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Review Article
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A Critical Review on Concept of Nanotechnology in Textile Engineering

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Abstract

Nanomaterials and biomaterials are becoming increasingly important in current scientific and industrial communities. Nanomaterials are beyond the perception of the human eye. Thus, to determine the structure, morphology, and exact formation of materials on the nanoscale, an authentic technique is required. Nanomaterials find extensive uses in various scientific disciplines. Textile Engineering is one of the important area of research. Today in various smart textiles different types of nanomaterials are used. Herein an attempt has been made to describe various nanomaterials used in textile such as antimicrobial textiles, flame retardant textiles, water proofing textile, odour resistant textile, wrinkle proof textile, uv- protection in textiles etc.

Keywords: Nanomaterials for Water Proofing; Antimicrobial Textile; Fireproof Textile; Wrinkle Proof Textile; Characterization

Introduction

Textile is the second largest sector of employability after agriculture particularly in developing country like India. Actually textile come into existence since the beginning of human civilization. Early man was hunter and used to dwell in the caves. He used to cover especially lower portion of body with animal skins or plant parts. Later on he started using the natural fibers like cotton, wool and silk for the manufacture of the fabric.

The textile industry can be broadly divided into four sub-categories such as (1) spinning, (2) weaving, (3) processing and (4) finishing. In the hundreds or thousands of the years of its history, textile industry has changed a lot from its past forms. The usefulness of nanoparticles in the manufacture of textile products with novel and enhanced properties was recognized from the researchers of both core nanotechnology domain as well as core textile domain. They tried to use nanoparticles mainly during textile processing stage. The different nanoparticles can be used to impart desired properties in the fabric. Some of the nanoparticles used in textile industries are discussed in the following section.

Nanostructured multifunctional fabric is a new frontier in textile technology. In the last few decades, textiles industry is increasingly harnessing the nanotechnology via functionalization to solve problems and for a variety of end purposes (Jadoun et al., 2020). Although textiles were originally used to cover the human body, but today it is trendy to wear clothes with multifunctional capabilities to live a better life. Textile products have been employed in a variety of consumer applications all around the world throughout history. Natural fibres like cotton, silk, and wool, as well as synthetic fibres like polyester and nylon, are still the most widely used fibres in the textile industry. Natural and synthetic fibres possessing certain distinct properties make them best suited for use as clothing [78].

Nanotechnology is currently regarded as one of the most promising technologies. It gives fabrics distinctive features, including anti-bacterial [40, 77], self-cleaning [114], super-hydrophobic/super-oleophobic [5, 82], flame-retardant [27], UV blocking [69], and wrinkle resistance [121], in addition to the fabric's inherent toughness and breathability.

The synthesis of nanoparticles (NPs) is one of the most fascinating achievements in nanotechnology. NPs have several distinguishing characteristics, such as superior magnetic, optical, surface chemical, and mechanical capabilities, as well as greater melting point. As a result, they are being looked at for a variety of uses.

Nanotechnology enables the manufacture of innovative textile products that combine the benefits of natural and synthetic fibres. NPs are fascinating to scientists because they bridge the gap between bulk materials and their atomic and molecular structure. The chemical approach is the most prevalent and traditional way of NPs synthesis. A wide range of research in nanotechnology has been concentrated on controlling the size, shape and physical form of Nano-sized metal particles, which is vital in tuning their chemical and physical properties. However, the majority of these methods suffer from various drawbacks like they make use a lot of energy, use dangerous chemicals, and are difficult to purify [61, 63, 97]. Metal NPs have recently been investigated for quantum of applications mainly including textile, medicinal, agricultural, environmental, and physiochemical [79, 83].

UV radiation, aerosol technology, lithography, laser ablation, ultrasonic fields, and photochemical reduction [52] processes are some of the most widely used methods to manufacture metallic Nano particles using physical methods. The some of the most widely used chemical synthesis processes, including sol-gel, sonochemical, and hydrothermal processes results in some chemically harmful component being adsorbed on the surface, which limits their usage in textile applications. Apart from this, these processes possesses other disadvantages like being expensive, requiring a lot of energy, being difficult to purify, and requiring the use of toxic chemicals. To overcome these technical snags, biological concepts have lately been devised, and are becoming very popular now days (Figure 1).

Over the previous decade, M. Montazer et al. [39] and Hebeish et al. [41] have conducted several investigations into the synthesis of various NPs for imparting multi-functional capabilities on textiles, such as self-cleaning, water repellence, flame retardancy, and antibacterial properties [38, 55, 67].

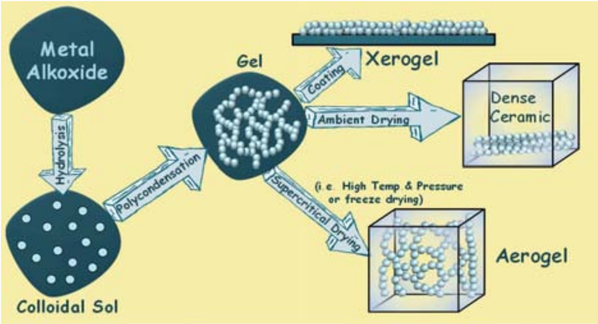

Figure 1: Sol-gel reaction mechanism.

