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Enhancing The Functional Performance of Medical Scrubs FabricsUsing Nanotechnology: A Review

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Abstract

Nanotechnology has emerged as a transformative technology in the enhancement of medical scrub fabrics, improving their functional properties to meet the demanding needs of healthcare professionals. Nanotechnology, which functions at the molecular level (1 nm to 10 nm), makes it possible to incorporate cutting-edge materials into scrub fabrics, which significantly boosts performance. These scrubs can effectively eradicate bacteria, viruses, and fungi upon contact by combining silver nanoparticles with other antimicrobial agents, which helps to prevent the spread of infections in healthcare environments. Additional functional improvements include the ability to self-clean, resist wrinkles, and be anti-static. All of which make hygiene and maintenance simpler. Furthermore, by applying waterproof coatings at the nanoscale, which cause liquids to bead up and roll off rather than be absorbed, nanotechnology has made it possible to create scrubs that are resistant to moisture. This prolongs the scrubs' lifespan and improves healthcare personnel comfort throughout extended shifts. The ZnO, TiO2, and CuO nanoparticles were low toxicity and environmentally beneficial qualities only serve to increase their allure. Overall, the protective, hygienic, and functional qualities of medical textiles, especially medical scrubs, have been enhanced by nanotechnology, making them more suitable for the demanding conditions of contemporary healthcare settings.

Keywords: Scrub Fabrics, Medical Textiles, Antimicrobial, Technical Textile, Nanotechnology.

1. Introduction

Doctors and medical staff are exposed to potential infections from patients, which can spread to their families and others. Traditional textiles in the medical field are insufficient to protect doctors and their staff, as they wear their own clothes for extended periods [1]. Technological advancements have led to the use of functional technical textiles as a safe means of prevention and protection from infection. Antimicrobial fabrics have gained attention due to their ability to reduce infection transmission in medical and healthcare environments [2]. In hospitals, clinics, and other healthcare settings, medical personnel must wear medical scrubs as a matter of course. Medical scrubs are meant to be a practical and comfortable uniform that encourages hygienic practices, professionalism, and cleanliness [3]. Medical scrubs must reduce the spread of bacteria and other contaminants, helping to maintain a sterile atmosphere. They also make it possible for medical staff to move around and perform their duties without discomfort from constricting apparel [4].Medical technical fabrics are considered a development For traditional fabrics to be high-performance and with additional properties, and the technical medical textiles sector is still a very small sector compared to other sectors of the textile industry in Egypt [5-6]. Antimicrobial fabrics have received great attention in recent years due to their ability to reduce infection transmission in medical and health care environments. They are functionally active smart textiles, which may kill microorganisms or inhibit their growth [7]. Antimicrobial properties can also enhance the performance and sustainability of consumer products. Microbes thrive in warm, moist environments. Moist fabrics worn or in contact with skin in warmer climatic conditions can often be a contributing factor to the spread of infection [8].Antimicrobial fabrics using nanotechnology provide additional properties such as protection against stains and extending the shelf life of the product. The treatment materials used for antimicrobial resistance of textiles are selected based on the type of fiber, processing conditions and the type of protection required [9]. Nanotechnology is used to treat doctors' scrubs fabrics to be resistant to fluids to reduce the spread of microbes and protect them from potential infection, and based on the importance of using different structural structures, textile materials, and treatments that help make the scrub more resistant to fluids and microbes and at the same time has the ability to breathe (air permeability and absorption perspiration) during the practice of work [10-11]. Therefore, the research aims to improve the properties of doctors' scrubs fabrics to resist fluids and

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microbes using nanotechnology and to suit daily use, to be highly technologically sustainable, and to achieve the best functional properties to protect doctors and those in contact with them from microbial diseases.

2. Medical Scrub fabrics

Medical Scrub uniforms are known as traditional suits worn by healthcare staff in different departments of hospital , especially in emergency and operating room (OR) It is often referred to as 'pajamas' and is worn underneath the surgical gown. It is made up of pants and a shirt like figure (1). Scrub suits manufacture with woven fabrics technique [5-6]. According with the Association of Operating Room Nurses, promote high-level of Cleanness and hygiene within the practice setting in the operating room (O.R.). Inside of OR, Thermal comfort of medical clothing scrub is a very serious parameter, since the lack of Comfort can lead to thermal stress that enhancing the physic and psychological conditions of The surgeon, as the ability to maintain constant vigilance and concentration of which, the Correct surgical procedure is dependent [12]. The thermal comfort of medical scrubs users depends, among many other things, on thermal insulation and how it is adjusted to clinics, emergency and the operating room's environmental conditions during the work shifts, as well as design, size, and fabric characteristics [13].

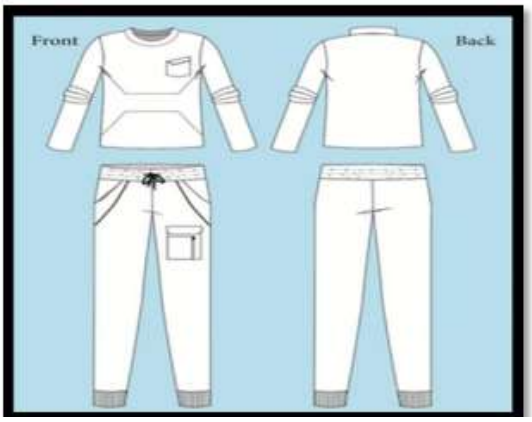

Figure 1.Medical scrub [6].

The fabrics of medical Scrubs in emergency and clinics also need special specifications to prevent the transmission of infection between medical staff and patients, which results in the transfer of various fluids and substances (blood, urine, stool, vomiting, and sputum) from patients to scrubs easily, and microbes are transmitted to them and cause microbial infections for doctors and those around [14]. The Low rate of technological sustainability of medical scrubs fabrics as a result of the poor quality of the materials used or the weakness of the treatments that are carried out on these fabrics [15]. The fabrics of med scrubs, which are available in the Egyptian market, are not suitable for daily use, and they do not absorb sweat well, which causes a feeling of inconvenience during work [6-16].It draws attention to important problems with medical scrub fabrics, highlighting the need for higher quality and more sophisticated treatments to improve comfort, functionality, and hygiene. Enhancing sweat absorption and preventing infections are critical for healthcare workers' health and productivity, particularly in high-stress settings like operating rooms.

