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ENHANCED ANTIMICROBIAL AND UV-PROTECTIVE HEALTHCARE TEXTILE FABRIC INCORPORATING ZINC OXIDE NANOPARTICLES SYNTHESIZED VIA SOL-GEL METHOD: A REVIEW

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ABSTRACT

Healthcare textiles have undergone a revolution thanks to the incorporation of nanotechnology into textile engineering, which has added features like UV protection and antimicrobial activity. In order to improve the antibacterial and UV-protective qualities of healthcare textiles, this study summarizes current developments in the manufacture and application of zinc oxide (ZnO) nanoparticles using the sol-gel method. Database searches and strict inclusion criteria were part of the systematic review approach used. Zinc oxide (ZnO) nanoparticles are being used more and more in textile applications because of their superior antibacterial qualities, UV protection, chemical stability, and biocompatibility. Results show that ZnO nanoparticles successfully enhance fabric functions, with uses ranging from protective apparel to hospital linens and wound treatments. The sol-gel production of ZnO nanoparticles, their integration into textile substrates, and the ensuing improvements in UV protection and antibacterial activity are covered in this work. The study addresses the long-term durability, safety, and environmental sustainability of functionalized textiles, highlighting the need for further investigation into green synthesis techniques and legal requirements.

KEY WORDS: Antimicrobial behavior; Healthcare textiles; Nanoparticles; Sol-Gel Method; UV Protection; Zinc Oxide

1. INTRODUCTION

Human skin exposure to ultraviolet (UV) radiation and microbiological contaminations have both sharply increased recently as a result of the ongoing ozone layer depletion in the atmosphere and the rise in social interactions, respectively. A quick review of recent research (1), reveals that a variety of chemicals are commonly employed as finishes to enhance the performance of fabrics. However, recent attempts to minimize or replace dubious safety chemicals with new ecologically friendly options have been made in response to the strong push to outlaw dangerous chemicals, such as chemical anti-microbial agents or flame retardants that contain halogen. Another crucial factor to take into account is the finishing process selection, which also affects the industrial closing costs. It is necessary to use cutting-edge and creative technologies to meet all of these objectives. In this sense, due to their unique and distinctive properties, textile alterations are continually being developed through the production of polymeric nanocomposites, primarily based on metallic or inorganic nanostructured components.

Functionalized textiles using nanotechnology have drawn a lot of scholarly attention as health concerns associated with these elements have grown. Because of their wide surface area, high surface energy, ease of ionization, and poisonous nature, titanium, silver, and zinc nanoparticles utilized in nano finishing have enormous potential for blocking UV radiation and preventing microbial proliferation, in addition to the traditional finishing processes (2).

The biocompatibility, low toxicity, sustainability, and cost-effectiveness of zinc oxide nanoparticles (ZnO-NPs) have made them a popular metal oxide nanoparticle and attracted the attention of researchers worldwide. They stand out as a possible contender in the domains of optical, electrical, food packaging, and biological applications because of their distinct optical and chemical characteristics. In the long term, biological procedures that use green or natural channels are simpler, less harmful, and more environmentally friendly than chemical and/or physical approaches. Furthermore, ZnO-NPs can significantly increase pharmacophore bioactivity and are less toxic and biodegradable (3).

There is great potential for improving antibacterial and UV protection qualities when ZnO nanoparticles are used in health care products (4). Starting with inorganic metal alkoxides or metal salts, the sol–gel process creates inorganic sols with particles that allow fiber surfaces to be modified chemically or physically, resulting in treated textiles' ultimate multifunctional qualities (5). The sol–gel method is predicated on the phase of transition from a liquid (sol) to a dense system (gel), which is subsequently heated and dried to create a porous matrix that is a combination of organic and inorganic materials. The organic and inorganic precursors involved may engage by covalent, coordination, or iono-covalent interactions, or weak bonds like ionic, hydrogen, or van der Waals (Class I) connections (6, 7). Recent advancements in the sol-gel synthesis of inorganic nanoparticles and nano-sols for textile applications that improve UV resistance, as well as have antibacterial or antimicrobial properties, were taken into account in this review.

This review paper examines the most recent advancements in nano-finishing technologies for textiles meant to fend off microbial infestations and UV radiation. A thorough discussion is given of the target-based nanomaterials, their characteristics, working mechanisms, application strategies, sustainability, durability, and current and future research directions.

1.1 APPLICATION OF NANOMATERIALS IN THE TEXTILE INDUSTRY

The textile industry is working to develop a wide variety of coatings that give them multipurpose qualities. Coated textiles work well in a variety of applications where solo nanoparticles or coatings fall short. However, the currently used synthetic nanomaterials, coatings, and chemicals have detrimental ecological effects (8). The field of study known as nanotechnology focuses on the production and alteration of materials at the nanometer scale (9). The goal of the quickly developing field of nanotechnology is to develop novel materials at the nanoscale. To put it another way, the goal of nanotechnology is to produce, characterize, and manage matter with a size between 1 and 100 nm (10). Nanotechnology is being widely used in the textile industry, and a remarkably large number of nanotextiles, including various consumer goods that contain nanoparticles, are available on the market (11-13). Nanomaterials are added to conventional textiles to create nanotextiles. These advanced textiles have a variety of features, such as antimicrobial properties, water repellency, UV protection, flame retardancy, and self-cleaning capabilities(14-18). Nanocoating and nano finishing have expanded the potential uses of textile materials in several industries (19-21).

The nanoparticles have a greater potential to provide various functionalities in textiles because of their higher surface area to volume ratio and nanoscale dimensions: (1) Carbon-based nanomaterials, including graphene, carbon nanofibers, and carbon nanotubes;(2) inorganic nanoparticles, including metal oxide, metal, and nano clay; (3)core-shell nanoparticles; (4) composite nanomaterials; (5) hybrid nanomaterials; and (6) polymeric nanomaterials are the most common types of nanomaterials used in textiles**. Table 1** lists several nanomaterials that are most commonly used for textile functionalization (22).