In this review, we cover current research on various nanomaterials to bring unique protuberant qualities into textiles, in order to harness nanotechnology to improve fabric quality.

Incorporation techniques in Nano-textile

Throughout the years, researchers all around the world have developed a variety of textile materials with multi-functional qualities by incorporating NPs into textile products [62, 122]. However, sonochemistry has recently acquired appeal as a synthetic technique for depositing NPs onto a variety of substrates, including textiles. Sonication was used to create highly dispersed NPs, which were then used as a Nano colloid in textiles [15, 38].

Nanomaterials can be incorporated into fabrics in two ways: during the fiber production process and during the textile finishing process. NPs can be added during fiber production by mixing them with the polymer prior to spinning. With this method, the NPs are evenly dispersed inside the fiber volume, and the resulting material is called as "nanocomposite". To achieve appropriate functionalization, the nanoparticle concentration in the fiber might be as low as 0.1 % [4]. This approach results into durable products since the nanomaterials are firmly integrated with the textile fiber. Organic polymers (like Polystyrene (PS) Nylon, etc.) are commonly employed to ensure that nanomaterials adhere well to the textile surface. Nanomaterials are often incorporated during the fabric finishing process. In this method, NPs become entrapped within the fiber and can only be removed by abrasion. This fact poses a moderate hazard to both employees and consumers involved in subsequent fabric production in terms of health and safety. It can be manufactured using traditional processes such as dipping (exhaustion) [137], printing [39], padding [46] , coating [116], etc.

Due to the interaction of nanomaterials and the textile products, there are additional concerns for the health and safety of personnel involved in fabric finishing procedures. Also, employees in the garment production, who will be handling nanomaterials-containing fabrics in all cutting, sewing, pressing, and packing procedures, should also be cautious.

Application of Nanotechnology in Textile Engineering

Anti-microbial Textile

Antibacterial agents are critical in a variety of industries, including the textile industry. There are two types of antibacterial agents now utilised in the textile industry: organic and inorganic agents. Inorganic antibacterial agents, such as NPs, are gaining popularity in textile applications because they are not only stable at the high

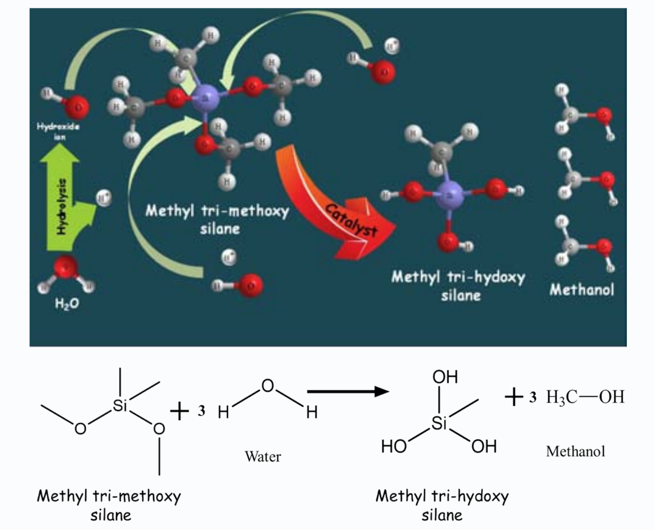

Figure 2a: Possible hydrolysis reaction mechanism of silicone alkoxide.

temperatures and pressures required in textile processing, but they are also generally regarded as safe (GRAS) for humans and animals when compared to organic materials. According to recent research, some NPs have a selective toxicity to bacteria while having negligible effects on human cells. Some metal-based NPs have sparked a lot of attention for their ability to control microorganisms, particularly bacteria and viruses that cause infectious diseases. Antibacterial effects of NPs on microbes are influenced by a number of factors.

Antibacterial mechanisms of NPs

The mechanism behind NP's antibacterial activity against variety of pathogens is yet to be fully uncovered. However, several studies have proposed the antimicrobial activity routes for NPs which may be described as ahead. At the beginning, NPs can electrostatically interact to the cell membrane of bacteria, affecting the membrane's integrity. They may cause bacterial cell wall or membrane damage, as well as harmful alterations in cellular organelles shown in Figure 6. It should be noted, however, that some of these mechanisms are mere speculation that and will require thorough investigations [68].