2.1 Types of Medical Stuff Uniforms

a. Scrubs: General scrubs are worn by healthcare workers including doctors and nurses. They come in an assortment of hues and styles that signify different departments or functions. For usage in certain fields such as surgery, paediatrics, or obstetrics [17].
b. Surgical gowns: To keep the operating room sterile and reduce the danger of infection, surgeons and their assistance dress in sterile gowns during procedures [18].
c. Laboratory Coats: Doctors, researchers, lab technicians, and chemists wear them because they offer an additional layer of protection and can hold documents and tools [19].
d. Paediatric Uniforms: To help kids feel at ease and welcomed staff personnel in paediatric wards should dress in colourful or patterned lab coats and scrubs [20].
e. Nursing Dresses /Uniforms: There are still hospitals that utilise the classic nursing uniform, which usually consists of an apron, frock, and cap [21].
f. Uniforms for Emergency Medical Services (EMS): For safety, emergency personnel should dress in effective, functional uniforms with plenty of high-visibility components [22].
g. Uniforms for Support Staff: Staff uniforms, practical and professional, consist of blouses, polo shirts, skirts, or trousers, worn by those in administration, housekeeping, maintenance, and food service [23].

2.1.1 Sortof Medical Textiles by Using

Disposable medical textiles, such as surgical drapes, masks, bandages, gauze, aprons, hats, and shoes coverings, are intended for use and disposal after use, with woven or non-woven textures and different purposes [24].

Reusable medical technical textiles, such as gowns, drapes, and scrubs, have been found to reduce medical waste by an average of 65% in operating rooms and clinics .A study by the American Reusable Textile Association found that reusable surgical gowns have a significant positive environmental impact, including waste management, energy consumption, water use, and greenhouse gas emissions. Additionally, reusable healthcare textiles improve patient care and hospital employee performance[25].

2.1.2 Medical Scrub fabrics Life Cycle

To properly comprehend and assess what constitutes a sustainable textile product and how these items can be manufactured in a more sustainable manner, a comprehensive life cycle analysis of the economic, environmental, and social factors that contribute to textile production is required, textiles have been designated as a priority resource stream that should be diverted from landfill sites at the end of their useful life. The life cycle flow chart (Figure 2) highlights the main areas in which the manufacture, use, and disposal of healthcare uniforms can result in resource and cost savings [26].

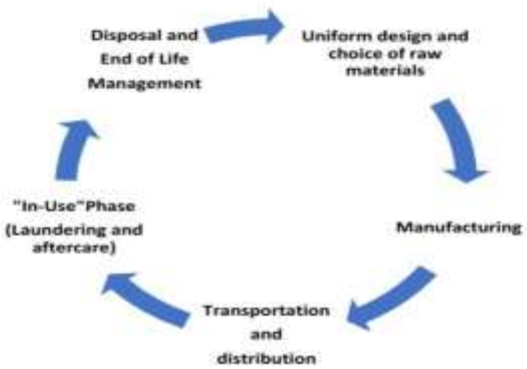

Figure 2.Life cycle flow chart of medical scrub fabrics (uniform) [26].

2.1.3 Innovative Medical Supplies and Personal Hygiene Items

Better bioclimatic and sanitary textiles are becoming more and more necessary for new medical treatments. [27] Examples of these qualities include:

- Skin protection against liquids, dust, and bacteria [28].
- Robust defence against bacteria, fungus, and the associated risk of infection [29].
- Features of thermoregulatory systems [30].
- Absorption of liquids and moisture [31].
- Laundry convenience, sterilisation, and antistatic conduct [26-32].
- Low concentration of dyes and textile compounds with excellent mechanical stability [33].
- Structure, can offer the aforementioned qualities, and they are frequently better than traditional textile materials for medical purpose [34].

2.1.4 Essential Properties of Medical Scrub Fabrics

- Breathability property: Medical scrubs fabrics should allow air circulation to keep the wearer cool and comfortable during long shifts in hospitals [35].
- Durability property: Medical scrubs fabrics undergo frequent laundering, so selecting fabrics with good durability ensures longevity [36].
- Moisture-wicking fabric: This type of fabric keeps the wearer comfortable and dry by removing perspiration from the body [37].
- Stain Resistance property: Considering the nature of the healthcare environments, stain-resistant fabrics are beneficial to maintain a clean appearance [38].
- Comfortable property: The fabric should be soft, non-irritating, and provide ease of movement for healthcare professionals workers [39].
- Environmental Impact: Consider the fabric's eco-friendliness. You can choose fabrics that are in line with your environmental values by choosing those made from sustainable materials or with eco-friendly production techniques. Take into account textiles that are sourced and manufactured in an ethical and socially conscious way. Choosing doctor's scrubs from manufacturers with ethical labour practices contributes to a more sustainable and conscientious supply chain [40].

- Static Resistance property: In environments where static electricity can be a concern, choosing a fabric with anti-static properties can help minimise discomfort and potential hazards for both the wearer and sensitive electronic equipment in hospitals [41].
- Easy to clean property: This fabric can be easily washed and dried, making it convenient for busy medical professionals uniforms who need reliable and practical clothing scrub [42].
- Softness property: The blend of materials used in medical scrubs uniform fabric makes it very soft to the touch, ensuring that the wearer is comfortable all day long [43].
- Affordable: This type of fabric is affordable, making it accessible to medical professionals' workers with varying budgets [44].
- Versatile: Medical scrubs fabric is available in a variety of colours and designs, making it suitable for different uses. It can be used as a uniform fabric in hospitals, clinics, and other healthcare facilities [45].
- Ability to Accommodate a Wide Range of Motion: Healthcare professional's workers are constantly on the move, performing various tasks that require flexibility and a wide range of motion. These need fabrics that have stretch properties, such as spandex blends, to allow unrestricted movement. Medical Scrubs with added stretch will ensure that you can perform your duties comfortably without feeling restricted [46-47].
- Biodegradability: refers to the chemical change in polymers facilitated by living organisms, such as microorganisms, and is crucial for biomedical uses as sutures and tissue engineering. While opinions on a good rate of biodegradation are divided, natural biopolymers are increasingly improving medical staff uniforms [48].
- The Characteristics of Antimicrobial: The Properties of Antimicrobial Materials: As previously, mentioned, antimicrobial materials are particularly useful in medical situations. These fabrics lessen the chance of contamination by inhibiting the growth of viruses and other harmful microbes. If you work in an environment where maintaining sterility is crucial, consider putting on antimicrobial fibre scrubs [49].
- Non-Wettability:A material's ability to allow liquids to stick to its surface, such as that of fibre, yarn, filament, cloth, or non-woven mat, is known as wettability. The most popular test in laboratories to assess a material's wettability is the water contact angle (WCA) test; a material is hydrophilic if its WCA is less than 90} and hydrophobic if it is greater than or equal to 90~ like figure (3). Wettability is important in biomedical applications because it has been shown to affect protein adsorption and, in turn, surface cell adhesion and proliferation. Therefore, the medical scrubs need to be non-wettability to stop the spread of blood and other liquids to the physicians and staff [50-51].

