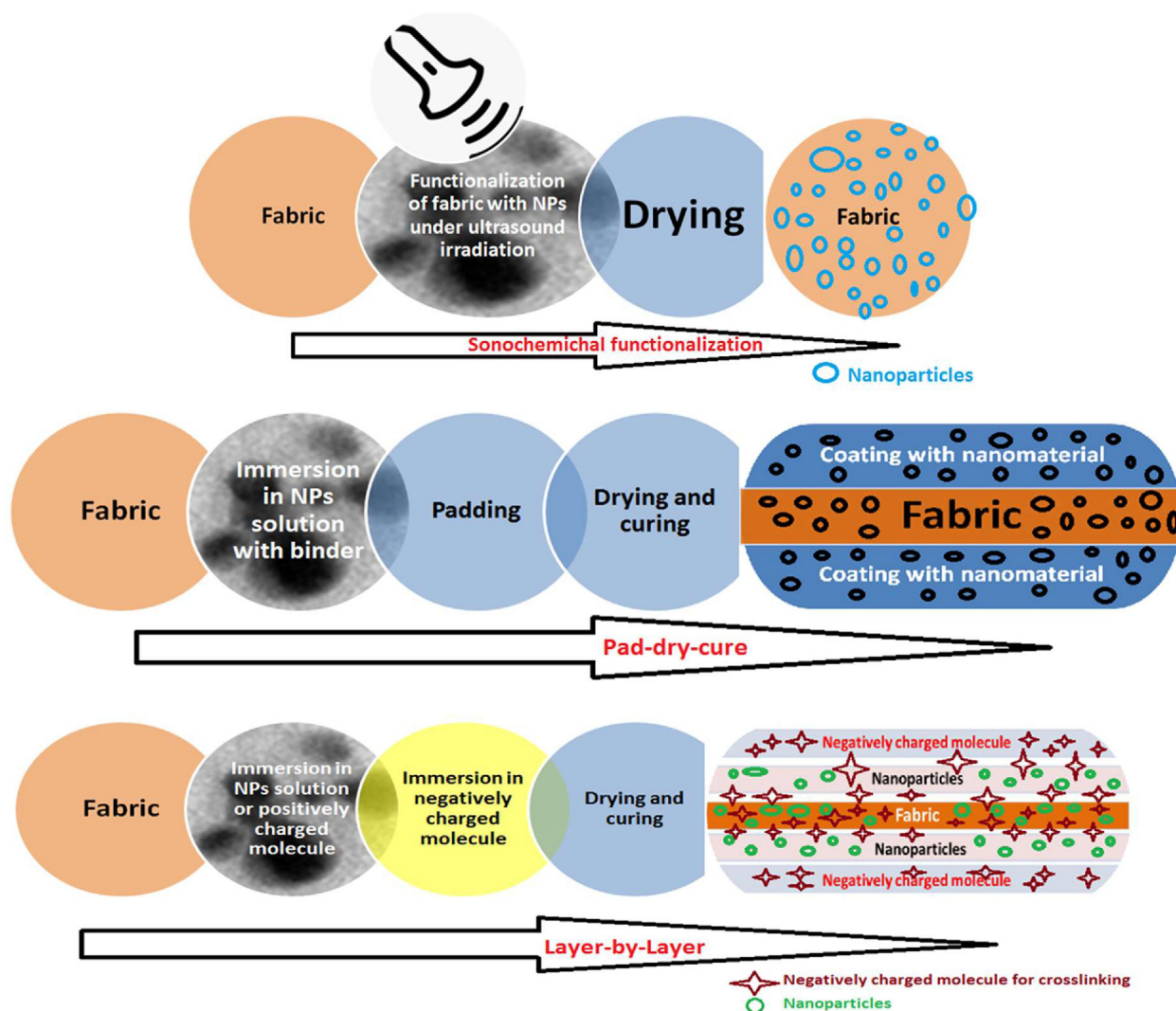


Figure 1. Schematic presentation of methods of functionalization of textiles

layer of nanomaterials on textiles with improved properties [62]. Sputtering which involves transfer of atom-by-atom or molecule-by-molecule of materials via the solid phase to the vapour phase and subsequent deposition has been used for the functionalization of textiles. Sputter coating is the latest technology that is used for the functionalization of textiles due to its inherent advantages that include versatility for deposition of several materials in mono and co-mixture, attainment of deposition at low temperature and excellent adherence of deposited materials to the fibres [62]. Irfan *et al.* [63] explored radio frequency co-sputtering as eco-friendly dry process to functionalize textile with silver nanoclusters/silica composite. Analyses showed that there was efficient deposition of the nanoclusters to create antimicrobial fabric with inhibition of the growths of *Escherichia coli*, *Staphylococcus aureus* and *Candida albicans*.

3.2. Sonochemical method

In sonochemistry, chemical deposition in the liquid phase is carried out under the influence of ultrasound irradiation of 20 kHz to 1 MHz to create cavitation. Under the extreme conditions of temperature, pressure and subsequent cooling, new compounds are formed due to chemical reactions that have occurred [64]. The technology has been exploited in depositing nanomaterials on textiles. These include AgNPs, TiO₂ NPs, CuONPs and ZnO NPs [65, 66, 67, 68] with excellent antimicrobial activities displayed against strains of *Escherichia coli* and *Staphylococcus aureus* by the functionalized textiles. The textiles were strongly adhered to by the nanoparticles, thereby preventing leaching of the nanoparticles after several washing cycles. Sonochemical functionalization of textiles can be achieved through a single step; however complex two-step procedure has been demonstrated to produce far more durable textiles [69]. Textiles that were functionalized with nanoparticles having resilient hydrophobic, antimicrobial and self-cleaning properties have been produced through sonochemistry [70, 71, 72] showing the growing trends in the application of sonochemistry to produce nanotextiles.

3.3. Pad-dry-cure method

Pad-dry-cure is the most typical process to apply nanoparticles to the surface of fabrics for long-lasting fabric goods. In this process, the crosslinking reactant, catalyst, softener, and other components are all dried on the fabric before the crosslinking reaction occurs during the curing stage. In our recent investigation [73], the pad-dry-cure approach was used to functionalize textile with AgNPs. The AgNPs were bio-synthesized using the wastewater of processing of fermented seeds of *Parkia biglobosa*. The AgNPs was applied on commercial cotton and silk using a self-cross-linking binder (Bondex 2550N, Jesons Industries Limited, Mumbai, India). The antibacterial efficacies of functionalized textiles were examined against *Staphylococcus aureus*, *Escherichia coli*, *Klebsiella pneumoniae*, *Klebsiella oxytoca*, *Proteus mirabilis* and *Aspergillus niger*. At dosage of 100 and 150 µg/ml, the AgNPs-functionalized cotton and silk effectively inhibited growth of the test isolates up to the 5th cycle of washing.