The bacterial cell wall's function is to give strength, rigidity, and structure to the cell while protecting it from osmotic explosion and damage. The cell walls of Gram-positive (+) and Gram-negative (+) bacteria differ in content and structure. Physically and chemically, Gram-negative cell walls are more complex than Gram-positive cell walls. The structure of the cell wall has a significant impact on the effects of NPs on bacteria. The characteristics of bacterial cell walls may be important in NP diffusion inside biofilm matrixes. Similarly, the action of NPs against bacteria are dependent on the bacteria's composition, contact surface, essential features, and species. There have been numerous researches on the antibacterial properties of various forms of NPs. The antibacterial impact of NPs appears to be proportional to their concentration. However, some of these studies contradict each other, implying that the mechanisms of NP toxicity in bacteria are complex. As a result, determining whether NPs are useful or harmful to bacteria is difficult. Another factor that influences bacterial growth against NPs is the rate of bacterial growth. Bacteria that grow rapidly are suppressed more effectively by NPs than bacteria that grow slowly. It's likely that the slow-growing bacteria's tolerance is linked to the expression of stress-response genes. As a result, antibacterial properties are greatly dependent on the strain. Another proposition is the generation of intracellular reactive oxygen species, such as hydrogen peroxide, a powerful oxidising agent that is toxic to bacteria [71, 84, 117, 135].

Mode of action of nanoparticles

The antimicrobial activity of silver NPs is not entirely understood, despite various postulated mechanisms. Silver NPs are thought to be a slow-release source of silver ions that react with protein thiol groups and disrupt DNA replication. Silver is also thought to produce free radicals, which harm the bacterial membrane. Furthermore, antibacterial activity may be induced through direct contact between a nanoparticle and a bacterial cell, resulting in structural damage to the cell wall [68].

Antibacterial and fungicidal characteristics can be imparted to textiles using Ag [6], TiO_2 [135], and ZnO [100] NPs. Because Ag NPs have a wide surface area, they are more likely to come into contact with bacteria and fungi. Silver nanoparticles (Ag NPs) kill bacteria by interacting with their proteins. This interaction disrupts the bacteria's cellular functions and inhibits their growth. They also reduce the cell's ability to breathe and absorb nutrients, slowing down the fundamental energy production process. Ag NPs bind to the cell wall and membrane when they come into touch with moisture or bacteria. While Ag NPs are innocuous in their metallic state, the Ag^+ ions are reactive and diffuse into the cytoplasm through the cell wall and membrane. To structurally modify the cell wall, Ag^+ ions attach to Sulphur-containing proteins on the cell membrane. Because of the variations in osmotic pressure, the cellular components are released into the extracellular fluid. Additionally, Ag^+ ions attach to phosphate-containing proteins, condensing DNA and causing cell death through a reaction with thiol group proteins. They also stop enzymes from working and prevent the cell from producing ATP. The growth and proliferation of bacteria and fungi that cause odor and itching are slowed by Ag NPs. Ag NPs, can also be used to inhibit germs and fungi from growing on socks.

TiO_2 NPs have been used in textiles to give antibacterial

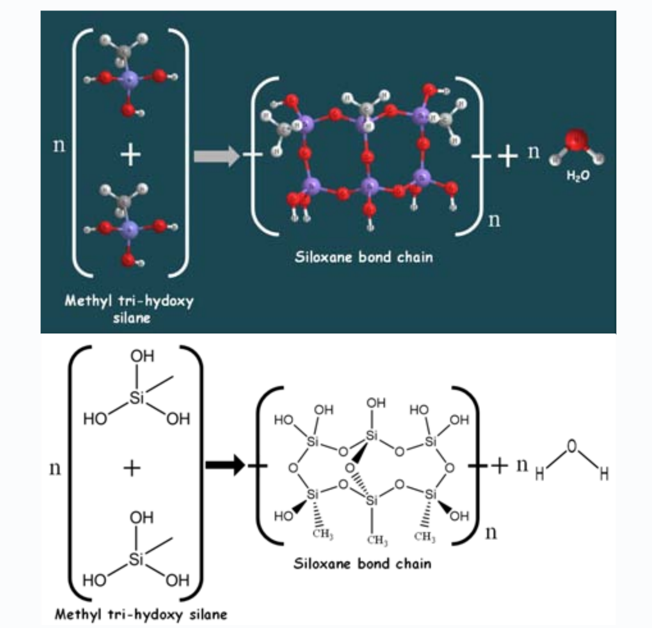

Figure 2b: Possible polycondensation reaction mechanism of silanol groups.

Table 1: Nanomaterials used in textile and their implication.