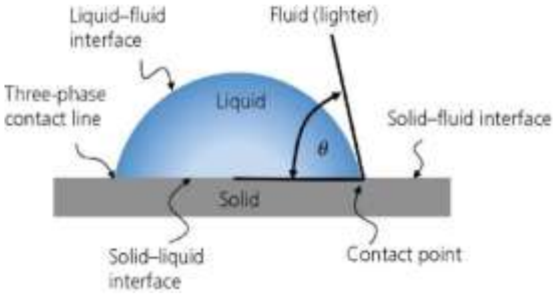

Figure 3.Displays the contact angle (θ) of a sessile drop, illustrating the contact line between the solid and liquid, and assumes the drop axisymmetric with its profile.[51].

Comfort, durability, and functionality should all be balanced in medical scrub textiles, in my perspective. In addition to eco-friendly materials and stretch ability that further improve safety, sustainability, and flexibility for healthcare personnel, features like breathability, antibacterial qualities, and stain resistance are crucial for hygiene and practicality

2.2 Commonly Materials Used for Medical Scrubs Fabrics

- Cotton is a popular material for scrubs due to its soft, breathable, long-lasting, and non-static electricity properties. It is easy to care, wash and iron, and is more cost than polyester blends [5]. Cotton fibers are strong, can withstand high temperatures, sterilization, washing, and ovulating, making them suitable for healthcare, bed, and doctor's uniforms [3-10].
- Polyester is another common scrub fabric, like cotton. It's a powerful, moisture wicking, wrinkle-resistant, and easily maintained synthetic fabric. Cotton and polyester are frequently mixed because of the former's resistance to stretched and shrinking. Polyester Fiber characteristics are high tensile strength, water repellent and quick drying, it has good thermal insulation properties, resistant to wrinkles and creasing, highly flexible ,high resistance to corrosion, resistant to chemicals, good dimensional stability low cost, stretching resistance, easy care and cleaning[3-5].
- Microfibers are a type of textile used in high-performance applications due to their thermo-mechanical, durability, flame, heat, and chemical resistance properties. They are used in medical textiles to improve linear precision and density. Microfibers are typically made of polyester and nylon polymers and are half the diameter of fine silk, cotton, wool, and human hair [5].Synthetic fibers can be converted into microfibers, commonly found in polyester-nylon. These microfibers have superior functional properties, such as higher water absorption due to their increased surface area. Polyester microfiber offers breathability, small diameter, lightweight, and durable clothing. It resists creasing, pilling,

and pilling. It's washable and dry cleanable, and features high-density yarns. The compact construction allows for high durability due to the strength of the threads. It's also suitable for doctor's clothing [20].

- Nylon fiber, a synthetic linear polyamide, is a commercially produced fiber made of repeated hydrocarbon chains linked by amide bonds. It is converted into yarn through melt spinning. Due to its polar groups, it absorbs moisture in healthcare applications [5].Nylon fibers offer durability, tensile strength, and are used in protective clothing, water resistance, and mold resistance. They are flexible, lightweight, and water-resistant [22-52].
- Spandex Often known as "stretch cloth," spandex is a synthetic fibre. Because spandex stretches but returns to its original shape when the garment is taken off, it prevents bagging and sagging [18].Compared to cotton scrubs, spandex scrubs are more stain-resistant and antiperspirant [22].
- Rayon is a silky, airy, breathable, and absorbent fabric with a look and feel similar to silk, cotton, and linen. The main benefit of rayon scrubs is that they are less expensive while still possessing the same qualities as a cotton blend [10].

These materials were chosen for medical scrubs because they provide a balance between comfort, toughness, and usefulness. Because of their distinct qualities, each material can withstand the difficult conditions found in healthcare settings.

2.3 Medical Scrubs Fabrics Structure

The woven structures that are employed in making the medical scrub fabrics as in twill or plain weave affect some characteristics of the fabrics, for instance, strength, and durability as well as texture and widely used types of weave construction, which does not hamper the aesthetic value, and serviceability of the fabric is commonly known as plain weave [34]. Its design is more complicated but its materials are more durable and strong, and it lets in a little easily to improve its usefulness. One side has an extremely fine feel, which creates a glossy, smooth surface. These delicate materials might not be used for scrubs, but they could be added to some medical apparel styles to make them seem more advanced over time. The feel, life, and even wear of the fabric are all determined by these woven structures, which is especially important for scrubs worn in demanding medical environments [5].

2.4 Impact of Contamination on Medical Scrub fabrics

Medical scrubs are crucial for preventing infection spread in medical environments. However, improper management can lead to contamination, allowing pathogens like germs, viruses, and fungus to spread. Contaminated scrubs can also contribute to healthcare-associated infections (HAIs), which can be fatal in rare cases. Scrub cleanliness mistakes are a major cause of HAIs, which can occur in patients or staff members [53]. Scrubs can spread antibiotic-resistant pathogens, posing health risks in hospitals. Contamination can accelerate the spread of these bacteria. Laundry challenges are also significant, as some diseases may not be completely eradicated. Healthcare facilities are implementing stricter scrub policies, including limiting use outside the workplace, requiring regular changes, and improving laundry protocols [54].