Table 1.Utilization of nanometal in textile functionalization

S/N.	Nanometal	Function	Reference
1	Nano clays	Active ingredient support, flame retardance, and abrasion resistance	(23)
2	Aluminum oxide	flame retardance, abrasion resistance	(24)
3	Silicon dioxide	Reinforcement enhanced the dyeability, abrasion resistance, water repellence, dirt repellence	(24)
4	Zinc oxide	Stiffness, abrasion resistance, self-cleaning, antibacterial property and UV protection	(25)
5	Titanium dioxide	Water repellence, dirt repellence, self-cleaning, UV protection	(26)
6	Silver	Electrically conductive, antibacterial property	(27)

2. REVIEWS METHODOLOGY

A systematic approach was employed to select relevant studies on zinc oxide (ZnO) nanoparticles synthesized via the sol-gel method for application in antimicrobial and UV-protective healthcare textiles. The main electronic databases that were searched were Google Scholar, Web of Science, PubMed, and Scopus. To refine the results, the search technique used a combination of keywords and phrases like "zinc oxide nanoparticles," "sol-gel synthesis," "antimicrobial textiles," "UV-protection," and "healthcare fabrics," together with Boolean operators. Peer-reviewed publications that specifically examined the sol-gel production of ZnO nanoparticles and assessed their incorporation into textile fabrics for antibacterial or UV-protective properties were required to meet the inclusion requirements. Furthermore, investigations were to include performance evaluations pertinent to textile applications and characterization of the produced nanoparticles. On the other hand, research that concentrated on other synthesis techniques, lacked adequate characterization information, or had no direct connection to textile applications was disqualified by the exclusion criteria. To ensure quality and uniformity, conference abstracts, review papers, and publications that were not available in English were also disqualified.

After a preliminary screening of abstracts and titles to find potentially pertinent papers, a full-text review was conducted to verify eligibility in accordance with the predetermined standards. This methodical methodology sought to improve the review's transparency, repeatability, and comprehensiveness by making sure that only relevant and excellent studies were added to the synthesis of the field's existing knowledge.

This review mainly focuses on:

- The synthesis of ZnO nanoparticles via the sol-gel method.
- Incorporation techniques into textile fabrics.
- Evaluation of antimicrobial and UV-protective properties.
- Potential for sustainable and durable healthcare textiles.

3. UV PROTECTION

Human, plant, and animal life are now at greater risk due to the depletion of the ozone layer in the Earth's atmosphere in recent years. Long-term exposure to ultraviolet (UV) radiation can cause health problems like aging, DNA damage, skin reddening, acne, and even skin cancer because it causes the production of free radicals (28).This suggests that UV light is one of the primary sources of free radicals, which cause direct biological harm and various cancers. Furthermore, discoloration of dyes and pigments, weathering, yellowing of plastics, and loss of gloss and mechanical qualities (cracking) can all be linked to UV radiation-induced damage (29).

Consequently, several products need to be protected to withstand prolonged exposure to UV light (30, 31). As a result, research and development of UV-protective materials has grown is an important issue. High transparency, a high UV-absorption coefficient, high photostability, and affordability are all necessary for a material to be UV-absorbing. Both organic and inorganic UV absorbers are marketed commercially. To shield organic materials from UV rays, organic UV absorbers have been employed. However, their utility is severely limited by the low durability of the polymer matrices that are frequently employed to embed the absorbers under UV irradiation **(**32, 33**).**

4. MATERIALS FOR UV PROTECTIVE TEXTILES FINISHING

The type, porosity, thickness, and color of a fabric all affect its UV protection; white summer clothing, in particular, offers very little protection. It is important to note that darker-colored textiles offer comparatively better UV protection since the dyestuffs used can more easily absorb the sun's UV rays (34). To effectively protect against UV radiation, UV-absorber molecules must be able to transform the energy of absorbed radiation into less dangerous thermal energy by a photophysical process (35). Inorganic compounds based on metal oxide semiconductors are powerful heat-resistant and efficient UV absorbers. They are employed as UV absorbers incorporated in polymers or as transparent inorganic matrices. It should be mentioned that protective coatings become more stable when nanoscale inorganic materials are used, and their UV absorption is extremely effective. Naturally, for nanoscale inorganic materials to absorb UV radiation, their band gap needs to be appropriate.

For instance, TiO_2 has a band gap with optical absorption in the wavelength range of around 310 to 400 nm, and its absorption does not extend the entire UV region, particularly the hazardous 290–350 nm region (36). However, CeO_2 (E_g=3.1 eV) has a strong yellowish coloring that restricts its usage in color-sensitive applications, such as protecting artwork, even though it can absorb light throughout the full UV spectrum (37). Nonetheless, ZnO with a broad band gap (E_g=3.37 eV, or 376 nm) possesses special electrooptical qualities, effective UV absorptivity, and strong visible-range transparency (because it absorbs light that equals or exceeds its band-gap energy) (38-41).

According to Li et al. (42), designing transparent epoxies and the incorporation of organic or inorganic UV-light absorbents can result in strong UV-light resistance of packaging materials. Because UV absorbers like ZnO usually do not migrate within a polymer matrix, their photostability and thermal stability offer benefits including improved stability and a nonmigratory nature, which can lead to greater efficacy and longer durability. ZnO is superior to other UV-protection options because it provides long-lasting protection, wide protection, and prevents skin bleaching (43).

5. ZNO NANOPARTICLES AND THEIR PROPERTIES

5.1 PROPERTIES OF ZNO NANOPARTICLES

Zinc oxide nanoparticles (ZnO-NPs) have caught the attention of scientists worldwide because of their broad biological activity. They can significantly increase pharmacophore bioactivity and are less harmful and biodegradable. Since their unique optical and chemical characteristics may be easily altered by changing their morphology and their broad bandgap, ZnO-NPs are the most widely utilized metal oxide nanoparticles in electronic and optoelectronics (44). Zinc is essential for many bodily functions, such as immune response, learning, memory, enzymatic activities, and protein synthesis. One necessary trace element is zinc. ZnO-NPs are very important because of their many applications, which include water purification, photocatalysis, and antimicrobial resistance (45).

The properties of ZnO-NPs distinguish them from traditional NPs. Cosmetics, sunscreen, LEDs, solar cells, transparent transistors, memory technologies, and catalysis all use zinc oxide as an ingredient. ZnO-NPs, which are white and odorless, have a molecular weight of 81.38 g/mol. ZnO-NPs are used in both biological and commercial applications due to their unique electrical, optical, catalytic, or photochemical properties. ZnO-NPs are used to prevent UV damage of wood and textiles (46). ZnO-NPs are an inorganic metal oxide that can be utilized as a medicine, packaging preservative, and risk-free antibacterial agent. The characteristics of ZnO-NPs depend on their size, shape, concentration, and length of contact with the bacterial cell. Zinc oxide has several uses, including in food technology, agriculture, cosmetics, optoelectronics, drug transporters, and antibacterial agents (47). Nanoscale zinc oxide (ZnO) is among the finest options for UV protection, due to its potential usage for UV preservation as well as its antibacterial qualities (48).

5.2 SOL-GEL METHOD FOR ZINC OXIDE NANOPARTICLES SYNTHESIS

Traditional techniques to produce metallic NPs, such as ZnO-NPs, involve physical and chemical processes. Traditional chemical synthesis techniques include hydrothermal, sol-gel, co-precipitation, and microemulsion methods. Physical methods include laser ablation, thermal evaporation, and high-energy ball milling. ZnO-NPs are synthesized using various techniques that can be broadly categorized into chemical, physical, and biological methods. In this study, we focused on the sol-gel synthesized method.