Nanomaterial	Antimicrobial Activity & Mechanism	Other Benefits	Applications
Silver Nanoparticles	Releases silver ions that disrupt bacterial cell walls and proteins	Strong and broad-spectrum antimicrobial properties	Clothing, hospital linens, sportswear
Zinc Oxide (ZnO) Nanoparticles	Generates reactive oxygen species (ROS) that damage microbial cells	UV protection, antibacterial, and antifungal properties	Socks, activewear, medical fabrics
Copper Oxide (CuO) Nanoparticles	Causes oxidative stress and disrupts microbial cell membranes	Effective against bacteria and fungi, durable in textiles	Medical textiles, protective clothing
Titanium Dioxide (TiO_2) Nanoparticles	Photocatalytic under UV light, generating ROS to kill microbes	UV protection, antimicrobial, self-cleaning	Outdoor clothing, upholstery, uniforms
Graphene Oxide	Physical disruption of microbial cell membranes	High antimicrobial efficacy, enhances fabric strength	Antimicrobial coatings, filters, masks
Chitosan Nanoparticles	Binds to microbial cell walls and disrupts cell functions	Biocompatible, biodegradable, and antimicrobial	Wound dressings, antimicrobial fabrics
Gold Nanoparticles	Induces oxidative stress and disrupts microbial enzyme functions	Non-toxic, biocompatible, enhances dyeing processes	Medical textiles, luxury fabrics
Carbon Nanotubes (CNTs)	Physically disrupts microbial cell walls	High durability, antimicrobial, improves fabric mechanical properties	Military uniforms, activewear
Magnesium Oxide (MgO) Nanoparticles	Creates an alkaline environment that inhibits microbial growth	Antimicrobial, eco-friendly	Medical fabrics, undergarments
Silica Nanoparticles with Ag or Cu coating	Acts as a carrier for silver or copper ions, enhancing durability	Extended antimicrobial effect, high wash resistance	Sportswear, socks, medical garments
Cerium Oxide (CeO_2) Nanoparticles	Generates ROS under UV exposure, damaging microbial cells	Antioxidant properties, UV protection	Outdoor wear, hospital textiles
Aluminium Oxide (Al_2O_3) Nanoparticles	Disrupts cell membranes of microbes	Enhances durability, antimicrobial	Protective clothing, uniforms
Copper-Silver Hybrid Nanoparticles	Combined release of copper and silver ions for enhanced effect	Broad-spectrum, prolonged antimicrobial action	Healthcare textiles, odour-resistant clothing
Fullerenes	Generates ROS under UV light, killing bacteria	Antioxidant and antimicrobial, lightweight	Protective fabrics, sportswear

Table 2: Nanomaterials used for Odor Control.

Technology/Material	Mechanism	Benefits in Textiles
Silver Nanoparticles	Release silver ions that inhibit bacterial growth, preventing odour formation	Long-lasting, durable, and effective odour control
Zinc Oxide (ZnO) Nanoparticles	Antibacterial and UV protection, reducing bacterial growth	Durable, maintains effectiveness even after washing
Copper Nanoparticles	Antimicrobial properties that reduce bacterial build up and odours	Natural odour control, eco-friendly
Chitosan	Binds to bacterial cell walls, preventing growth and odour	Biodegradable, suitable for eco-friendly textiles
Activated Carbon/Charcoal	Adsorbs and neutralizes odour molecules	Effective against a wide range of odours, breathable
Cyclodextrins	Encapsulate odour molecules and release fragrance	Provides controlled release, suitable for deodorizing fabrics
Bamboo Charcoal Fibbers	Naturally antimicrobial, adsorbs moisture and odours	Eco-friendly, odour-resistant, moisture-wicking
Triclosan	Antimicrobial agent that prevents bacterial growth and odour	Used for strong and lasting odour control
Polyhexamethylene Biguanide (PHMB)	Antimicrobial polymer that inhibits bacteria	Durable, safe for skin contact, effective against odours
Graphene Oxide	Antibacterial and adsorptive properties	Durable, adds strength to fabrics, antimicrobial
Silica-Based Coatings	Absorb moisture and odour molecules	Helps keep fabrics dry and odour-free, improves comfort

characteristics due to their catalytic activity. The incorporation of Au-doped TiO_2 nanocomposites or TiO_2/SiO_2 nano-composites into cotton textiles provides self-cleaning properties while also boosting photo-catalytic activity. Furthermore, ZnO has antimicrobial characteristics that are similar to TiO_2. ZnO nanoparticles (NPs) applied to textiles can inhibit the growth of both gram-positive (like Staphylococcus aureus) and gram-negative (like Escherichia coli) bacteria. This can be considered a form of self-cleaning as it reduces bacterial contamination on the textile surface. Additionally, textiles were endowed with antibacterial properties by attaching core-corona structured SiO_2 and Ag nanoparticles to densely packed textile surfaces through electrostatic interactions. The corona of these nanoparticles can be further functionalized with antibacterial agents like quaternary ammonium salts or metal coatings to enhance their antimicrobial efficacy. Table 1 describes various nanomaterials used in textiles and their applications.