Rojas-Lemo *et al.* [74] also used the pad-dry-cure process to deposit AgNPs at concentrations of 10 and 20 ppm on cotton fabric in order to test their bactericidal activities against *Staphylococcus aureus* 25923. The experiments revealed that cotton fabric infused with nanoparticles at 10 and 20 ppm had strong bactericidal effects, eliminating bacterial colonies by 98.86–99.94%. Similarly, Xu *et al.* [75] explored pad-dry-cure technique to infuse AgNPs on cotton fabric via carboxymethyl chitosan that was covalently linked to cotton. The antimicrobial fabric that was produced was durable and displayed excellent antimicrobial activities (94%) against *Escherichia coli* and *Staphylococcus aureus* even after 50 washing cycles. Previous authors have also used the technique to functionalize textiles with TiO₂@Ag, Ag/ZnO and TiO₂/SiO₂ nanoparticles for excellent antimicrobial, photocatalytic and self-cleaning applications [76, 77, 78].

3.4. Layer-by-layer (LbL) method

It is a simple, adaptable and important method for coating non-polar flat surfaces with nanocomponents from various chemical groups [79]. This is accomplished by layering oppositely charged materials in alternate layers. The layers are held together by electrostatic forces. To conduct a layer-by-layer functionalization of textiles, immersion, electromagnetic, spray and spin techniques are used. On an aminolyzed-charged polyethylene terephthalate film, Fabra *et al.* [80] employed the layer-by-layer deposition process to build five alternating layers of various polyelectrolyte solutions consisting of alginate, zein-carvacrol nanocapsules, chitosan, and chitosan-carvacrol emulsions. The antimicrobial activity of active nano-laminated films against *Alternaria sp.* and *Rhizopus stolonifer* was investigated. Ahmed and Emam [81] used the same process to deposit AgNPs-carboxymethyl cellulose (CMC) composite on cotton fabrics, with the AgNPs crosslinking CMC with the cotton. The functionalized fabric had improved antimicrobial, electrical resistance and UV-shielding properties. Authors have used this technique to functionalize textiles with TiO₂, SiO₂, WO₃, and ZnO/SiO₂ for different applications as photocatalytic, antimicrobial, hydrophobicity, and UV-shielding [82, 83, 84, 85]. The layer-by-layer technique has been described as a novel deposition strategy to functionalize textiles with antimicrobial agents [86].

4. Multi-drug resistant microorganisms (MDRs)

Multi-drug resistance is a phenomenon whereby microorganisms become resistant to multiple antibiotics. It is a threat to global health. Statistics have shown that almost 2 million individuals in the United States are infected with antibiotic-resistant bacteria, resulting in nearly 23,000 fatalities each year [118]. Current projections estimate that mortality from bacterial infections would outnumber cancer deaths by 2050 [119,120] with attendant consequences of 10 million deaths annually and economic cost of USD100 trillion. Infections caused by multidrug-resistant bacteria usually require long-term antibiotic therapy, which results in high costs (USD55 billion per year in the United States) and low patient compliance to treatment [121, 122]. Though, there is lack of reliable data on antimicrobial resistance in the sub-Saharan Africa due to weak surveillance and diagnostic capacity [123, 124], but there are reports on the widespread of MDR strains [125, 126, 127, 128]. Our previous studies have reported prevalence of MDR bacteria from environmental, food, water and clinical sources in Nigeria [129, 130, 131, 132, 133, 134, 135].

The use of antibiotics has also been implicated in enhancing resistance among microorganisms. This can be due to irrational usage of antibiotics, extended therapy for MDR bacterial infection, and use as preventive treatment for numerous illnesses [119]. In hospitals in the United States, around half of the *Staphylococcus aureus* strains were resistant to methicillin, resulting in methicillin-resistant *Staphylococcus aureus* (MRSA). Resistance to multiple antibiotics has been found in 17.3% of clinical infections that were caused by *Escherichia coli*. Similarly, antibiotic resistance has emerged in *Enterococcus*, *Enterobacteriaceae*, *Pseudomonas aeruginosa*, and *Acinetobacter* [119]. MDRs are becoming an increasing public health concerns, making it difficult to treat many healthcare-associated diseases with existing medicines and represent major sources of illnesses and mortality across the world [136, 137, 138, 139].

MDR issues also have direct consequences on the attainment of goals of sustainable development (SDG) of the United Nations; particularly goal 1 (no poverty), goal 3 (good health and well-being), and goal 6 (clean water and sanitation) which necessitate concerted efforts to combat. Health is intertwined with productivity, wealth creation, clean environment and availability of potable water. Discovery and production of novel antibiotics to address MDR require a significant financial and manpower commitment, as well as considerable time. Also, high dosages of antibiotics will be needed to treat these MDR infections, which may

result in severe toxic and unpleasant consequences to which other treatment plans need to be developed [140, 141]. Indeed, antibiotic resistance is a global crisis and alternatives that have been suggested include the use of probiotics, antibodies, vaccines and nanomaterials [140, 141, 142]. Thus, the use of nanoparticles (NPs) has been promoted to be a viable technique for managing infections caused by MDRs [140, 141, 143, 144, 145, 146, 147]. Because of their unique physical and chemical properties, several nanoparticles have demonstrated therapeutic potentials against MDR strains.

5. Deployment of nanoparticles against harmful and multi-drug resistant microorganisms

Nanotechnology is being more widely used in therapeutic settings, particularly as a new paradigm for infectious disorders. MDR infections are becoming more common as sources of morbidity and death across the world [141] which underscores the crucial need for new antimicrobial treatments that are both safe and effective. Nanoparticles can penetrate harmful germs and disrupt critical molecular processes, resulting in novel biocidal actions. Nanoparticles have antimicrobial activities that can overcome the common antimicrobial resistance mechanisms such as enzyme inactivation, reduced cell permeability, alteration of target sites or enzymes and enhanced efflux of antibiotics through overexpression of efflux pumps [148, 149].

Nanoparticles can be used as alternatives to standard antibiotics due to a number of properties. To begin with, they have huge surface-area-to-

volume ratio that enhances the contact area with target organisms. Nanoparticles can interact with bacterial cells on a nanoscale, control permeability of the cell membrane and causing interference of molecular processes [150, 151]. Furthermore, nanoparticles have the potential to augment the inhibitory effects of different antibiotics [152, 153, 154, 155, 156, 157, 158, 159]. Antibiotics that were conjugated with NPs have shown good synergistic antimicrobial activities against bacteria, prevent biofilm formation and used to fight MDR [145].