A flexible and popular method for creating nanoparticles and nanostructured materials is the sol-gel process. This method uses carefully regulated chemical processes to transform a liquid precursor solution, called a sol, into a solid gel network. Making a precursor solution with metal alkoxides, metal salts, or other metal-containing substances is the first step in the procedure (49).

The sol-gel process was used to create the zinc oxide nanostructure. Based on the experiment of Hasnidawani et al (2016), ZnO nanoparticle was synthesized as, weighing balance was used to weigh 2 g of zinc acetate dihydrate and 8 g of sodium hydroxide in order to create a sol. A measuring cylinder was then used to measure 10 and 15 milliliters of distilled water. Following that, 8 g of sodium hydroxide and 2 g of zinc acetate dihydrate were dissolved in 10 ml of distilled water and 15 ml, respectively. For almost five minutes each, the solutions were continuously swirled. Once thoroughly combined, the sodium hydroxide solution was added to the zinc acetate solution while being continuously stirred for approximately five minutes using a magnetic stirrer. Next, 100 milliliters of ethanol were added to a burette to remove the impurities from the final product, and the solution comprising zinc acetate and sodium hydroxide solution was added dropwise. A white precipitate is developed after the reaction, and to create a white powder or ZnO flakes, the slurry was further dried for 6 hours at 100 °C in a vacuum oven. This was further calcined in a muffle furnace for four hours at 600 °C to produce NP-ZnO (50, 51).

Generally, during sol-gel methods, different processes are performed, explained as follows:

A colloidal solution (sol) is first created, and it is subsequently transformed into a gel and solid in the sol–gel process. The procedure includes polymerization, condensation, and hydrolysis. The final product is then produced by heating and treating the gel to cause the solvents to evaporate (52). The sol–gel process can be used to produce ZnO-NPs with a controlled chemical composition.

The sol–gel process has the advantage of faster growth and nucleation, control over nanoparticle size and morphology, lower synthesis temperatures, is environmentally friendly, with minimal use of hazardous chemicals, uniform dispersion of nanoparticles, as well as the ability to produce nanoparticles on a large scale in industrial settings. However, because of the high energy, dangerous chemicals, and expensive equipment needed, the chemical approach has some disadvantages, as shown in

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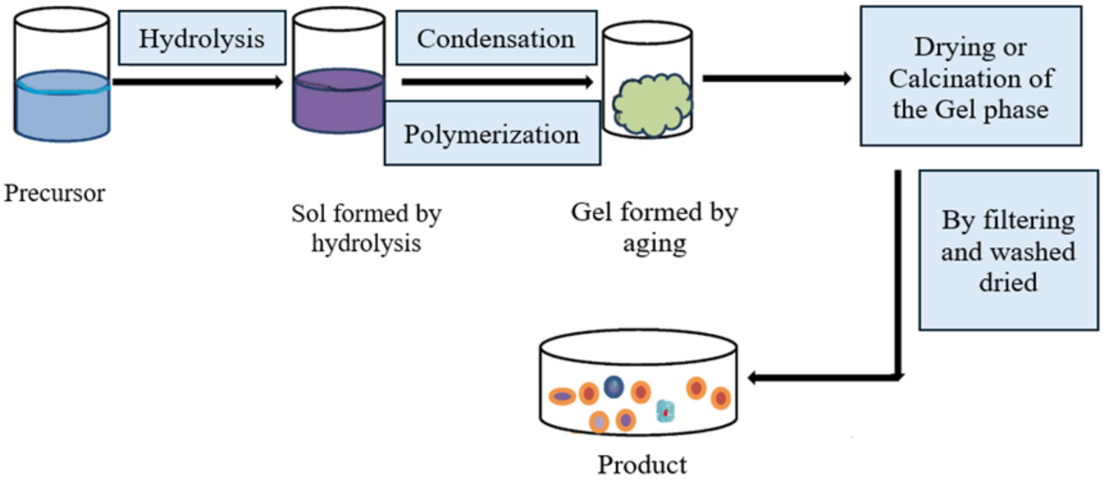


Figure 1.Diagrammatic representation of the procedures required to use the sol-gel method to produce zinc oxide nanoparticles (53).

5.3 TECHNIQUES OF INCORPORATING TEXTILE SURFACES WITH ZNO NPS

Applying Zinc Oxide Nanoparticles (ZnO NPs) to textile surfaces has attracted considerable interest recently, owing to the diverse multifunctional attributes of ZnO NPs, such as their antimicrobial, UV-blocking, and self-cleaning properties. Various techniques have been established to apply ZnO NPs to textile surfaces, with each method presenting distinct benefits and drawbacks. The integration of ZnO nanoparticles into textile fabrics can be achieved through various techniques, and the most commonly used coating methods are explained below, each influencing the durability, uniformity, and functionality of the final product:

1. **Sol-Gel Process**: This method features the hydrolysis and condensation of zinc precursors like zinc acetate or zinc nitrate to create a sol, which is then applied to the textile surface. The sol is later gelled and calcined to yield ZnO nanoparticles. The sol-gel process facilitates a uniform coating and strong adhesion of ZnO nanoparticles to the textile surface.
2. **Electrostatic Self-Assembly (ESA) Technique:** This approach takes advantage of the electrostatic attraction between positively charged ZnO nanoparticles and negatively charged textile fibers. ZnO nanoparticles are suspended in a solvent and then applied to the textile surface utilizing an electrostatic field. The ESA technique is straightforward, cost-effective, and applicable for coating textiles with complex geometries.
3. **Layer-by-Layer Assembly (LbL):** This method involves applying layers of negatively charged polyelectrolytes and positively charged ZnO NPs alternately to the textile surface. By precisely controlling the coating's thickness and composition, the LbL technique makes it possible to create multifunctional coatings with specialized qualities.
4. **The Pad-Dry-Cure Method:** It is a traditional textile finishing technique that involves padding a ZnO NP dispersion over the textile surface, then drying and curing it. Because of its ease of use and scalability, the pad-dry-cure method is frequently employed in industry; yet, to guarantee long-lasting coated textiles, it may require additional binders or fixing agents (54).
5. **Plasma-Enhanced Chemical Vapor Deposition (PECVD):** This method uses plasma-enhanced chemical vapor deposition to deposit ZnO NPs onto textile surfaces. PECVD makes it possible to produce uniformly thin coatings that adhere well and do no harm to the textile substrate.
6. **Hydrothermal Method**: This technique uses a hydrothermal reaction to create ZnO NPs on the textile surface in situ. Although high temperatures and pressures may be necessary, the hydrothermal approach enables the production of highly crystalline ZnO NPs with regulated morphology and size.
7. **Ultrasonic-Assisted Coating**: In this technique, ZnO NPs are dispersed in a solvent using ultrasonic waves, and then they are coated onto the textile surface. ZnO NPs may be efficiently and uniformly deposited by ultrasonic-assisted coating, particularly on intricate textile geometries.
8. **In Situ Synthesis:** ZnO nanoparticles are synthesized directly on or within the textile fibers by applying precursor solutions, followed by chemical reactions that generate nanoparticles in situ, leading to strong bonding and enhanced durability (55).
9. **Spraying:** A nanoparticle suspension is sprayed onto the fabric surface, suitable for post-treatment processes and selective application, especially in textile finishing (56).