Anti-Odor textiles

Anti-odor textiles are designed to reduce or eliminate unpleasant odors in clothing, particularly inner wears. These fabrics incorporate various technologies that inhibit the growth of odor-causing bacteria or neutralize odors. Anti-odor NPs as shown in Table 2 catches odor-causing microorganisms and either inhibit their growth or destroys them. For example, the tourmaline nanomaterial-based Nano-finishing on textiles is supposed to have an ability to separate up to 75 percent sticky moisture, 99.99% bacteria, and 90% odors that imparts an odor-resisting characteristics to it. The incorporation of fragrant material (aroma) in anti-odor/antimicrobial finishing by Nano-encapsulation in synthetic fibers or formulation may aid in the release of fragrance during use [117].

Flame-Retardant Textiles

Flame-retardant textiles are specially treated fabrics designed to resist ignition, prevent flames from spreading, and reduce smoke

Table 3: Nanoparticles used in Flame-Retardant Textiles.

Type of Flame Retardant	Description	Applications
Inherent Flame-Retardant Fibbers	Some fibres are naturally flame-resistant due to their chemical composition. Examples include aramids (like Kevlar, Nomex), modacrylics, and certain polyesters.	Used in firefighting suits, military uniforms, and protective industrial clothing.
Treated Fabrics	Fabrics made from standard fibres (e.g., cotton, polyester) that are treated with flame-retardant chemicals to enhance fire resistance.	Common in home textiles, curtains, carpets, and upholstery.
Blended Flame-Retardant Fibbers	Blends of flame-retardant and standard fibres to balance comfort, cost, and safety.	Often used in protective clothing and industrial applications.

Table 4: Common Flame-Retardant Chemicals and Compounds.

Flame-Retardant Chemical	Mechanism of Action	Commonly Used In	Flame-Retardant Chemical
Phosphorus Compounds	Forms a char layer that insulates the fabric from heat.	Cotton fabrics, polyester, blended textiles	Phosphorus Compounds
Halogenated Compounds	Releases halogen radicals that inhibit combustion reactions.	Industrial textiles, upholstery, outdoor fabrics	Halogenated Compounds
Nitrogen Compounds	Forms a protective barrier and releases nitrogen, diluting oxygen.	Used in synthetic fibres and certain natural fibres	Nitrogen Compounds
Boron Compounds	Releases water when heated, cooling the fabric and forming a char layer.	Carpets, upholstery, curtains	Boron Compounds
Metal Hydroxides (e.g., Aluminium Hydroxide)	Decomposes to release water, which cools the fabric.	Clothing and building materials	Metal Hydroxides (e.g., Aluminium Hydroxide)
Silicone-Based Coatings	Forms a protective, heat-resistant coating that inhibits flame spread.	Firefighter gear, high-temperature industrial textiles	Silicone-Based Coatings

Table 5: Some Other Nanoparticles used in Flame-Retardant Textiles.

Nanomaterial	Mechanism of Action	Benefits in Textiles	Applications
Carbon Nanotubes (CNTs)	Forms a protective char layer that insulates and reduces flame spread	Enhances strength, flexibility, and thermal stability	Fire-fighter gear, protective clothing, industrial textiles
Graphene Oxide	Creates a thermal barrier that delays ignition and flame spread	Increases thermal conductivity, enhances fire resistance	Fire-resistant clothing, upholstery, composites
Clay Nanoparticles (e.g., Montmorillonite)	Forms a heat-resistant barrier that slows down fire propagation	Non-toxic, improves stability and mechanical properties	Home furnishings, curtains, carpets, automotive textiles
Silica Nanoparticles	Creates an insulating barrier that slows heat transfer	Lightweight, transparent, improves fabric durability	Curtains, upholstery, automotive interiors
Aluminium Hydroxide Nanoparticles	Releases water vapour when heated, cooling the fabric and reducing flame spread	Eco-friendly, effective at high temperatures	Fire-fighter uniforms, industrial and protective clothing
Boron Nitride Nano sheets	Acts as a heat shield, reducing heat and flame spread	High thermal stability, enhances mechanical properties	High-performance fabrics, fire fighter gear, military uniforms
Zinc Oxide (ZnO) Nanoparticles	Generates a char layer that prevents flame spread	Antibacterial, UV-protective, non-toxic	Outdoor fabrics, protective work wear
Magnesium Hydroxide Nanoparticles	Releases water vapour upon heating, cooling the material	Eco-friendly, non-toxic, effective flame suppression	Household textiles, protective clothing
Titanium Dioxide (TiO_2) Nanoparticles	Forms a protective barrier and reduces surface temperature	Durable, provides UV protection	Outdoor furniture, automotive textiles, clothing
Phosphorus-Doped Nanoparticles	Promotes char formation and inhibits combustion	Durable, highly effective flame retardant	Upholstery, curtains, military uniforms
Silicon-Based Nanoparticles	Forms a heat-resistant layer, reducing heat and flame spread	High thermal stability, adds durability	Industrial textiles, automotive fabrics
Intumescent Nano coatings (e.g., Expandable Graphite)	Swells when exposed to heat, forming an insulating barrier	Reduces heat transfer, limits flame spread	Fire-protective clothing, building materials
Metal Oxide Nanoparticles (e.g., Iron Oxide)	Promotes char formation and flame resistance	Non-toxic, improves durability and heat resistance	Outdoor textiles, curtains, upholstery

production. These textiles are crucial in various industries, including military, firefighting, industrial safety, and home furnishings, to reduce fire hazards. Flame retardancy in textiles can be achieved through the use of flame-retardant fibers or by applying chemical treatments to regular fibers. Table 3 and Table 5 describes nanomaterials used in flame retardant textiles. Prior to use of nanomaterials, some chemicals were used as flame retardants. Table 4 describes various chemicals used as flame retardant.