2.5 Evidence of Microbial Activity on Medical Scrubs

Research has repeatedly shown that in healthcare settings, medical scrubs are contaminated with harmful microorganisms, including drug-resistant forms. Even after a single shift, scrubs can get extremely contaminatedwith patient microorganisms, increasing the risk of transmission [54]. Some bacteria can survive on scrubs due to inadequate laundry, which can lead to the spread of illnesses linked to healthcare. Extended wear and incorrect handling are two factors that increase the microbial load on medical garments. Cutting-edge antimicrobial fabric treatments present a viable way to stop the growth and transmission of pathogens through medical scrubs fabrics [55]

2.6 Infection Control

In the healthcare places, infection control is very important for all. It prevent the infection from spreading for all people.

2.6.1 Pathogenic Microorganism's

In places, where good hygiene is necessary—particularly in hospitals—infection control is becoming an increasingly pressing issue. It is well recognized that bacteria, viruses, and fungus are examples of microorganisms that cause and worsen issues in hospitals and other environments by spreading illnesses and infections through bedding, clothes, and other materials. Because of their illnesses, hospitalized patients are more likely to get infected, and HAIs are among the top 10 causes of mortality [54]. Antibiotic-resistant microorganisms arise from wrong or overuse of the drugs, which causes them to adapt. When an antibiotic is no longer able to kill bacteria, they are said to be resistant to it. It should be mentioned that fungi live at ph 4.0–6.5 and bacteria at ph 7.0–8.0 on average. In textile fabrics, fungal growth occurs more quickly when the relative humidity is higher than 80%. Thus, under typical usage and storage settings, microorganisms cause damage to fibres and are present in large amounts on textile materials [56]. They also spread illnesses and infections.A comprehensive list of harmful microorganisms may be found in figure (4).

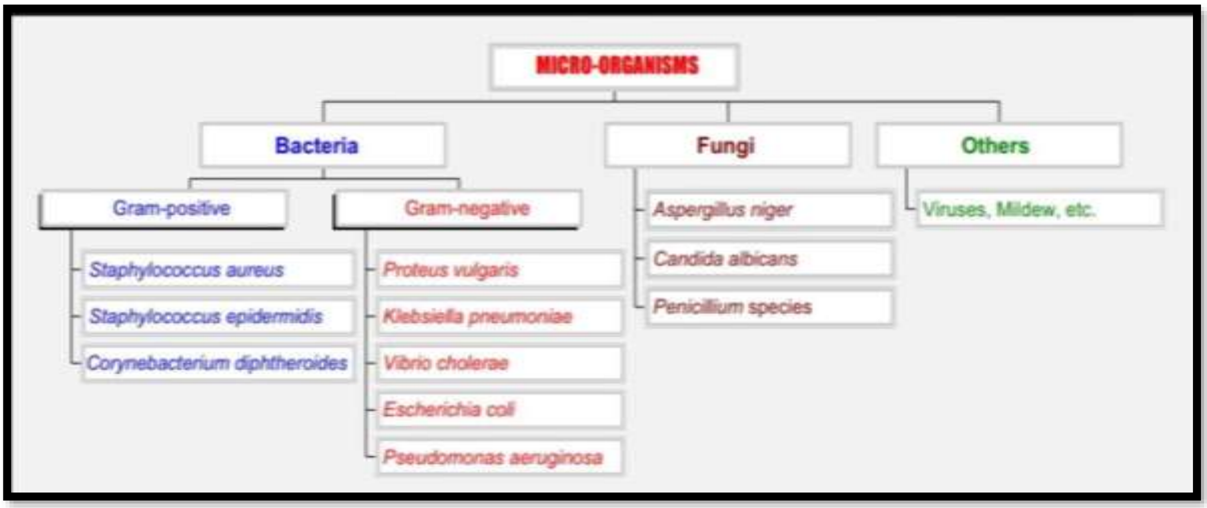

Figure 4. Classification of Microorganisms [57].

3. The Nanotechnology in Medical Textiles

Nanotechnology is playing a crucial role in designing smart fabrics, allowing for the alteration, synthesizing, and engineering of biological, chemical, and physical characteristics of materials. Advances in nanotechnology have opened up significant challenges and opportunities in the textile industry, with nano textile materials showing immense potential for advanced applications. Nanoscience, the study of structures and particles on nanometer scales, is utilizing nanoparticles and nanomaterials in advanced products, including nano-sensing finishes and materials for high-end applications [58].

3.1. Techniques for Using Nanoparticles in Textile

The following are some techniques for applying nanoparticle coating on doctor's scrubs in order to provide superhydrophobic qualities:

- Sol-Gel Process: The fabric is treated with a solution containing hydrophobic nanoparticles, such as titanium dioxide or silica. As it dries, the gel creates a layer that improves water repellence property on treated fabric [59].
- Dip Coating: After submerging the cloth in a solution of nanoparticles, it is slowly removed. This guarantees that the nanoparticles stick to the cloth in a uniform layer [60].
- Spray Coating: This technique allows for consistent coverage by spraying nanoparticle suspensions onto the cloth. This technique may be adjusted to work with varying characteristics of nanoparticles and is scalable [61].
- Layer-by-Layer Assembly: This method involves the deposition of positively and negatively charged nanoparticles in alternating layers to create a thick coating that increases surface roughness and hydrophobicity [62].
- Chemical Vapour Deposition (CVD) : This technique allows for exact control over the coating's thickness and homogeneity by depositing nanoparticles from a vapour phase onto the used fabric .[63]
- Covalent Bonding: Using silanes or other coupling agents, nanoparticles may be chemically attached to the fabric's surface to form a stable and long-lasting hydrophobic coating [64].

3.2. The important of using The Nanotechnology in Medical Scrubs Fabrics Treatments

Antimicrobial qualities added by nanotechnology improve medical scrubs and lower the risk of infection in hospital environments. With their ability to withstand liquids and stains, these cutting-edge textiles offer improved hygiene and a polished look. Medical personnel find that wearing long shifts is more comfortable thanks to the lightweight nature of nanomaterials. [65]Furthermore, nanotechnology can help with moisture wicking, which keeps scrubs comfortable and dry. The longevity of these textiles, which results in longer-lasting clothing, is the main advantage. In the end, scrubs with nanotechnology integrated into them mark a major advancement in medical clothing [66].