The mechanisms of antimicrobial actions of nanoparticles have been summarized to include generation of toxic reactive oxygen species, inhibition of the synthesis of cell wall, DNA damage, denaturing of proteins and vital enzymes, accumulation of metal ions in cell membranes to alter permeability and functionality, disruption of metabolic activities, lethal stretching of cell membrane, intracellular leakage, and production of H_2O_2 among others [73, 160, 161, 162, 163]. Thus, through their multiple actions, nanoparticles can be viewed as ‘Trojan horse’ to deal with drug resistance phenomenon in microorganisms as they exert biocidal activities in myriad of ways (Figure 2). Therefore, nanoparticles can be aptly described as the next-generation antimicrobials, because of their broad effectiveness against both gram-positive and gram-negative bacteria and fungi in both *in vitro* and in animal studies with high level of biocompatibility [164, 165, 166]. In addition to curtailing MDR strains, metal nanoparticles also possess several other beneficial biomedical attributes. These include antioxidant [167, 168, 169, 170, 171], anticoagulant [4, 172, 173, 174, 175], thrombolytic [4, 172, 173], anti-inflammatory [176, 177], anti-diabetic [178, 179, 180],

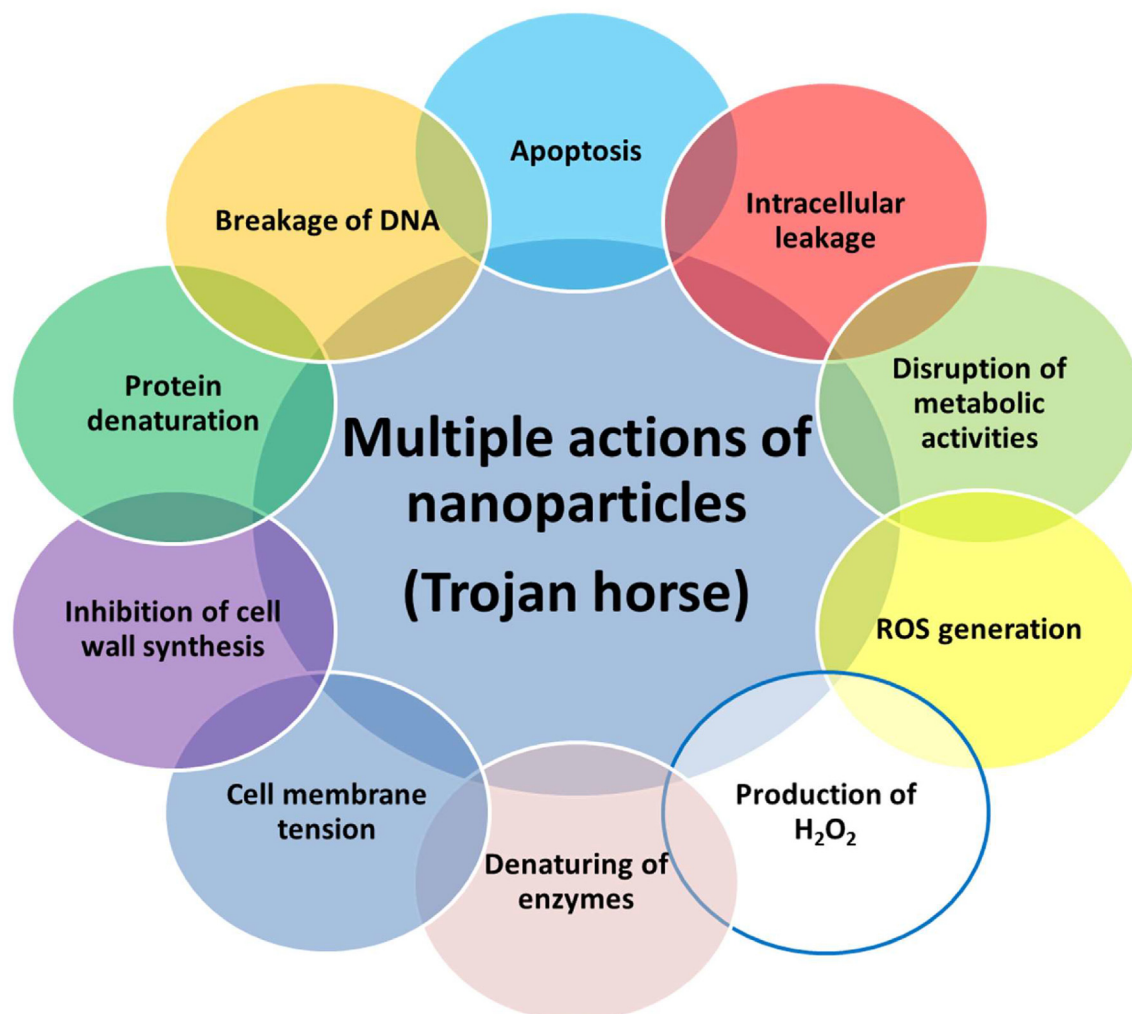


Figure 2. The multiple antimicrobial actions of metal nanoparticles as ‘Trojan horse’

anti-cancer [179, 180, 181, 182, 183] and wound healing [184, 185] properties. In translational studies, nanoparticle-based antibiotic delivery systems can be created by coating nanoparticles on implanted devices, wound dressings, bone cement and dental materials [186, 187, 188, 189, 190] to kill germs and prevent infections.

6. Roles of nanotextiles as antimicrobial agents in curtailing MDR and emerging pathogens

Antimicrobial textiles are functionally active textiles that can kill or restrict the growth of microorganisms [191]. The growth of the microorganism on fabric has a variety of negative consequences, not only for the fabric but also for the user. These side effects include the production of unpleasant odour, loss of mechanical strength of fabrics, appearance of stains and discolouration, and a higher risk of user to microbial infections. Microbial contamination is a major concern, particularly for textiles used in hospitals for health and hygiene care [192, 193]. The same thing holds for athletic apparel and textiles that are used in water and air purification systems, packaging of foods and feeds, [194, 195]. As a result of consumers' growing awareness of the implications on personal cleanliness and the health hazards that are linked with certain microbes such as *Escherichia coli*, *Micrococcus luteus*, *Staphylococcus aureus*, *Pseudomonas aeruginosa* and *Acinetobacter baumannii*, research and demand for antimicrobial textiles have skyrocketed in recent years [191, 196], with nanotextiles being actively discussed for different smart applications [57]. Figure 3 illustrates the antimicrobial actions of textiles that were functionalized with green synthesized AgNPs and Ti-AgNPs in our laboratory. The nanotextiles were active against *Aspergillus niger* and MDR strains of *Staphylococcus aureus* and *Klebsiella oxytoca*.

6.1. Nanotextiles as antiviral agents

The most common modes of transmission of illnesses caused by viruses are from human to human, environment to human and from

contaminated surfaces to human. The provision of materials that will be capable of destroying germs at these three levels will therefore be a huge success to curtail viral infections. Nanotextiles are part of strategies that can break the transmission by serving as barrier to viral dissemination or through inactivation of viruses. Thus, there is need to evaluate antiviral activities of nanotextiles. The standard protocol to evaluate antiviral activity of textiles is the ISO 18184:2019 [197,198]. The fundamental method for determining the antiviral activity of a compound is to expose the virus to the compound and assay for the survival of the virus in susceptible cells [191]. To test the antiviral property of nanotextiles, several studies have suggested a protocol of using the textile to filter viral suspension followed with the incubation of the filtrate with susceptible cells. Through this, the viral load can be determined to establish the antiviral activity of the nanotextile.