The type of textile substrate, the desired qualities of the coated textile, and the process's scalability and cost-effectiveness all influence the coating method selection. Each of these approaches has advantages and disadvantages of its own. To improve these strategies and create fresh approaches for applying ZnO NPs to textile surfaces, more research is being conducted.

As it is observed from **Figure 2** ,SEM is used to examine the ZnO nanoparticles coated with the PFW surface; particle aggregation is visible. However, generally speaking, the suggested coating technique can achieve a continuous, comparatively uniform covering of the ZnO particles. Given that inadequate coating of photocatalyst particles on fabric surfaces is frequently observed, this finding is encouraging (57, 58). Additionally, the ZnO particle layer can be created on the PFW fibers' surface by employing the suggested coating technique. Unlike with photocatalyst treatment of fabrics, there is no film forming between the fibers. The photocatalyst particles will readily be released into the solution system because the photocatalyst film that forms between the fibers is prone to breaking. When it comes to coating photocatalyst particles on the surface of fabric, there are two primary problems: (i) inadequate coating with an uneven distribution of coated particles, and (ii) photocatalyst film cracking. To solve it, the applied coating, which is the aqueous heat attachment method’s parameters should be adjusted.

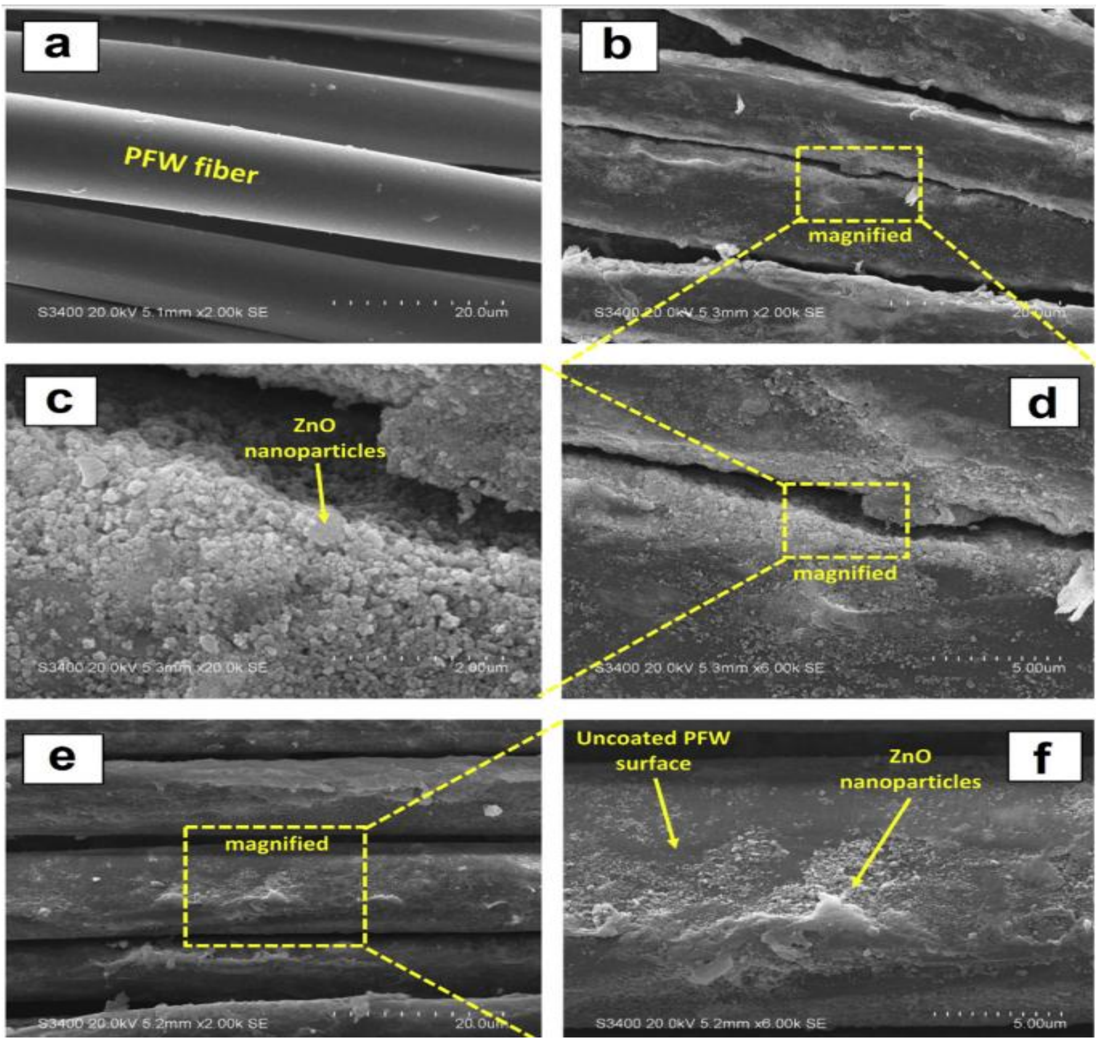


Figure 2.SEM images of PFW (a), ZnO/PFW(b-d), and ZnO/PFW after 6th cycle(e-f). Reprinted from (59).

5.4 ADVANTAGES OF INCORPORATING ZNO NANOPARTICLES INTO TEXTILES

ZnO nanoparticles can be incorporated into textile fibers to provide long-lasting antibacterial and UV protection without seriously sacrificing the fabric's natural qualities, such as breathability and comfort. Additionally, the nanoscale size enables deep penetration into fiber matrices and uniform coating, guaranteeing continued functionality during several washing cycles. ZnO's cost-effectiveness, chemical stability, and environmental friendliness all contribute to its appropriateness for widespread healthcare textile applications. Integrating ZnO nanoparticles into healthcare textiles offers numerous benefits that enhance the functionality, safety, and durability of the fabrics. The key advantages include:

- **Enhanced Antimicrobial Efficacy:** Broad-spectrum antibacterial action against viruses, fungi, and bacteria is demonstrated by ZnO nanoparticles. They effectively inactivate microorganisms by producing reactive oxygen species and releasing zinc ions, which lowers the risk of contamination and infections in healthcare settings (60).
- **UV Protection:** Textiles benefit from ZnO nanoparticles' superior UV-blocking qualities because of their potent UV absorption ability. This lessens skin damage and associated health problems by protecting patients, healthcare professionals, and outdoor users from damaging UV radiation (61).
- **Durability and Washability:** When properly incorporated, ZnO nanoparticles can withstand multiple washing cycles without significant loss of functionality, ensuring long-term antimicrobial and UV-protective effects (62).
- **Cost-Effectiveness and Scalability:** The synthesis of ZnO nanoparticles via cost-efficient methods such as sol-gel, combined with their widespread availability, allows for scalable production suitable for large-scale textile manufacturing.
- **Chemical Stability and Safety:** ZnO nanoparticles are chemically stable under various environmental conditions and are considered safe for human contact, especially when embedded within textile fibers. Their biocompatibility makes them suitable for personal healthcare products (63)
- **Environmental Benefits:** ZnO is less harmful to the environment than other metal-based nanoparticles, and its application in textiles can lessen the need for chemical disinfectants, promoting more ecologically friendly medical procedures.

- **Improved User Comfort:** Nanoparticle coatings can be designed to be lightweight and unobtrusive, maintaining fabric breathability and comfort while providing advanced functionalities.

6. ANTIMICROBIAL PROPERTIES OF ZINC OXIDE NANOPARTICLES

Antibacterial textiles, especially cotton-based ones, are in greater demand as a means of preventing microbial growth, which can cause fabric deterioration and hygiene problems (64, 65). Researchers have postulated several potential bactericidal processes, including the idea that smaller NPs have quicker cell penetration and more surface reactivity, which releases Zn^{2+}. One of the key ideas in antibacterial mechanisms is the release of Zn^{2+} from ZnO NPs, which is known to suppress several bacterial cell functions, including active transport, bacterial metabolism, and enzyme activity. The bacterial cell was then killed by the toxicity of Zn^{2+} on its biomolecules (66, 67). The attachment of NPs to the bacterial cell membrane by electrostatic forces is another potential mechanism for ZnO NPs' antibacterial action. ZnO NPs' positive zeta potential facilitates their adhesion to negatively charged bacterial cells, allowing them to enter the cells (68). The bacterial cell integrity may be harmed by this interaction, which could disrupt the plasma membrane structure and cause intracellular contents to leak out, ultimately leading to cell death (69). Furthermore, the buildup of ZnO within the cell disrupted the bacteria's metabolic processes, which ultimately resulted in their demise. **Error! Reference source not found.** depicts the mechanism of ZnO NPs' antibacterial activity. As a result, the aforementioned bactericidal processes offer superior modes of action in contrast to the propensity of traditional therapeutic medicines to produce microorganisms that are resistant to several drugs.

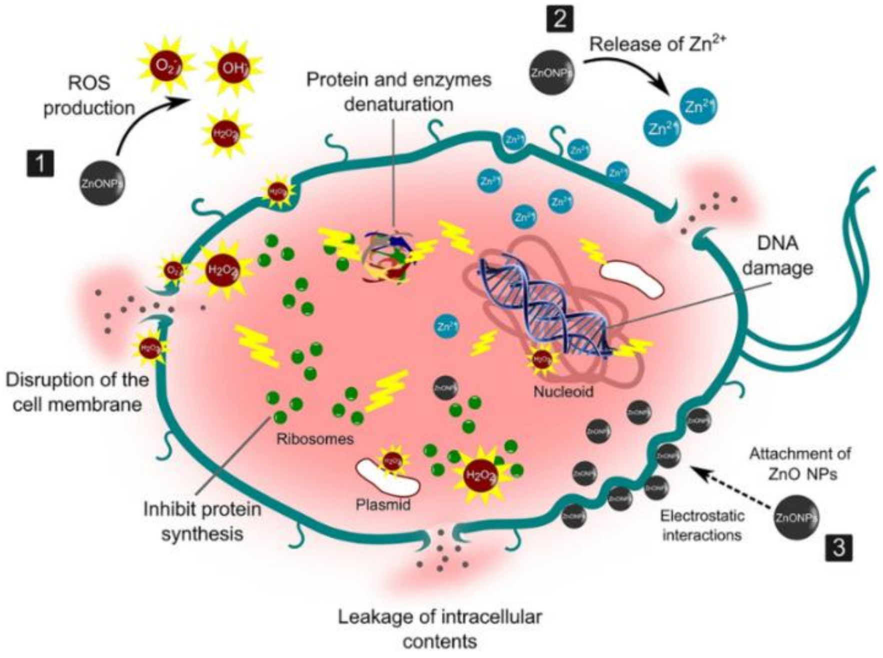


Figure 3. Diagrammatic representation of ZnO NPs' antibacterial action on bacterial cells. Adapted from (70).

The three ways that ZnO NPs work as an antimicrobial agent are (i) by generating reactive oxygen species (ROS), which causes oxidative stress and damage to the membrane and DNA, ultimately leading to bacterial death; (ii) by dissolving into Zn2+, which disrupts the metabolism of enzymes, amino acids, and proteins in bacterial cells; and (iii) by directly interacting with the cell membrane through electrostatic forces, which damages the membrane plasma and results in intracellular content leaks

The antimicrobial activity of NP-ZnO combined with the poly-hydroxy-amino methyl silicone (PHAMS) binder on the surface of cotton textile fabric demonstrated a 95% to 99.9% reduction against Staphylococcus aureus (a Gram-positive bacterium) and Klebsiella pneumoniae (a Gram-negative bacterium), regardless of how ZnO and PHAMS were applied. This required a minimum of 4% PHAMS and 3% NP-ZnO or 4 to 8% PHAMS and 1% NP-ZnO; both produced comparable results about microbial reduction tests according to AATCC 147

Figure **4.** (a) Growth of Staphylococcus aureus and Klebsiella pneumonia in control fabric; (b) Absence of Staphylococcus aureus and Klebsiella pneumonia in 4% poly-hydroxy-amino methyl silicone (PHAMS) and 5% zinc oxide (ZnO)-treated fabric;.