Traditional flame-retardant systems may be replaced by flame-retardant Nano-additives, which are eco-friendly alternatives, according to material experts. The effect of NPs in combination with typical flame retardants on the flame retardation of a variety of textile polymers has been investigated [17, 35, 74]. The findings showed that the majority of NPs might improve the flame retardancy and thermal stability of textile polymers. The main way nanoparticles improve fire resistance is by creating a protective layer on the fabric. This layer is made stronger by carbonizing the fabric and neutralizing harmful chemicals that can fuel the fire. However, the degree of improvement is determined by a number of factors, including nanoparticle composition and morphology, nanoparticle migration speed to the surface, nanoparticle dispersion in the polymer matrix, and polymer-nanoparticle compatibility. Cotton fabric are made more resistant to UV rays and fire by coating it with a special material made of tiny particles. This material is a combination of different substances like polypyrrole, zinc oxide, and carbon nanotubes [11]. Cotton covered with a polypyrrole-Zinc oxide-carbon nanotube composite showed enhanced characteristics as compared to cotton that was not coated. Similarly, a special fire-resistant coating for cotton fabric is done by mixing a traditional fire-retardant chemical with tiny silica particles (nanoparticles). Then how these tiny silica particles helped the fire-retardant chemical work better to protect the fabric from fire is

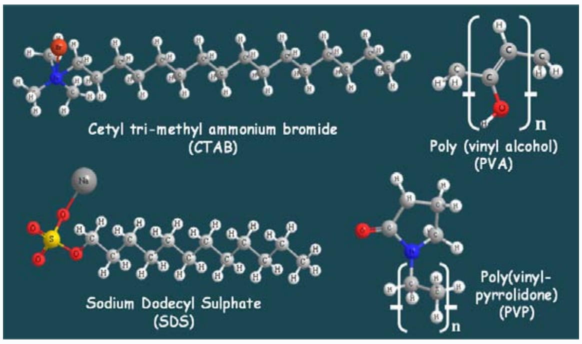

Figure 3: Structures of stabilizing chemicals.

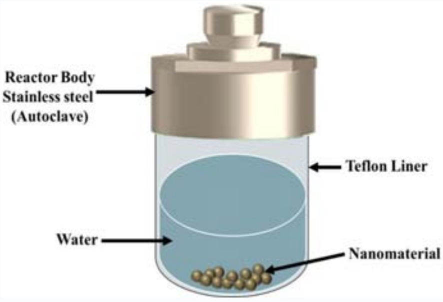

Figure 4: Hydrothermal setup.

tested. The test findings revealed that incorporating Nano-silica into a traditional intumescent flame-retardant system might improve the fire protection properties of a cotton fabric-intumescent flame-retardant system to a certain extent, but at the expense of the system's thermal stability [126].

UV-protection

UV blockers made from inorganic materials are generally better than organic ones because they are more stable and less harmful, especially when exposed to high temperatures and UV radiation. To be considered UV-protective clothing, cotton fabrics must have a UV protection factor (UPF) between 40-50 or greater than 50. UPF measures how well a fabric shields your skin from the sun's harmful UV rays. This factor depends on the type of fiber, the weaving pattern, the colors used, and the finishing treatments applied to the fabric [1]. Based on these standards, a plain, untreated cotton fabric with a UPF of 10 is not considered adequately protective for outdoor use. While both SPF (sun protection factor) and UPF measure sun protection, they differ in how they're determined. SPF is based on human testing, while UPF is calculated through objective measurements. UPF measures the average amount of UV radiation that passes through a fabric compared to what reaches unprotected skin [3].

Metal oxide NPs have mostly been used in antibacterial, self-decontaminating, and UV blocking applications for both military and civilian health products. Nylon fibres with ZnO NPs can provide UV protection as well as reduce static electricity. A composite fibre incorporating TiO_2 or MgO NPs can have self-sterilizing characteristics [53]. Inorganic UV blockers are often semiconductor oxides like TiO_2 [20, 31], ZnO [49], SiO_2 [88] and zinc oxide (ZnO). Titanium dioxide (TiO_2) and zinc oxide (ZnO) are two of the most regularly used semiconductor oxides. Nano-sized titanium dioxide and zinc oxide are more effective at blocking UV radiation than larger particles. This is because nanoparticles have a larger surface area, allowing them to absorb and scatter more UV light [104].