Hamouda *et al.* [199] reported the first trial of producing antibacterial and antiviral winter sweaters using cotton. To achieve uniform treatment, the cotton yarn was looped around a perforated dyeing tube, allowing the solution to pass from inside to outside in a dyeing unit. To functionalize the cotton, it was immersed in 400 ppm AgNO₃ and the mixture was boiled. Trisodium citrate was used as reducing agent to catalyze the formation of AgNPs *in situ* at 100 °C for 45 min. The functionalized cotton produced 51.7% viral inhibition against MERS-CoV with moderate cytotoxicity. This type of low-cost winter clothing with high microbe protection is recommended to be worn, especially during pandemics, to help mitigate the risks of viral infection [199].

Incorporation of graphene in nose masks have the potential to kill coronaviruses and it has been advocated for the fight against COVID-19 [200,201]. Coronaviruses (CoV) are enveloped positive-sense RNA viruses that cause several illnesses in animals and humans. These illnesses include the common cold, Severe Acute Respiratory Syndrome (SARS-CoV) and Middle East Respiratory Syndrome (MERS-CoV) [202]. In 2019, there was outbreak of SARS-CoV-2 in Wuhan China [203] which spiraled in to global health emergency, which as of 3 March 2022 had 438,968,263 confirmed cases, including 5,969,439 deaths as reported by

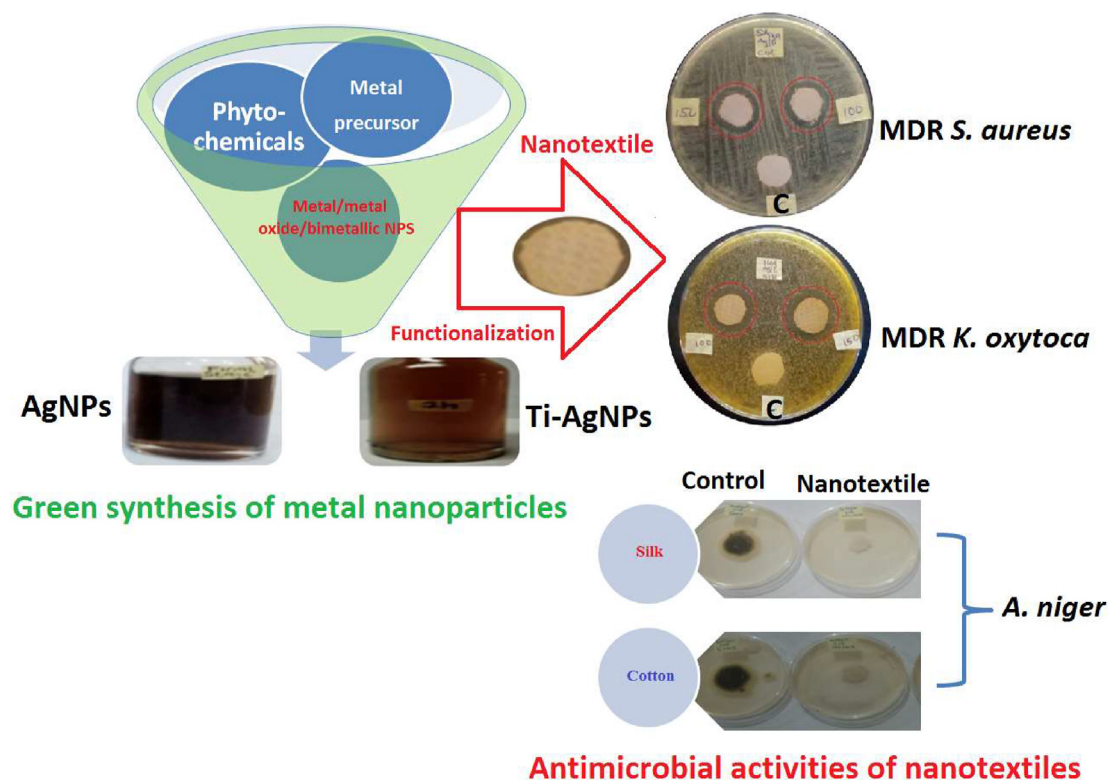


Figure 3. Antimicrobial activities of textiles functionalized with green synthesized AgNPs and Ti-AgNPs against *Aspergillus niger* and multi-drug resistant strains of *Staphylococcus aureus* and *Klebsiella oxytoca* (C, control: unfunctionalized textiles had no inhibitory activity)

WHO [204]. Parts of the efforts mounted against the spread of SARS-CoV-2 was the use of nose mask, where nanotechnology was deployed into producing masks infused with nanomaterials that are capable of killing the virus.

Graphene-silver nanoparticles composite was used to create nose mask that demonstrated a 99% elimination of SARS-CoV-2 in just a few seconds [205]. The nanoinfused nose masks have smaller pore sizes unlike the conventional respiratory masks that have larger pore sizes than SARS-CoV-2. Also, conventional masks lack self-disinfecting properties [206]. They are fragile [207], cannot be re-used [208], and their filtration efficiency reported to be about 85% for particles that are less than 300 nm due to their wider pores [209]. In the case of nose mask produced via graphene-silver nanoparticles, the hydrophobicity of graphene prevents the adhesion and growth of microbes on the surface of fabrics. In addition, graphene lyses microbial cell wall, while the sp² hybridized carbon atom in it provides additional antimicrobial activity.

Zhong *et al.* [206] developed a photothermal, self-disinfecting, and superhydrophobic coating on respiratory masks to solve the self-disinfecting problem. Within a minute of solar irradiation, the plasmonic heating of AgNPs in the mask raises its surface temperature to 80 °C to kill microbes. The superhydrophobic nature of the mask prevented the accumulation of droplets on the respirator surfaces. A silicon-based nanoporous model was created by El-Atab and colleagues [210] which can be re-used in N95 mask. The design was based on patterns of silicon with potassium hydroxide etching. The hard template was then used as a hard mask to transfer the designs onto a lightweight hydrophobic anti-fouling polymeric membrane. It was inferred that SARS-CoV-2 infections could be prevented by using the membrane inside reusable breathing masks.

Seino *et al.* [211] used a radiochemical technique to create AgNPs that were immobilized on the surface of cotton textile fibers with potent actions against Influenza A and Feline calicivirus. In addition, there are various antiviral polysaccharides that could be employed in pharmacotherapeutic applications to combat the infection. These antiviral polysaccharides could limit the spread of viruses when used to coat masks, clothing, and work surfaces. The biocompatible and biodegradable polysaccharides can bind to the spike proteins of coronaviruses. Therefore, layer-by-layer nanocoated materials can function as decoy receptors to bind spike proteins and subsequent inactivation of viruses [212]. Pristine silver nanoparticles have also been shown to have antiviral activity against extracellular SARS-CoV-2 [213].