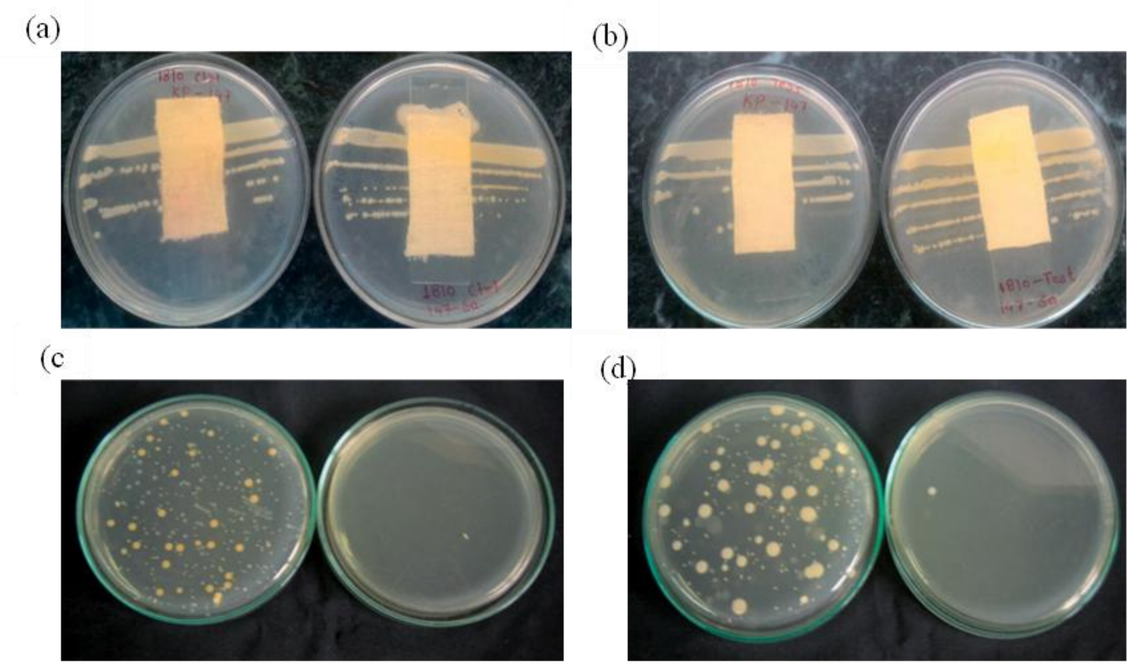


Figure 4. (a) Growth of Staphylococcus aureus and Klebsiella pneumonia in control fabric; (b) Absence of Staphylococcus aureus and Klebsiella pneumonia in 4% poly-hydroxy-amino methyl silicone (PHAMS) and 5% zinc oxide (ZnO)-treated fabric; (c) Reduction in Staphylococcus aureus after 24 hrs of incubation in 4% PHAMS and 5% ZnO-treated fabric; (d) Reduction in Klebsiella pneumonia after 24 hrs of incubation in 4% PHAMS and 5% ZnO-treated fabric. Adapted from (71).

The potential for NP-ZnO to combine with moisture and generate a Zn di-hydroxide or a Zn tetra-hydroxide solution is recognized as the cause of ZnO's antibacterial action. This produces OH & H^+, which releases HO_2 gradually. When dissolved oxygen and free radicals mix, hydrogen peroxide (H_2O_2) is created (72). This can pass through microbial cell membranes, killing the bacteria with the resulting active oxygen species, enhancing the UPF factor, and providing a photo-catalysis action of zinc oxide. The bacterial effect increases with the surface-to-volume ratio, and this leads to NP-ZnO showing better results than regular ZnO. Furthermore, NP-ZnO is rougher and more abrasive than bulk ZnO because of its large surface area. Thus, it increases the antibacterial efficacy of NP-ZnO and produces more mechanical damage to the microbial cell membrane (73, 74).

Table 2. Effect of ZnO-NP on UV-Protection and bacteria growth of cotton fabric (71)

Experiment no.	**Treatment (%) (owf)***	**UPF%**	**Bacterial reduction%**(AATCC-100)**	
			Klebsiella pneumonia AATCC 4352	**Staphylococcus aureus AATCC 6538**
1	Untreated fabric	5	0	0
2	2% PHAMS	5	0	0
3	4% PHAMS	5	95.5	96.2
4	6% PHAMS	5	99.3	97.3
5	8% PHAMS	5	99.95	99
6	10% PHAMS	5	99.9	99.3
7	2% PHAMS and 1% ZnO	10	0	0
8	4% PHAMS and 1% ZnO	10	93.6	95.9
9	6% PHAMS and 1% ZnO	5	95.0	96.4
10	8% PHAMS and 1% ZnO	5	95.1	97.09
11	10% PHAMS and 1% ZnO	5	96.7	98.9
12	4% PHAMS and 3% ZnO	15	99.9	99.5
13	4% PHAMS and 5% ZnO	20	99.9	99.9
14	4% PHAMS and 8% ZnO	10	99.9	99.9
15	4% PHAMS and 10% ZnO	10	99.9	99.9
16	8% PHAMS and 3% ZnO	5	99.9	99.9
17	8% PHAMS and 5% ZnO	15	99.9	99.9
18	5% ZnO	10	75.61	88.94

Where: *All treatment percentages are determined based on the dry weight of the fabric(owf);

** Bacteria reduction percentage means percentage of bacterial growth reduction as compared to the same on untreated (control) cotton fabric; NP-ZnO: zinc oxide nanoparticles; UPF: UV protection factor; PHAMS: poly-hydroxy-aminomethyl silicone; AATCC: American Association of Textile Chemists and Colorists

Table 2. Effect of ZnO-NP on UV-Protection and bacteria growth of cotton fabric (71) , shows that increasing the ZnO-NP percentage from 1 to 5% (max) while maintaining a constant PHAMS (4%) resulted in significant dampening of UV transmission, resulting in a UPF value of 5 to 20 (see trials 3, 8,12,13). Keeping ZnO constant (1%) and increasing PHAMS from 2% to 8% (see experiments 7, 8, 9,10) or without NP-ZnO (see experiments 2, 3, 4,5) results in UPFs of 5 or lower, except in experiments 6 and 7, where PHAMS content is limited to 4% in combination with 1% ZnO-NP. Thus, when PHAMS is less than 4%, UV-blocking capabilities rise as NP-ZnO levels increase. Increasing PHAMS likely masks part of the active ZnO, lowering the UPF. The combination of ZnO and PHAMS offers both UV protection and antibacterial properties, while UV protection is lower (under 20; a UPF of 15 to 24 is regarded as satisfactory)

Using a 4:1 weight ratio of 4% PHAMS and 1% NP-ZnO results in a well-balanced product with a UPF value of 10 and microbiological reduction of 93.6% and 95.9% against Staphylococcus aureus and Klebsiella pneumoniae growth, respectively, according to AATCC 100 testing. Using 4% PHAMS and 5% NP-ZnO powder (60% 30-500 nm) results in a UPF of 20 and a 99.9% reduction in germs, making it a viable choice. Previous research (Burcin 2012) (74), suggests that using a polystyrene-block-polyacrylic acid copolymer as a dispersion medium and binder, along with NP-ZnO powder, results in an excellent mix of UPF and antimicrobial properties at a 4:1 ratio.