Medical scrubs function much better thanks to nanotechnology in a number of ways. First, by including moisture-wicking qualities, it enhances moisture management and keeps medical staff dry and comfortable. Second, the antimicrobial treatments improve safety and hygiene by lowering the amount of bacteria and odours. [3] Third, stain resistance is increased by nanotechnology, which facilitates cleaning and upkeep of the scrubs' appearance. Fourth, comfort throughout extended shifts is improved by the lightweight and breathable nature of nano fabrics. Ultimately, scrubs retain their practical qualities even after several washings thanks to the robustness of these materials. All of these improvements make the working environment for medical professionals more efficient and comfortable [67].

3.3 Nanoparticles in the Finishing of Medical Scrub Fabrics

Nanoparticles are increasingly used in the finishes of medical textiles like doctor's scrub fabrics to enhance their functionality and performance in healthcare places as antimicrobial Properties by preventing the growth of bacteria and viruses, nanoparticles made of silver, zinc oxide, and copper can lower the risk of infection [68]. Stain Resistance by enhancing stain repellence, nanoparticles enable scrubs to keep their clean look even after coming into contact with body fluids [69]. Wrinkle and Moisture Resistance on Fabrics can be treated with silica or other nanoparticles to increase their ability to wick away moisture and become more comfortable [70]. UV Protection: During outdoor activities, healthcare personnel can be shielded from UV radiation by specific nanoparticles. Generally, the performance of medical scrub cloths is much improved by nanoparticles, which also improves comfort and hygiene in medical environments [71].

3.4. Nanomaterials Used in High Performance of Medical Scrubs Textiles Treatments

Usage of Nanoparticles in medical scrubs, doctors wear scrubs, because they perform several important functions in a hospital. Some of these categories include, but are not limited to the type of nanocrystals, which are used in making the scrubs and their intended medical usage [72].Numerous nanoparticles are incorporated into the designs of medical scrubs to make them more functional. In which important types include:

- Silver nanoparticle: These particles have a strong medical activity because they are known to be very efficient in skin infections antiseptics [71].
- Copper Nanoparticles: They are effective against a multitude of conditions and also contain antimicrobial characteristics [72].
- Titanium Dioxide nanoparticles: Usage of titanium dioxide nanoparticles in textiles is in laser finishing for UV-shielding, antimicrobial and chemical durability enhancement [73].
- Zinc Oxide Nanoparticles: Antimicrobial agents and UV filters used in manufacturing outdoor medical devices owing to their excellent antimicrobial properties and UV-blocking capabilities [74].
- Nanofibers: Light and strong polymers such as polyester or polypropylene are melded to form fibres that improving ventilation and control of moisture content and mechanism [75].
- Graphene and Graphene Oxide materials: These materials are lightweight and improve strength, flexibility, and antimicrobial properties [76].
- Silica Nanoparticles: Enhance water and stain resistance, facilitating easy upkeep and cleaning of doctor's scrubs fabrics [77].
- Polymer Nanocomposites: Blend different materials using Nanotechnology to improve chemical resistance, flexibility, and durability [78].

These nanomaterials improve functioning performance and properties as comfort, safety, and overall performance in medical settings environments [79].Since it improves functionality, durability, and safety, I believe the introduction of nanoparticles in medical scrubs is a major achievement. While materials like silica nanoparticles and nanofibers enhance comfort and ease of maintenance, silver nanoparticles and graphene offer crucial antibacterial qualities that make them perfect for healthcare settings.

3.5 The main Benefits of Nanotechnology Application in Medical Scrubs

i. The Antimicrobial properties [80].
ii. Self-Cleaning and superhydrophobic properties [81-82].
iii. Air Permeability property [5].
iv. Resistance to Wrinkles properties [83].
v. Low Toxicity [84].
vi. Durability [60-85].
vii.

3.6. Application of Nano Coatings in Infection Prevention and Control Measures

The use of nano coatings could help in improving medical scrubs by serving as a negative defence towards the pathogens and infection. These coatings, which are usually engineered with the use of copper and silver nanoparticles, have antimicrobial properties that enhance barrier efficacy against germ and viral colonization. Health care institutions stand to benefit from such technology by reinforcing infection control strategies as part of healthcare raiment's. In addition, nano coatings are durable as they retain their effectiveness after many washes and last for a long period. Ultimately, such an innovative approach has an advantage of protecting both health workers and patients in safer healthcare environments [86].

4. Antimicrobial Mechanism by Nanotechnology

Nanoparticles can exhibit potent antimicrobial activity through several mechanisms. The small size and high surface area to volume ratio of nanoparticles allows them to more effectively interact with and disrupt microbial cell membranes. Many nanoparticles, such as silver and copper, can also generate reactive oxygen species that damage cellular components [87]. Nanoparticles may interfere with essential microbial processes like enzymatic activities and nutrient transport. The ability of nanoparticles to penetrate into microbial cells and accumulate within them contributes to their antimicrobial efficacy. The multimodal antimicrobial mechanisms of nanoparticles make it difficult for microbes to develop resistance [80-81]. Nanoparticles exhibit antimicrobial capabilities through various processes, including cell membrane disruption, generating reactive oxygen species (ROS), inhibiting cellular metabolism, releasing ions with antimicrobial properties, disrupting biofilms, converting light energy into heat, and functionalizing their surface with specific molecules as shown in figure (5). These processes make nanoparticles efficient against viruses, fungi, and bacteria. They can also disrupt biofilms, convert light energy into heat, and enhance their antimicrobial effectiveness by modifying their surface with specific molecules. The combination of these mechanisms allows nanoparticles to be highly effective as antimicrobial agents, making them valuable in applications such as medical textiles, wound dressings, and healthcare environments. Their multifaceted approach reduces the likelihood of resistance development compared to conventional antimicrobial agents [88]. The antibacterial actions of nanoparticles, in my opinion, constitute a revolutionary development in infection control, providing a multimodal strategy that efficiently damages microbial cells while preventing the emergence of resistance. Because of this, they are quite useful in medical applications, especially when it comes to improving the functionality and safety of textiles and healthcare settings.