Using a microwave synthesis approach, Hazarika *et al.* [110] also created antiviral nanofabric facemasks coated with zinc (oligolactate) (ZL), with potent antiviral activity against Newcastle disease virus (NDV). In another experiment, varying concentrations of ZL, silk nanocrystal (SNC) and with poly (lactic acid) (PLA) were made into nanofibres

by electrospinning. The nanofabric produced from the fibres was hydrophobic and offered great protection against water droplets. Breathability and reusability tests revealed that the facemask could be washed in ethanol and reused for up to four cycles without losing its surface qualities. Within ten minutes, the PLA/ZL nanofabric layer had 97% antiviral activity against NDV.

From the foregoing, antiviral nanotextile materials are increasingly being used to suit daily demands and limit the danger of infection through human contact with frequently touched environmental surfaces, which has been a difficult issue in recent years, particularly with the outbreak of the coronavirus pandemic. With efficient nanotextiles, the transmission of viruses and infections can be totally prevented. In synergy with other technologies such as 3D printing and electrospinning, nanoparticles can be used to create personalized smart nanomaterials as nose masks that will meet the demands of efficient elimination of viruses, breathability and moisture control [214]. This is important in offering protection to the front-line healthcare workers that cannot replace their masks frequently. Table 2 presents advances in the use of nanotextiles for antiviral capabilities.

6.2. Nanotextiles for the control of fungi

Cotton fabrics are well-known for being ideal breeding grounds for fungi, owing to their high moisture retention capacity, wide specific surface area and abundance of substrates for microbial growth [43, 223, 224]. Much work has gone into the creation of functional materials in the last few years in order to prevent the global problem of fungal proliferation on cotton surfaces. However, there are few publications on functionalized fabrics that described purely antifungal capabilities compared to those that reported general biocidal properties [225]. Hydrophilic cotton fabrics, such as those used in hospitals and sportswear are susceptible to microbial growth, thereby posing hygiene and health concerns. As a result, interests in the creation of multifunctional antimicrobial cotton fabrics have grown to address the healthcare concerns. Cotton textiles are also employed in medical applications such as bandages for wounds where biocidal activities are needed.

Katerine *et al.* [89] impregnated silver nitrate on siliceous matrixes that were doped with carbon obtained from spent batteries. The nanocomposite was synthesized using sol-gel technique. Thereafter, pad-dry-cure process was used to apply the hybrid nanoparticles on cotton cloth. The hybrid material demonstrated antifungal activity against *Cladosporium* sp., *Chaetomium globosum* and *Aspergillus* sp. Rilda *et al.* [90] reported spreading of TiO₂-SiO₂/Chitosan NPs on the surface of cotton fabrics. Various molar ratios of TiO₂:SiO₂ were investigated on the effect of antifungal activities of the nanotextiles. The amount of TiO₂ contained in the nanomaterials influenced the antifungal activity of the

Table 2. Antiviral activities of nanotextiles.

Type of textile	Nanomaterial for functionalization	Properties of nanotextiles	Target viruses	References
Cotton	Zinc (oligo-lactate)	Antibacterial, antiviral, hydrophobicity, breathability	Newcastle disease virus	[110]
Cotton	AgNPs	Antibacterial, antiviral	MERS-CoV	[199]
Cotton	Graphene-AgNPs	99% reduction of SARS-CoV-2; anti-odour	SARS-CoV-2	[205]
Cotton	AgNPs	Antiviral, hydrophobicity and photothermal	Envisaged for use against SARS-CoV-2	[206]
Cotton	AgNPs	Antiviral	Influenza A and Feline calicivirus	[211]
Nylon-cotton	ZnO NPs	Antiviral and breathability	Transmissible gastroenteritis virus (TGEV, a porcine alpha coronavirus)	[215]
Cotton	ZnO NPs	Antibacterial, antifungal and antiviral	HSV-1, Adeno, and CoxB2	[216]
Polyester	SeNPs	Antibacterial, antiviral and colour fastness	SARS-CoV-2	[217]
Cotton-polyester-spandex	AgNPs	Antiviral and breathability	SARS-CoV-2	[218]
Cotton	AgNPs	Antiviral	SARS-CoV-2	[219]
Electrospun nanofibres	ZnO NPs	Antibacterial and antiviral	Avian influenza	[220]
Polycotton	AgNPs	Antibacterial, antifungal and antiviral	SARS-CoV-2	[221]
Cotton	Ag/SiO ₂ NPs	Antiviral	Respiratory syncytial virus (RSV) and influenza virus type A (FluVA).	[222]

nanotextile using *Aspergillus niger*. The hybrid TiO₂-SiO₂/chitosan (2:1) NPs had superior ability to create hydroxyl radicals and superoxide anion which break fungal cell membrane. In another study, *Aspergillus terreus* was used to synthesize AgNPs by Balakumaran *et al.* [226] and employed to functionalize textiles through immersion under shaking. The nanotextiles displayed excellent activities against *Penicillium sp.*, *Aspergillus niger* and *Rhizopus oryzae*.

The antifungal activities of functionalized textiles with AgNPs against *Aspergillus niger* were reported by Aguda and Lateef [73]. Fungal spores were extracted in normal saline and used for the antifungal test. Mycelial growth on the surfaces of nanotextiles was determined after 48 h on PDA plates. The untreated fabrics in the control plates supported growth of the fungus, whereas the AgNPs-treated fabrics showed 100% antifungal potency against *Aspergillus niger*. El-Bendary *et al.* [235] employed AgNPs that were produced by *Bacillus subtilis* to functionalize polyester and wool-polyester. The functionalized textiles inhibited the growth of *Candida albicans*.

A survey of the antifungal activities of nanotextiles is presented in Table 3. Nanoparticles such as Ag, Se, ZnO, TiO₂, SiO₂, CuO, and Fe₃O₄ among others have been used to functionalize cotton, silk, polyester, polypropylene non-woven fabric, viscose, poly-cotton, and cellulose fibres. The functionalized textiles displayed antifungal activities against *Aspergillus niger*, *Phaeoaniella chlamyospora*, *Aspergillus fumigatus*, *Aspergillus flavus*, *Candida albicans*, *Candida glabrata*, *Candida utilis* and *Candida parapsilosis*.

6.3. Nanotextiles for the control of bacteria

Cotton is very important in the apparel industry because of its unique combination of properties, including softness, strength, elasticity, biodegradability, water affinity, and permeability. Because of being mainly composed of cellulose, it is susceptible to microbial degradation than synthetic fibers. Cotton offers more favorable conditions for microbial growth with consequences of decreased strength and generation

Table 3. Antifungal properties of nanotextiles.