Water repellence

Water-repellent textiles are designed to resist water penetration, keeping the fabric dry by causing water to bead and roll off rather than soak into the material. This effect is often achieved by applying special coatings or by using materials with hydrophobic (water-repellent) properties, making the textiles ideal for outdoor clothing, sportswear, and technical fabrics used in tents, awnings, and other protective gear. Table 6 shows common water repellant chemicals. After the invention of nanomaterials, some nanomaterials could be successfully used as water repellants. Table 7 shows various nanomaterials used as water repellants.

Methods and Technologies for Water Repellence in Textiles

Hydrophobic Coatings: One common method to make textiles water-resistant is through hydrophobic coatings. This involves applying chemical treatments to the fabric's surface to create a barrier that repels water droplets and prevents water from penetrating the fabric.

Nanotechnology for Water Repellency: Nanotechnology offers another approach to water repellency. By applying nanoparticles to textile fibers, a nano-scale rough surface is created. This mimics the "lotus effect," where water droplets bead up and roll off the surface, improving water resistance without affecting breathability.

Synthetic Fibers: Some synthetic fibers, like polyester and nylon, are naturally water-repellent due to their hydrophobic properties and are often used in water-resistant garments.

Polymer-Based Treatments: Durable Water Repellent (DWR)

Table 6: Common Water Repellant Chemicals.

Chemical	Type	Properties	Applications
Fluorocarbons	Long-chain polymers	Excellent water and stain repellency, durable	Outdoor gear, high-performance wear
Silicones	Polysiloxane compounds	Good water repellency, flexible, breathable	Activewear, outdoor textiles
Paraffin Waxes	Hydrocarbon compound	Moderate water repellency, low cost, short durability	Outdoor jackets, workwear
Polyurethane (PU) coatings	Polymer-based coatings	Water-resistant, durable, slightly stiff	Synthetic leather, bags, footwear
Durable Water Repellent (DWR)	Mixture of chemicals	Long-lasting water repellency, abrasion-resistant	Sportswear, technical garments
Wax-based repellents	Natural/synthetic wax	Moderate repellency, eco-friendly, needs reapplication	Canvas bags, casual wear
Teflon (PTFE)	Fluoropolymer	High water and stain repellency, durable	High-performance and industrial use
Alkyl Ketene Dimer (AKD)	Ketene-based compound	Hydrophobic, biodegradable, widely used in paper/textile	Coatings for paper, some fabrics

Table 7: Nanomaterials used for Water-Repellency.

Nanomaterial	Mechanism of Action	Benefits in Textiles	Applications
Silica Nanoparticles	Creates a rough, textured surface that enhances water beading and roll-off	Durable water repellency, maintains fabric breathability	Outdoor clothing, sportswear, tents, upholstery
Fluorinated Nano-polymers	Forms a thin hydrophobic barrier by repelling water molecules on a molecular level	Provides long-lasting water repellency, stain resistance	Rainwear, windbreakers, outdoor upholstery
Titanium Dioxide (TiO_2) Nanoparticles	Adds UV resistance and creates a self-cleaning effect (lotus effect)	UV protection, water repellency, self-cleaning properties	Sportswear, outdoor furniture, automotive fabrics
Graphene Oxide	Forms a hydrophobic coating that reduces water absorption	Lightweight, enhances fabric durability, maintains breathability	High-performance outdoor gear, sportswear
Carbon Nanotubes (CNTs)	Creates a nanoscale layer that repels water while allowing vapour permeability	Strong water repellency, retains fabric softness and flexibility	Protective clothing, activewear, military uniforms
Silicone-Based Nanoparticles	Forms a flexible, durable, and water-repellent coating	Eco-friendly, maintains fabric softness, adds durability	Rain jackets, umbrellas, camping gear
Zinc Oxide (ZnO) Nanoparticles	Roughens fabric surface for water repellency, adds antimicrobial and UV protective properties	UV protection, antibacterial, enhances water resistance	Outdoor clothing, furniture fabrics, automotive textiles
Aluminium Oxide (Al_2O_3) Nanoparticles	Forms a water-resistant, heat-stable barrier	Durable, lightweight, improves fabric longevity	High-temperature textiles, protective outdoor clothing
Polyurethane Nanocoatings	Forms a water-tight yet breathable layer over fabric fibres	Flexible, breathable, provides lasting water repellency	Rainwear, windbreakers, tents
Copper Oxide (CuO) Nanoparticles	Provides both water repellency and antimicrobial properties	Reduces microbial growth, improves water resistance	Medical textiles, sportswear, outdoor gear
Silver Nanoparticles	Offers water repellency and antimicrobial protection	Reduces odour, prevents bacterial growth, long-lasting water repellency	Sportswear, medical textiles, high-performance fabrics
Clay Nanoparticles (e.g., Montmorillonite)	Creates a barrier to water infiltration, enhances durability	Eco-friendly, cost-effective, durable water repellency	Outdoor gear, industrial protective clothing
Polyhedral Oligomeric Silsesquioxane (POSS)	Forms a nanoscale, water-repellent surface on fibres	Lightweight, durable, highly effective water repellency	Outdoor clothing, high-performance fabrics
Metal Oxide Nanocomposites	Creates a durable water-resistant coating with added UV protection	Provides dual benefits of water repellency and UV resistance	Tents, umbrellas, outdoor fabrics