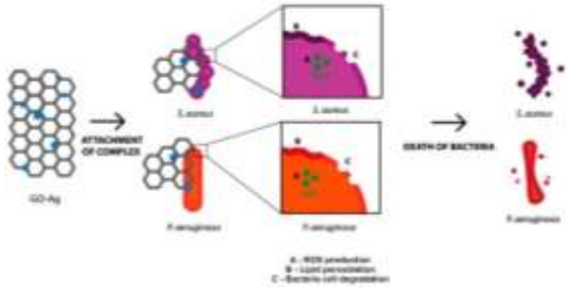

Figure 5.Mechanism of action of GO-Ag nanocomposite toward bacterial cells.
Including attachment of the complex, generation of ROS, lipid peroxidation and degradation of outer layer of bacteria resulting in bacteria death [88]

4.1 Mechanism of Antimicrobial on Medical Scrub Using the Nanotechnology

Healthcare personnel benefit from nanotechnology-based antimicrobial scrubs that inhibit bacteria growth. These scrubs contain nanoparticles, such as silver nanoparticles (AgNPs) and copper nanoparticles (CuNPs), which interact with fungus, viruses, or bacteria to impair their essential functions. Silver ions disrupt cell processes, while copper ions produce reactive oxygen species, damaging proteins and membranes [72-89].Antimicrobial textile types: those that leach out may be more biocidal because they release the active agents, whereas those that don't leach out may be more biostatic or biorepellent because they firmly bind the active agents like figure (6).Nanotechnology in antimicrobial scrubs is a significant approach since it successfully prevents germ development, improving healthcare personnel' safety and cleanliness.

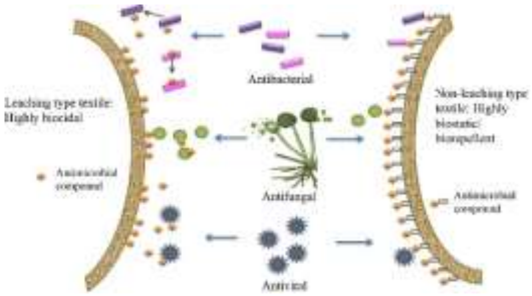

Figure 6. Mechanism of Antimicrobial Textiles [89].

4.2. Antimicrobial Textile Types

The antimicrobial fabric can be either non-leaching or leaching depending on the treatment and antimicrobial ingredient employed. Its mechanism can also be either biocide or biostatic. Microorganisms are killed by biocides, while their growth is inhibited by biostatics. Based on whether they are directed against bacteria, fungus, or viruses, these biocides and biostatics can be further divided into groups like (Table1). Biostatic fabrics are recommended for clothing because they protect the skin's natural bacterial flora and do not harm human skin; biocidal fabrics are recommended for use in medical and environmental settings [90-91]. Engineered nanomaterials and synthetic polymers offer potential antimicrobial solutions, but further biomedical studies and clinical trials are needed to ensure safety, biocompatibility, and practical application in healthcare settings.

Table 1. Different categories of biocidal and biostatic textile [89]

Activity of Antimicrobial	Textile types	Compounds of Antimicrobial	Mechanism
Bacteriostatic	Polyurethane	Metallic silver	Non-leaching
Bactericidal	Loomstate, scoured and bleached cotton fabrics	Silver nanoparticles	Leaching
Fungicidal	Hydrophilic polyurethane	SiO2/Ag+Cu Particles	Non-leaching
Fungistatic	Cellulose fibers	Cross -linking chitosan	Non-leaching
Virucidal	Polyurethane Polyisoprene	Silver nanocluster/ silicacomposite sputtered coating	NA (disposable)
Virustatic	Cotton	Treatment with 3% sodium pentaborate pentahydrate, 0.03% triclosan and 7% Glucapon	Non-leaching

.4.3 Antimicrobial Agents Efficiency of Engineered Nanomaterials

The antimicrobial properties of engineered nanomaterials depend upon a variety of key geometries like area and aspect ratios, shape and surface texture, etc. Due to their smaller particle sizes Saint wasting "the potential attack sites" the arising targets rather proves a wide spread inhibition. Such conformation often influences its ability to diffuse within the bacterial membranes. Even the surface coatings and functionalization can determine to a large extent property that are required for positive or negative Antimicrobial activity. Still, it is possible to realize the materials according to the anticipated performance in antimicrobial activity by well understanding these factors [92].

Synthetic polymers mimic host defense peptides, showing broad antimicrobial activity and rapid bactericidal kinetics. However, none is currently in clinical trials, with no resistance-inducing properties. Conducting polymers like polyaniline, polypyrrole, and polythiophene have good antimicrobial activity but lack extensive biomedical studies. Preparing polymer blends and nanocomposites with biopolymers and nanomaterials can improve biocompatibility and properties [93].

4.4 The Methodology of Antimicrobial Finishes Application in Textiles

Antibacterial finishing of textiles can be achieved through two methods: incorporating antimicrobial agents into the polymer solution before extrusion or spinning bath, or applying them on ready-made natural or synthetic fibers. The pad-dry-cure system is widely used, which involves preparing antimicrobial solutions, passing the fabric through padding rollers, immersing it in the solution, drying it at 80°C for 5 minutes, curing it at 150°C for 1½ minutes, and conditioning it for 6 hours at 27°C and 65% relative humidity [94].

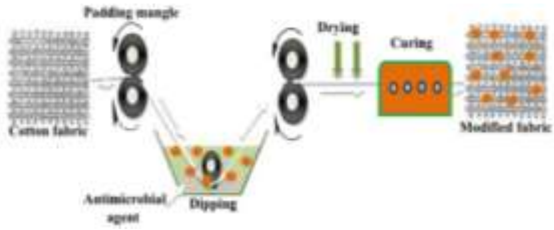

Fig 7. Pad-dry-cure method [94].

5. Medical Scrubs with a Superhydrophobic and Self-Cleaning Nano finish

Medical scrubs with super hydrophobic and self-cleaning nano-finishes increase performance by warding off impurities and water.

a. Super hydrophobic Finishes: These finishes, which are usually made with coatings like silica nanoparticles or fluoropolymers, provide a surface on which water beads and rolls off, avoiding stains and moisture retention like lotus leaf surface in figure (8) [22-95].