Type of textile	Nanomaterial for functionalization	Properties of nanotextiles	Target fungi	References
Cotton and silk	AgNPs produced using wastewater of fermented seed of <i>Parkia biglobosa</i>	Antifungal and antibacterial	<i>Aspergillus niger</i>	[73]
Cotton	TiO ₂ /SiO ₂ by chemical synthesis	Antifungal	<i>Candida albicans</i> and <i>Aspergillus niger</i>	[90]
Wool	SeNPs	Dyeing, antibacterial and UV-blocking properties	<i>Candida utilis</i>	[97]
Cotton, poly-cotton, fiber and silk	AgNPs produced using leaf extract of <i>Ageratum conyzoides</i>	Hydrophobicity and antifungal	<i>Aspergillus sp</i>	[227]
Cotton-polyester	Bimetallic Ag/CuNPs by chemical synthesis	Antifungal and antibacterial	<i>Candida albicans</i>	[228]
Cotton-polyester	Fe ₃ O ₄ nanoparticles via ultrasound	Magnetic, photocatalytic, sonocatalytic, antifungal, antibacterial and enhanced strength	<i>Candida albicans</i>	[229]
Cotton	ZnO NPs by chemical synthesis	Antifungal and antibacterial	<i>Aspergillus niger</i>	[230]
Cotton	ZnO NPs by <i>in situ</i> synthesis	Antibacterial, antifungal and antiviral	<i>Candida albicans</i> , <i>Aspergillus niger</i> , and <i>Aspergillus fumigatus</i>	[216]
Cotton	CuO NPs by chemical synthesis	Antifungal and antibacterial	<i>Candida albicans</i>	[231]
Electrospun cellulose fibre	ZnO NPs by chemical synthesis	Antifungal and water repellancy	<i>Phaeoaniella chlamyospora</i>	[232]
Cotton and silk	Ag/TiO ₂ NPs by wastewater of <i>Parkia biglobosa</i>	Antifungal and antibacterial	<i>Aspergillus niger</i>	[233]
Cotton and polyester	AgNPs synthesized by <i>Bionectria ochroleuca</i>	Antifungal and antibacterial	<i>Candida albicans</i> , <i>Candida glabrata</i> , and <i>Candida parapsilosis</i>	[234]
Polyester and wool-polyester	AgNPs biosynthesized by <i>Bacillus subtilis</i>	Antifungal, antibacterial and UV-protection	<i>Candida albicans</i>	[235]
Cotton	AgNPs synthesized by whey protein isolate	Antibacterial and antifungal	<i>Aspergillus niger</i>	[236]
Cotton	AgNPs by chemical synthesis	Antibacterial and antifungal	<i>Candida albicans</i>	[237]
Polypropylene nonwoven fabric	AgNPs synthesized by <i>Ocimum sanctum</i>	Antifungal and impedance	No fungal attack of the textile electrode	[238]
Cotton and silk	Graphene, Ag and Cu NPs	Antibacterial and antifungal	<i>Candida albicans</i>	[239]
Cotton and polyester	AgNPs synthesized by <i>Aspergillus tubingensis</i>	Antibacterial, antibiofilm and antifungal	<i>Candida albicans</i> , <i>Candida glabrata</i> , and <i>Candida parapsilosis</i>	[240]
Polyester	CuNPs by sonosynthesis	Antibacterial, antifungal, reduced wettability and improved tensile strength	<i>Candida albicans</i>	[241]
Cotton	Ag-ZnONPs synthesized by the extract of <i>Azadirachta indica</i>	Antibacterial and antifungal	<i>Candida albicans</i>	[242]
Cotton	AgNPs synthesized by extract of <i>Beta vulgaris</i>	Antibacterial and antifungal	<i>Candida albicans</i>	[243]
Cotton	TiO ₂ NPs	Antifungal, crease recovery, dyeing and UV-protection	<i>Candida albicans</i>	[244]
Wool	Fe ₃ O ₄ nanoparticles synthesized by co-precipitation	Antifungal and magnetic	<i>Candida albicans</i>	[245]
Cotton	ZnO NPs synthesized by co-precipitation	Antifungal, UV/NIR radiation shielding, and coolness	<i>Aspergillus flavus</i> and <i>Aspergillus niger</i>	[246]
Linen, tents and lenoh	AgNPs synthesized by <i>Pleurotus ostreatus</i>	Antibacterial and antifungal	<i>Aspergillus niger</i>	[247]

Table 4. Antibacterial properties of nanotextiles including activities against MDR strains.