7. BIOCOMPATIBILITY AND CYTOTOXICITY OF ZNO NANOPARTICLES

Nanoparticles add important practical qualities to textiles while preserving their elasticity. Nano textiles are used now in a number of industries, including protection, sports, and healthcare. Although nanotechnology is seen to have the potential to significantly alter the state of technologies today, there are worries about how it will affect people and the environment. The first section establishes the fundamentals of nanoparticle toxicology while emphasizing the need for further research to thoroughly describe nanoparticles and their interactions, bioactivity, and potential hazards to both people and the environment. The need for procedures covering and measuring nanoparticles is highlighted by the current regulations on nanomaterials in textiles, such as REACH (Registration, Evaluation, Authorization, and Restriction of Chemicals), EPA (Environmental Protection Agency), and OSHA (Occupational Safety and Health Administration). Additionally, it takes into account the incorporation of green nanotechnology, offers guidelines for the safe application of nanotechnology to eliminate adverse environmental effects, and recommends the use of recyclable and natural materials (75).

Although the focus on the environmental advantages and sustainability of zinc oxide (ZnO) nanoparticles in healthcare textiles is valid, it is equally important to take into account their toxicity and safety profiles to guarantee responsible use. Numerous investigations have brought to light possible issues with ZnO nanoparticles' cytotoxicity and biocompatibility, especially when they are utilized in consumer goods that have extended skin contact. For example, there are concerns over the safety of ZnO nanoparticles in medical and personal care applications because some research indicates that they can cause oxidative stress and inflammation at the cellular level (76).

Furthermore, ZnO nanoparticles' toxicity profiles are greatly influenced by their size, shape, concentration, and surface coating, which calls for careful risk evaluations catered to particular applications (77). Standardized testing procedures are still developing, though, and there aren't many thorough long-term studies. In order to reduce any possible health hazards related to ZnO nanoparticles, researchers and producers are urged to carry out thorough biocompatibility evaluations, including in vitro and in vivo toxicity investigations. Furthermore, surface alterations and encapsulating techniques are being investigated to lessen the toxicity and bioavailability of nanoparticles while preserving their functional characteristics (78).

To sum up, in order to convert laboratory discoveries into safe, sustainable, and financially feasible medical goods, safety, toxicity, and regulatory factors must be incorporated into the creation of textiles based on ZnO nanoparticles. Standardized safety evaluations and regulatory compliance should be given top priority in future studies to promote responsible innovation in this exciting area.

8. APPLICATIONS AND FUTURE PERSPECTIVES

Zinc oxide (ZnO) nanoparticles are currently receiving a lot of attention in the textile industry because of their strong antibacterial capabilities, UV protection capabilities, and chemical stability. Because of these properties, ZnO nanocomposites are especially well-suited for healthcare fabrics that need to be UV-shielding and infection-controlling, such as hospital linens, wound dressings, and sportswear. The trend of publications related to "antimicrobial textiles" and "UV-protective textiles" in Scopus over the past 20 years (1999-2018) has been increasing. In order to show the scientific development of Antimicrobial Resistance research and its tendencies, **Figure 5** employs modeling, a machine learning technique, and offers an interactive user interface for additional analysis. A flexible, economical, and eco-friendly way for creating ZnO nanoparticles with regulated size and shape that improves their incorporation into textile substrates without sacrificing fabric comfort or breathability is the sol-gel synthesis process (79). With continuous developments in material engineering and nanotechnology, the future of ZnO-based healthcare textiles is bright. In order to provide ZnO nanoparticles with more characteristics, including anti-inflammatory effects, increased biocompatibility, and longer-lasting antibacterial action, recent research is concentrating on functionalizing them with other bioactive chemicals. Another promising area is the creation of smart fabrics that react to environmental cues, such as UV exposure or bacterium detection, to release antimicrobial chemicals (80). Additionally, initiatives are being made to improve the environmental sustainability of the synthesis of nanoparticles, such as the use of eco-friendly stabilizers and green solvents in the sol-gel process. These developments may result in the creation of multipurpose, highly effective healthcare textiles for a range of uses, such as wound healing, PPE, and everyday clothing with built-in UV protection. ZnO nanoparticle incorporation into recyclable and biodegradable textiles supports global sustainability objectives and holds out the possibility of more efficient and ecologically conscious healthcare textiles in the future (81).