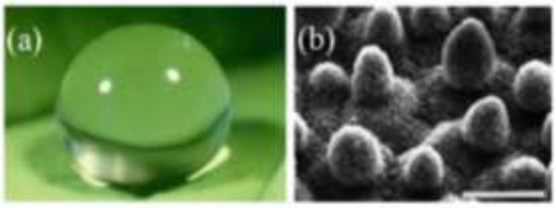

Fig 8. Super-hydrophobic phenomenon on lotus leaf surface some water droplets on lotus leaf surface, b SEM image of lotus leaf [95].

b. Self-Cleaning Properties: These coatings, which are frequently made from photocatalytic substances like titanium dioxide, may decompose organic debris when exposed to light, making it easier for the scrubber to stay clean. [42-81-82].

The 'Lotus effect', or superhydrophobic qualities, describe a water droplet's capacity to resist more than just water. Low contact angle hysteresis and a water contact angle of more than 150° are required to accomplish these qualities as table (2). Lithography, wax solidification, tempting, re-conformation of polymers, vapour deposition, plasma procedures, and the sol-gel process are some of the methods used to create superhydrophobic textiles. In order to create superhydrophobic surfaces, methods such as hierarchical micro/nanostructures and nanoparticles have proven essential. Enhancing the coating on fibre and self-healing fabric can increase the stability and durability of flexible self-cleaning surfaces, which is what researchers have been focussing on. The development of superhydrophobic textiles for wider industrial applications depends on these surfaces [82].

Table 2. Super hydrophobicity of the surface according to WCAs [96].

Water Contact Angel	Property
$\theta < 5°$	Superhydrophilic
$5° < \theta < 90°$	Hydrophilic
$90° < \theta < 150°$	Hydrophobic
$\theta > 150°$	Superhydrophobic

By using these techniques, scrubs' ability to withstand liquids may be greatly increased, making them more appropriate for use in medical settings.The use of superhydrophobic and self-cleaning nanofinished in medical scrubs is a revolutionary solution that improves hygiene, durability, and comfort, reducing maintenance requirements and enhancing performance.

5.1 Self-Cleaning Fabrics for Medical Scrubs

An American company called Nanotextile manufactured and marketed the self-cleaning cotton fabric known as Nano Care. By producing nano-care fabrics, fabric is able to alter the cylindrical structures of cotton fibres. Nanoscale, cotton fibres resemble tree trunks. The tiny whiskers fuzz covers these tree trunks thanks to nanotechnology, which creates an air cushion around the fibre [82-97].

When water hits fabric, it forms beads on the whiskers. These beads compress the air in the spaces between the whiskers, adding to their buoyancy. Technically speaking, the fabric has been made extremely non-wettable or super-hydrophobic. The whiskers also create fewer surfaces for dirt to come into contact with. When water is applied to soiled fabric, the dirt sticks to the water much more readily than it does to the textile's surface, and the water removes the dirt as it beads up and rolls off the fabric's surface. Consequently, the mechanism of the lotus plant's leaves, as depicted in (figure 9), is the foundation for the soil-cleaning concept [98].

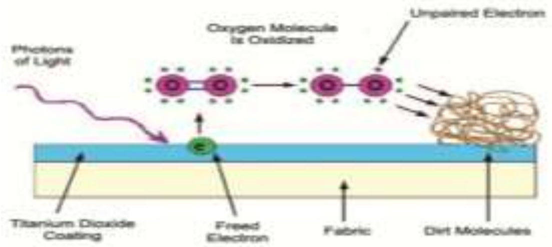

Fig 9 Fabric coated with a thin layer of titanium Dioxide particles [99].

Self-cleaning fabrics require a long time to break down stains due to titanium dioxide's inefficiency in using sunlight energy. Titanium dioxide provides electrons to oxidize oxygen molecules in the air, which are freed via the photoelectric effect. However, only high energy blue and UV light photons have enough energy to excite electrons to the conduction band, limiting the amount of light energy needed for large stain removal [99]. Self-cleaning medical scrubs, inspired by the lotus effect, improve hygiene and reduce maintenance. Enhancing titanium dioxide efficiency could enhance stain removal and healthcare practicality.

6. Air Permeability Property inMedical Scrubs Textiles

The term "air permeability" describes the fabric's capacity to permit air to flow through textiles, such as medical scrubs. This is a crucial component of comfort, especially for clothing used in medical environments where prolonged wear and physical activity can cause moisture and heat accumulation [5].

6.1.Pores Size (Particle Filtration Efficiency (PFE))

Measuring the size of the pores is one of the crucial tests since it shows how well fabrics or cloth masks can either block or permit the passage of different particles. Since the primary factor, influencing both the respiration process and the effectiveness of particulate filtering is the size of the pores. A cloth mask's ability to filter depends on a variety of factors, including the type of fabric, number of layers, thread count, and weaving structure [100].

6.2. The Important Variables that Affect Medical Scrub Fabrics Air Permeability

- Composition of Fabric: Cotton, polyester, or a combination of the two are frequently used to make scrubs. Compared to synthetic fibres like polyester, cotton has a better air permeability and is inherently breathable. However, in order to improve moisture wicking and durability while sacrificing some air permeability, polyester is frequently combined with cotton [3].
- Weave Structure: The ease with which air flows through a cloth is determined by its weave. While fabrics with tight weaves may impede airflow, they offer superior resistance to fluids and pollutants. Generally, Fabrics with looser weaves have more air permeability [101].
- Thickness of Fabric: Air permeability is often reduced with thicker textiles. It is crucial to balance fabric thickness in medical scrubs to provide protection and comfortability [102].
- Treatments and finishes: Antimicrobial, water-repellent, and stain-resistant finishes are applied to many scrubs. Through the creation of a barrier on the fabric's surface, these treatments can lessen air permeability [103].

Healthcare professionals benefit from air-permeable scrubs because they assist control body temperature and offer comfort throughout extended shifts [104].The medical scrubs' capacity to permeate the air is crucial for maintaining comfort and controlling body temperature over extended shifts. Achieving both breathability and protection in healthcare settings requires striking a balance between fabric composition, weave structure, and finishes.