Type of textile	Nanomaterials for functionalization	Properties of nanotextiles	Bacteria	References
Cotton and silk	AgNPs	Antibacterial and antifungal	<i>Staphylococcus aureus</i> , <i>Escherichia coli</i> , <i>Klebsiella pneumoniae</i> , <i>Klebsiella oxytoca</i> , <i>Pseudomonas aeruginosa</i> , and <i>Proteus mirabilis</i>	[73]*
Cotton	ZnO NPs	Antibacterial, UV-protection, tensile strength and crease resistance	<i>Staphylococcus aureus</i> and <i>Escherichia coli</i>	[87]
Cotton	AgNPs	Antibacterial	<i>Staphylococcus aureus</i> , <i>Escherichia coli</i> , <i>Bacillus subtilis</i> and <i>Pseudomonas aeruginosa</i>	[94]
Wool	Silica, titania, and AgNPs	Antibacterial, hydrophilicity and self-cleaning	<i>Escherichia coli</i>	[96]
Wool	SeNPs	Dyeing, antibacterial and UV-blocking properties	<i>Staphylococcus aureus</i> , <i>Escherichia coli</i> , and <i>Bacillus cereus</i>	[97]
Wool, Cotton	ZnO, TiO ₂ , and CuONPs	Antibacterial, antifungal, UV-blocking, and self-cleaning	<i>Staphylococcus aureus</i> and <i>Escherichia coli</i>	[98]
Silk	PtNPs	Antibacterial, catalysis and dyeability	<i>Escherichia coli</i>	[116]
Cotton-polyester	Bimetallic Ag/CuNPs	Antifungal and antibacterial	<i>Staphylococcus aureus</i> and <i>Escherichia coli</i>	[228]
Cotton-polyester	Fe ₃ O ₄ nanoparticles	Magnetic, photocatalytic, sonocatalytic, antifungal, antibacterial and enhanced strength	<i>Staphylococcus aureus</i>	[229]
Cotton	ZnO NPs	Antifungal and antibacterial	<i>Staphylococcus aureus</i> and <i>Escherichia coli</i>	[230]
Cotton	CuO NPs	Antifungal and antibacterial	<i>Staphylococcus aureus</i> , <i>Escherichia coli</i> , <i>Pseudomonas fluorescens</i> and <i>Bacillus subtilis</i> .	[231]
Cotton and silk	Ag/TiO ₂ NPs	Antifungal and antibacterial	<i>Staphylococcus aureus</i> , <i>Escherichia coli</i> , <i>Klebsiella pneumoniae</i> , <i>Klebsiella oxytoca</i> , <i>Pseudomonas aeruginosa</i> , and <i>Proteus mirabilis</i>	[233]*
Cotton and polyester	AgNPs	Antifungal and antibacterial	<i>Staphylococcus aureus</i> and <i>Escherichia coli</i>	[234]
Polyester and wool-polyester	AgNPs	Antifungal, antibacterial and UV-protection	<i>Escherichia coli</i> , <i>Staphylococcus aureus</i> , <i>Pseudomonas aeruginosa</i> , <i>Bacillus cereus</i> , and <i>Salmonella typhi</i>	[235]
Cotton	AgNPs	Antibacterial and antifungal	<i>Staphylococcus aureus</i> and <i>Escherichia coli</i>	[236]
Cotton	AgNPs	Antibacterial and antifungal	<i>Staphylococcus aureus</i> and <i>Escherichia coli</i>	[237]
Cotton and silk	Graphene, Ag and Cu NPs	Antibacterial and antifungal	<i>Escherichia coli</i> , <i>Staphylococcus aureus</i> , and <i>Pseudomonas aeruginosa</i>	[239]
Cotton and polyester	AgNPs	Antibacterial, antibiofilm and antifungal	<i>Staphylococcus aureus</i> and <i>Escherichia coli</i>	[240]
Cotton	Ag-ZnONPs	Antibacterial and antifungal	<i>Staphylococcus aureus</i> and <i>Escherichia coli</i>	[242]
Cotton and polypropylene spunbonded/melt blown/spunbonded	AgNPs	Antibacterial	<i>Escherichia coli</i> , <i>Staphylococcus aureus</i> , and <i>Pseudomonas aeruginosa</i>	[251]*
Cotton	Zn-doped CuO NPs	Antibacterial	<i>Staphylococcus aureus</i> and <i>Escherichia coli</i>	[252]*
Cotton	AgNPs	Antibacterial	<i>Escherichia coli</i> , <i>Staphylococcus aureus</i> , and <i>Pseudomonas aeruginosa</i>	[253]**
Cotton	TiO ₂ NPs	Antibacterial and antifungal	<i>Staphylococcus aureus</i> and <i>Escherichia coli</i>	[254]**
Cotton	Bi ₂ MoO ₆ and Ag nanoparticles	Antibacterial	<i>Staphylococcus aureus</i> and <i>Escherichia coli</i>	[255]
Cotton	Graphene oxide	Antibacterial	<i>Streptococcus iniae</i> and <i>Escherichia coli</i>	[256]
Cotton	ZnSnO ₃ nanoparticle	Antibacterial, self-cleaning, flame resistance, and UV-protection	<i>Staphylococcus aureus</i> and <i>Escherichia coli</i>	[257]
Wool, polyester, wool-polyester	AgNPs	Antibacterial, antifungal, dyeing and UV-protection	<i>Bacillus cereus</i> , <i>Escherichia coli</i> , <i>Pseudomonas aeruginosa</i> , <i>Salmonella typhi</i> and <i>Staphylococcus aureus</i>	[258]
Cotton, viscose, polyester, and wool-polyester	AgNPs	Antibacterial and antifungal,	<i>Bacillus cereus</i> , <i>Escherichia coli</i> , <i>Pseudomonas aeruginosa</i> and <i>Staphylococcus aureus</i>	[259]

*studies where MDR strains were used; **MRSA used.

of unpleasant odors by textiles. Microbial growth can also lead to incidences of allergic reactions and other health risks [225].

Most frequently, hospital fabrics, sport wears and underwear come in contact with germs. In the last few decades, nanotechnology has helped to improve production of antibacterial textiles and materials. The effects of nanoparticles like zinc oxide nanoparticles, titanium dioxide nanoparticles, copper (II) oxide nanoparticles, and silver nanoparticles on the antibacterial properties of natural cotton, wool, silk, and some synthetic fibers have been remarkable in the process of obtaining functionalized textiles with antimicrobial properties against germs of public health concerns.

Tania and Ali [87] reported evaluation of three different zinc oxide nanoparticle recipes: ZnONPs (ZnO-A), ZnONPs with a binder (ZnO-B),

and ZnONPs with a binder and wax emulsion (ZnO-C) to functionalize cotton fabrics. The nano-treated and untreated fabrics were tested against *Staphylococcus aureus* and *Escherichia coli*, and all the nanofabrics significantly reduced growth of the two bacteria by 50.54–90.43% within 1 h. After 24 h of exposure, the nanofabrics ZnO-B and ZnO-C showed 99% reduction of the two bacterial populations.

Foltynowicz *et al.* [248] investigated the antibacterial properties of AgNPs-coated socks using linen and cotton materials. Selected strains of bacteria such as *Staphylococcus aureus*, *Staphylococcus epidermidis*, *Bacillus megaterium*, and *Pseudomonas aeruginosa* were tested for antimicrobial activity with improved activities by the treated socks. Elsayed and Elsamani [249] created diabetic socks using TiO₂ nanoparticles. The modified socks controlled moisture absorption and inhibited the growth

of *Staphylococcus aureus*. The functionalized socks could be used by diabetic patients.

Fabrics in direct contact with the human skin such as socks, gloves, towels and underwear have also been functionalized with nanostructures with antibacterial properties to prevent or reduce the risk of skin diseases. These include allergic reactions and skin inflammation. In a clinical trial, Perelshtein *et al.* [250] investigated the impact of functionalization of textiles with ZnONPs in the hospital. Bed sheets, pillow covers and pyjamas were produced from functionalized textile. The materials were used by 21 patients with results of reduction of nosocomial infections. The performance of the materials can make the hospital safer. Table 4 details the antibacterial activities of textiles that were functionalized with different nanomaterials such as AgNPs, ZnONPs, TiO₂ NPs, CuO NPs, Bi₂MoO₆, PtNPs, Fe₃O₄ NPs, SiO₂ NPs, SeNPs, ZnSnO₃ NPs, and graphene. The most widely used model bacteria for the determination of antibacterial activities have been *Staphylococcus aureus* and *Escherichia coli*.