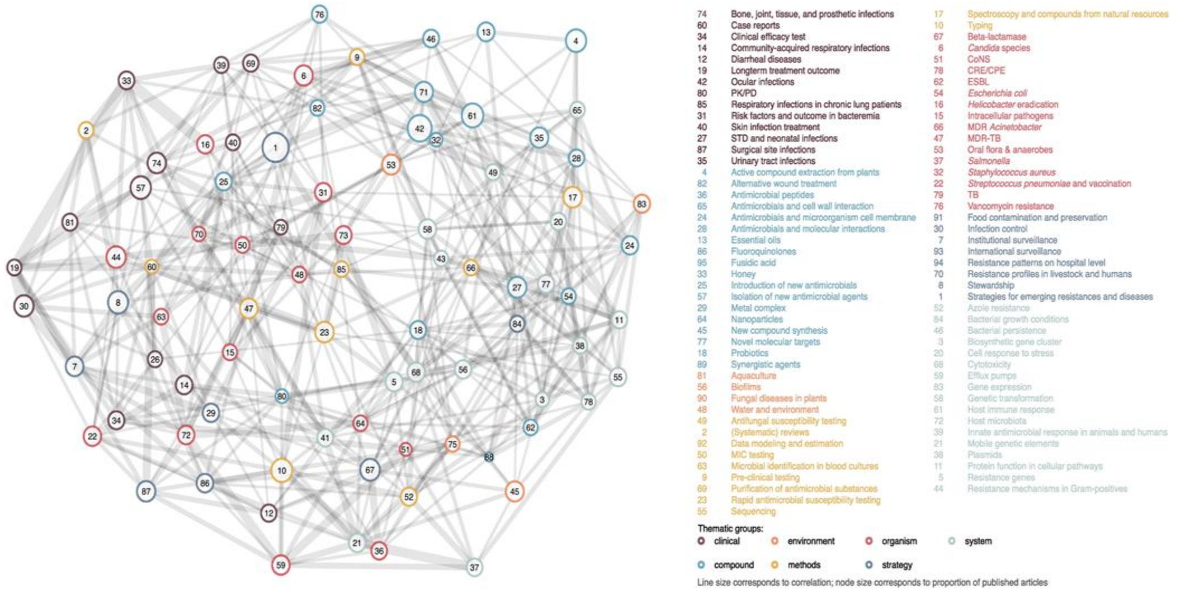
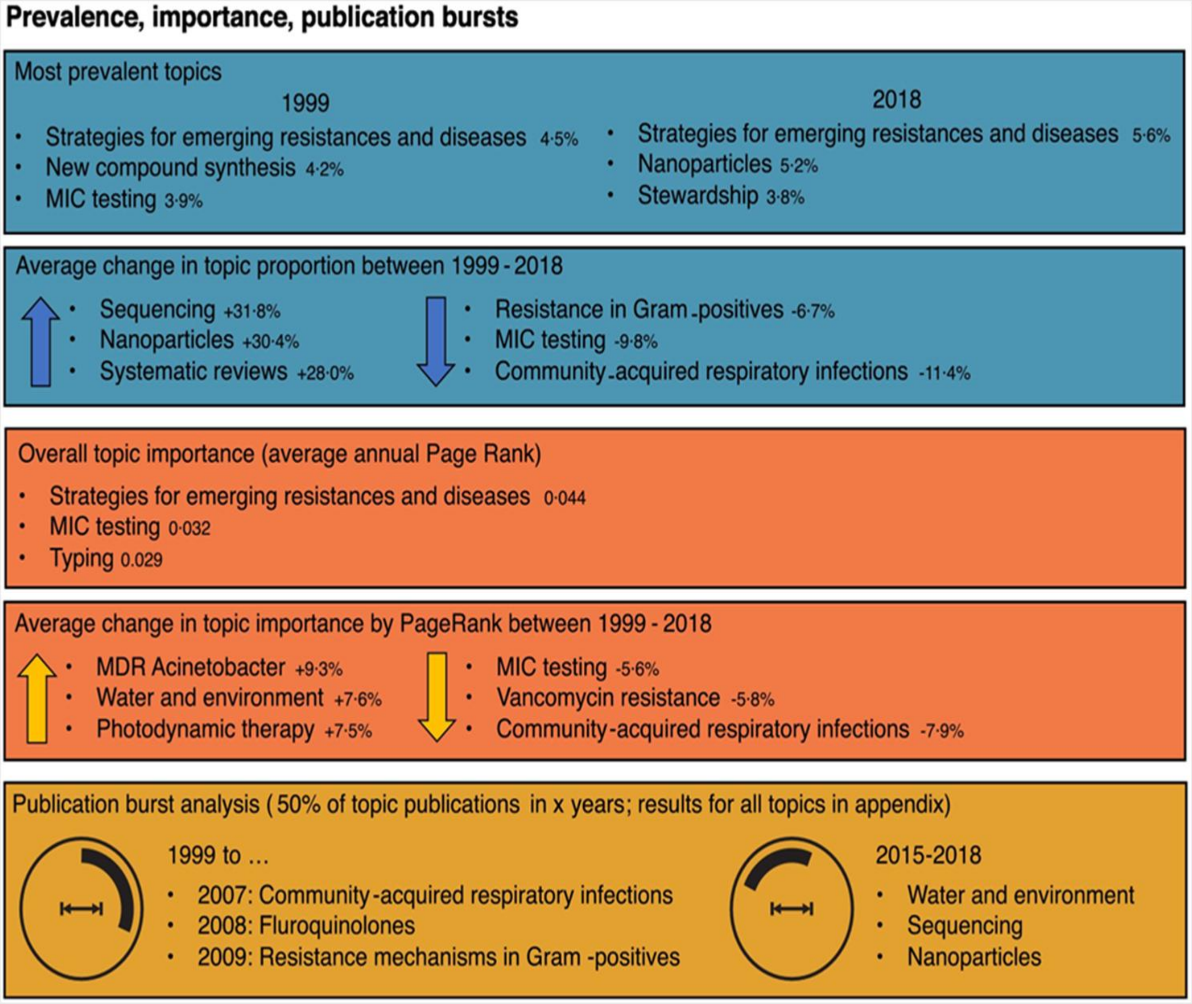


Figure 5. Topic network in antimicrobial resistance research based on topic co-occurrence generated. Adapted from(82)



Prevalence, importance, publication bursts

Most prevalent topics

1999
- Strategies for emerging resistances and diseases 4·5%
- New compound synthesis 4·2%
- MIC testing 3·9%

2018
- Strategies for emerging resistances and diseases 5·6%
- Nanoparticles 5·2%
- Stewardship 3·8%

Average change in topic proportion between 1999 - 2018

- Sequencing +31·8%
- Nanoparticles +30·4%
- Systematic reviews +28·0%

- Resistance in Gram-positives -6·7%
- MIC testing -9·8%
- Community-acquired respiratory infections -11·4%

Overall topic importance (average annual Page Rank)

- Strategies for emerging resistances and diseases 0·044
- MIC testing 0·032
- Typing 0.029

Average change in topic importance by PageRank between 1999 - 2018

- MDR Acinetobacter +9·3%
- Water and environment +7·6%
- Photodynamic therapy +7·5%

- MIC testing -5·6%
- Vancomycin resistance -5·8%
- Community-acquired respiratory infections -7·9%

Publication burst analysis (50% of topic publications in x years; results for all topics in appendix)

1999 to …
- 2007: Community-acquired respiratory infections
- 2008: Fluroquinolones
- 2009: Resistance mechanisms in Gram -positives

2015-2018
- Water and environment
- Sequencing
- Nanoparticles

9. CONCLUSIONS

Significant improvements in antibacterial activity and UV protection are possible when ZnO nanoparticles synthesized using the sol-gel process are incorporated into healthcare textiles. The sol-gel method offers a regulated, environmentally responsible way to create superior nanoparticles. Effective application methods produce long-lasting textiles suitable for a range of medical uses, promoting skin safety and infection prevention. These sophisticated fabrics will be widely used in clinical and commercial settings as a result of ongoing research centered on environmental safety, scalability, and regulatory compliance. Generally, this review highlights the potential benefits of ZnO nanoparticles in the treatment of antimicrobial and UV-protective healthcare textile fabric materials and indicates that further study in this field may result in the creation of more complex and functionalized materials that take sustainability into account.

HIGHLIGHTS

- The review highlights the benefits of the ecologically friendly and adaptable sol-gel approach for managing particle size, shape, and purity when discussing the synthesis of ZnO nanoparticles.
- ZnO NPs greatly enhance textiles' antibacterial capabilities against a variety of diseases, such as bacteria and fungi, making them appropriate for use in medical settings.
- The paper emphasizes how ZnO NPs give textiles superior ultraviolet (UV) shielding properties, hence lowering the transmission of damaging UV radiation, which is crucial for patients and healthcare professionals.
- A thorough examination of the sol-gel process reveals its advantages, which make it the perfect technique for textile functionalization. These advantages include low processing temperatures, consistent nanoparticle distribution, cost-effectiveness, and environmental sustainability.
- The analysis highlights how these nanocomposite textiles can improve safety and hygienic standards in a variety of healthcare textiles, such as hospital linens, protective gear, and wound dressings.
- The practicality of the functionalized fabrics is highlighted in the research by discussing how long the antibacterial and UV-protective qualities last after several washing cycles.

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