7. Anti-Static Property by Nanotechnology

Synthetic fibres like nylon and polyester accumulate static charge due to low water absorption. Cellulosic fibres, with more moisture, had better dissipate charges. Nanotechnology has been used to improve textile anti-static properties, with materials like saline nanosol, zinc oxide whiskers, nanoantimony-doped tin oxide and nanosized titanium dioxide providing effective anti-static properties [105]. Therefore, it is important to use natural materials in doctor's scrubs or synthetic materials in low present. Using the Nanotechnology in fabrics treatment improves the anti-static properties for the medical staff clothes (Scrubs) especially in synthetic materials as figure (10) [99].Enhancing medical scrubs' anti-static qualities using nanotechnology is essential for guaranteeing patient comfort and safety, particularly when synthetic materials are utilized.

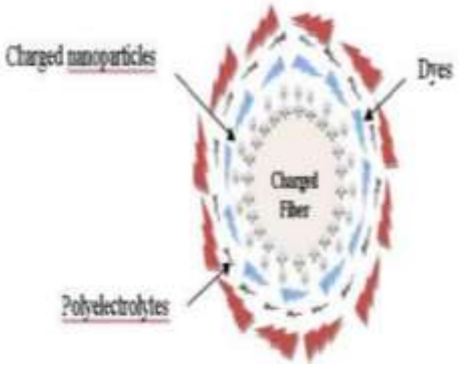

Fig 10 Electrostatic self-assembly of nanolayers on charged textile fibers [105].

8. Wrinkles Resistance in Medical Scrubs by Nanotechnology

Under conventional methods, resin is frequently used to give fabric resistance to wrinkles. Applying resin does have certain drawbacks, though, such as a reduction in the fiber's tensile strength, abrasion resistance, water absorbency, dye ability, and breathability. In order to get around the drawbacks of using resin, some researchers improved the wrinkle resistance of cotton and silk, respectively, by using nano-silica and nano-titanium dioxide. Under UV light, nano-titanium dioxide was used as a catalyst along with carboxylic acid to catalyse the reaction that links the cellulose molecule to the acid. However, when nano-silica was combined with maleic anhydride as a catalyst, the outcomes offer a variety of benefits, including the ability to repel water, have antibacterial qualities, retain strength, and prevent wrinkles in treated textiles like figure (11) [83-94-106].Nanotechnology is the best way to increase wrinkle resistance in medical scrubs since it improves fabric performance without sacrificing strength, breathability, or other crucial characteristics.

Fig 11. Anti -wrinkle resistance before and after treatment of fabric [106].

9. 9. Low Toxicity

At the nanoscale, substances like silver are effective at low quantities, lowering the possibility that they may be harmful to people or environment while remaining deadly to microbes. The medical staff scrub's fabrics are prepared using low-toxicity nanotechnology treatments, and so are safe for healthcare workers and patients. Choosing biocompatible nanomaterials such as silver, zinc oxide and titanium oxide are chosen due to their antimicrobial properties. Stabilization techniques are useful in avoiding detachments and reducing leaching during wash or wear and usage. Governmental organizations or agencies that regulate and monitor feel usage of nanoparticles have done some measures to protect the health of people while improving the productivity [76-84].Enhancing medical scrubs' anti-static qualities using nanotechnology is essential for guaranteeing patient comfort and safety, particularly when synthetic materials are utilized.

10. Durability

Because of the nature of its incorporation into the fabric, the nanoparticles technology assists in providing stain-free clothes that can retain the antimicrobial activity of the clothes for a longer duration. Currently, nanotechnology is used to enhance the useable period of medical scrubs through dependability of the fabric to tear, wash, and other over-environmental effects. Silver, zinc oxide or titanium oxide nanoparticles form strong bonds through the fabric fibers and provide this nice feature that does not easily wear off. In these embodiments, the polymer nanocomposites coatings are highly abrasion resistant and retain their moisture management and antimicrobial properties even after washing and heavy wear to the coatings. Also, fabrics that incorporate nanotechnology have better durability as they endure over a long period when fabric is less repetitive healthy for the fabrics even at the microscopic scale. As a result of these enhanced durable scrubs, the treatment of healthcare workers becomes cost-effective and environmentally friendly due to the ability of scrubs to maintain protective and functional properties for a longer period of time [36-60-85-96].Using nanotechnology to make medical scrubs more durable is a great development because it guarantees long-lasting protection, affordability, and environmental sustainability**.**

11. Conclusion

The application of nanotechnology is illustrated in this paper through enhanced functional characteristics such as moisture management, antimicrobial properties, self-cleaning property, durability, and odour control in the context of medical scrub fabrics. Moreover, it makes it possible to incorporate nanoparticles like titanium oxide, nano copper, silver and zinc oxide, which enhance sweat-management fabrics, offer microbial protection, and enable more effective, odourless fabric usage over time. Another benefit of nanotechnology was found that it can strengthen the fabric used, meaning scrubs can be washed and worn repeatedly without losing their functionality. However, there is little to no risk associated with many nanomaterials, and there are minimal to no risks associated with applying them. However, many nanomaterials have low inherent risk, and the methods used to apply them pose little to no risk to patients and healthcare workers. Since healthcare professionals now demand hygienic apparel with improved comfort and functional performance, nanotechnology greatly improves the characteristics of medical scrubs. Better work environments, reduced risk of infection, and enhanced sanitation are made possible by this method for medical professionals. Finally, In the future, the manufacturers of medical scrubs garments will use nanotechnology to improve the functional performance of medical scrubs fabrics instead of traditional methods.Because of its softness, flexibility, durability, balance of ventilation, and simplicity of maintenance—especially when combined with a cotton-polyester blend—twill weave is perfect for medical apparel, according to studies. Zinc oxide nanoparticles (ZnO NPs) are becoming a better substitute for silver nanoparticles (AgNPs), despite the latter is antibacterial and odour-reducing capabilities. ZnO NPs are the best option for improving medical apparel since they have potent antibacterial properties, are less harmful, more reasonably priced, and environmentally friendly.

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