However, there are fewer reports on the use of MDR strains in assessing the antibacterial activities of textiles that were functionalized with nanoparticles [73, 233, 251, 252, 253, 254]. In a recent work, Aguda and Lateef [73] investigated the antibacterial potentials of functionalized silk and cotton against clinical MDR strains of *Staphylococcus aureus*, *Escherichia coli*, *Klebsiella pneumoniae*, *Klebsiella oxytoca*, *Pseudomonas aeruginosa*, and *Proteus mirabilis*. The tested bacteria were resistant to 4–8 antibiotics. Fabrics were treated with biosynthesized AgNPs (100 and 150 µg/ml) and exposed to the bacterial lawn on Mueller-Hinton agar. The AgNPs-functionalized textiles inhibited all the test isolates up to the fifth wash cycle, but the control textiles had no antibacterial effect. Similarly, AgNPs biosynthesized by the leaf extract of *Azadirachta indica* was used to functionalize textiles which showed tremendous activities against MDR strains of *Staphylococcus aureus*, *Escherichia coli* and *Pseudomonas aeruginosa* [251].

The paucity of data on the actions of nanotextiles on MDR strains may cast doubts on the generalized antimicrobial potentials of nanotextiles. The use of ATCC *Escherichia coli* standard only may underestimate the survival of MDR strains on nanotextiles [260]. Therefore, there is the need to expand the testing panel of nanotextiles using MDR strains of different bacteria to ensure the validity of their potencies and applications. Such strains may include but not limited to MDR *Klebsiella pneumoniae*, *Escherichia coli*, *Acinetobacter baumannii*, *Staphylococcus aureus* and *Enterococcus faecium*.

7. Challenges in the developments of nanotextiles for biomedical applications

Despite the huge potentials that accompany the developments of nanotextiles; they are not without encumbrances. These include validity of claims of antimicrobial properties, toxicity, durability, disposal and environmental concerns. For instance Blevens *et al.* [198] in the wake of scourge of COVID-19 evaluated 40 face masks that were claimed to contain silver or AgNPs for antimicrobial and antiviral activities. It was discovered that only 21 of the face masks had substantiated claims. Analysis of two samples from the substantiated masks revealed the presence of copper, zeolite and titanium nanoparticles in addition to AgNPs. The study concluded that the certified products could not be credible and therefore recommended stricter regulations on product testing to ensure efficacy and compliance with standards on inhalation. While it is expedient to establish guidelines for testing of nanotextiles to guarantee the contents and validity of claims, such endeavours would have to overcome the challenges that contribute to the efficacy of nanotextiles. These include type of nanoparticles, mode of synthesis of nanoparticles, particle size, morphology and the method of functionalization.

The inclusion of nanoparticles in consumer products including textiles can expose users to nanomaterials. Tolve *et al.* [261] analyzed the potential risks to children upon exposure to different products that

contain AgNPs. It was established that for a sippy cup, a child has potential non-dietary ingestion exposure of 1.53 µg Ag/kg while using the cup to drink infant formula milk. In analyzing 8 selected textile products consisting of wipes, bandages and fabrics (underwear, pant, gloves and baby blanket), the silver contents varied from 4 ± 1 to 1133 ± 82 mg/kg. Exposure of children and other vulnerable groups to these quantities of silver might present some health concerns.

In a simulated study using artificial sweat and saliva, Stefaniak *et al.* [262] established that the mode of functionalization of textiles influenced the release of Ag⁺. While the finishing process caused the release of 0.51 ± 0.04% of Ag⁺ from the nanotextile, the masterbatch processed nanotextile released 0.21 ± 0.01% Ag⁺. The study can be extrapolated to explain heterogeneity in the exposure of skin to metal ions from nanotextiles that were functionalized using different techniques. Kim *et al.* [263] reported that the release of Ag⁺ from consumer products is more influenced by the method of manufacturing rather than the Ag content of the products. In a simulated sweating experiment, it was estimated that the maximum exposure of Ag in 1 h from nanotextile was 0.81/2.03 µg Ag/kg body weight with a standard body weight of 77 kg for a male, which does not represent a health concern [263].

With the surge in the fabrication of nanotextiles, there have also been concerns on their environmental impacts. These include release of metal ions, accumulation of particulates and toxicity towards non-target organisms. It has been advocated that the increased use of nanomaterials in textiles necessitates assessment of their potential negative effects on humans and the environment [264]. The complexity of nanomaterials that are used in the functionalization of textiles which include carbon-based nanomaterials, inorganic nanoparticles, core-shell nanoparticles, composite, hybrid and polymeric nanomaterials [265] can greatly influence the environmental fate and impacts of nanotextiles. The heterogeneity of nanomaterials in addition to their diverse physico-chemical attributes poses challenges in determining the life cycle of products that contain them.

Nevertheless, nanotextiles can have negative impacts on the release of nanomaterials in the environment, which may be influenced by their utilization, recycling and disposal. Through usage, laundry and disposal, nanomaterials in functionalized textiles may get in contact with human through the skin and inhalation. They may also enter and accumulate in wastewater and soil. The toxicity of bare nanoparticles and those of functionalized materials are well-documented in literature [266, 267, 268, 269], thereby necessitating the development of life cycle assessment to establish their potential risks to the environment, health, safety and sustainability (EHS/S) [270]. Also, development of sustainable separation and analytical procedures to quantify nanomaterials in nanotextiles as well as their fate in the environment has been advocated [271]. Other issues with regards to developments of nanotextiles for biomedical applications include breathability for face mask [110, 218] to avoid creation of oxygen tension and enhancement of reusability on the basis of efficiency [207, 272].

8. Future trends in the fabrication of nanotextiles for biomedical applications

Nanotextiles portend great opportunities as critical components of efforts at achieving good health and well-being in the 21st century to tackle MDR and emerging diseases. Aside the traditional antimicrobial and UV-protection properties that are ascribed to nanotextiles, they can also be deployed for other functionalities that may have positive impacts on health. These applications include but not limited to anticoagulant, thrombolytic, wound healing, anti-inflammatory and antioxidant activities. New range of applications can greatly improve developments in personalized medication through the deployment of smart medical textiles for wide range of physiological sensing applications. Wearable nanotextiles can be utilized for drug delivery, electroencephalography, electrocardiography, electromyography, electrooculography, bioimpedance, and several other biomedical applications when integrated

with electronics [57]. Though studies have been focused mainly on the use of Ag, ZnO and TiO₂ NPs to functionalize textiles; it is expected that advances in the exploitation of other forms of nanomaterials will herald new functionalities that may expand the scope of applications of nanotextiles in the healthcare sector. These include the use of SeNPs, magnetic nanoparticles and graphene.

9. Conclusion

The surface modification of textiles with nanostructures to provide antimicrobial properties has been extensively studied in the last few years. This review examined the roles of nanoparticles in functionalization of textiles as combating agents against microorganisms that include multi-drug resistant strains (MDRs). Several reports on their antiviral, antifungal, and antibacterial activities were reviewed. Similarly, the basic attributes of nanotextiles, methods of functionalization, and their activities on the control of microorganisms were discussed. It also examined the challenges and prospects of nanotextiles for biomedical applications. This work can serve as an interesting piece for researchers who wish to extend their horizon of knowledge in the breakthrough of nanotechnology against disease-causing microorganisms, thereby improving the healthcare for mankind in their applications.

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