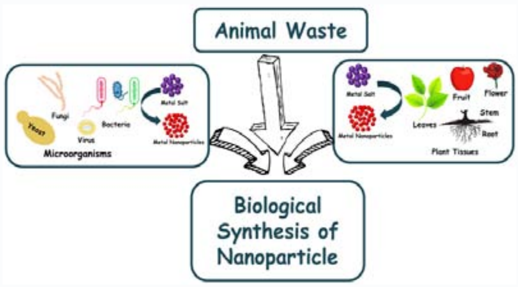

Figure 5: Various biological approaches to synthesis of nanoparticle.

finishes, made from compounds such as fluoropolymers and silicone, are commonly applied to textiles for long-lasting water repellency (Table 7).

Nano Textile improves water repellency by adding tiny, hair-like structures called Nano-whiskers to the fabric. These whiskers are basically hydrocarbons, and they are much smaller than traditional cotton fibers, typically about 1/1000th of the size of a conventional cotton fiber, and they create a soft, fuzzy surface that repels water without weakening the fabric [8]. Water droplets sit on top of these Nano-whiskers because the spaces between them are too small for the droplet to penetrate, yet large enough to allow air to pass through. This creates a durable, breathable water-repellent surface. Nano-TiO_2 impregnation involves creating a 3D surface structure using gel-forming substances. This structure repels water and prevents dirt from sticking to the fabric [18]. As seen in Figure 7, the mechanism is comparable to that of the lotus effect in nature [138]. Lotus plants have rough and textured super-hydrophobic surfaces. When water droplets fall over them, they condense and roll off if the surface slopes slightly. As a result, even during a strong shower, the surfaces remain dry. Furthermore, as the raindrops roll, they take up minute particles of dirt, keeping the lotus plant's leaves clean even during light rain. A cotton fabric, on the other hand, can be given a hydrophobic quality (illustrated in Figure 8) by incorporated NPs. To increase the water repellent property of cotton fabric, a special coating was applied using a process called audio frequency plasma. This coating, made of tiny particles, creates a rough surface on the cotton that repels water. This process keeps the cotton soft and durable while making it highly water-resistant [13].

Nanomaterials offer several advantages over traditional methods in creating water-repellent textiles:

Enhanced Water Repellency: Nanomaterials provide super hydrophobic properties by creating Nano-scale textures on fabric surfaces. This increases the water contact angle, allowing water to bead up and roll off more effectively than traditional coatings.

Durability and Longevity: Nanomaterial coatings are generally

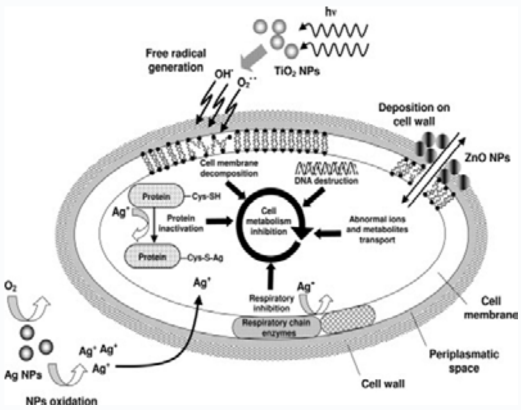

Figure 6: Possible mechanism of nanoparticles' antibacterial activity (Reproduced with permission (Moritz & Geszke-Moritz, 2013). Copyright, 2013 Elsevier).

more durable and resistant to washing and abrasion. The nanoscale treatment penetrates fabric fibers deeply, making it less likely to wear off after multiple washes or extensive use.

Breathability: Nano-coatings can maintain the fabric's breathability, allowing air and moisture vapor to pass through while repelling water. This is crucial for comfort in applications like active wear and outdoor clothing, which traditional water-repellent coatings can sometimes restrict.

Lightweight: Nanomaterials add minimal weight to fabrics. Traditional water-repellent treatments often require multiple layers or thick coatings, which can make the fabric heavy and stiff, whereas nanomaterial coatings preserve flexibility.

Eco-Friendly Alternatives: Some nanomaterials, like silica-based coatings, are more environmentally friendly than fluorocarbon-based repellents, which can be harmful to the environment. Nanotechnology allows for precise control over material usage, reducing waste and environmental impact.

Enhanced Self-Cleaning Properties: Nanomaterials create surfaces that repel not just water but also dirt and other contaminants. This is due to the lotus effect, where Nano-textured surfaces prevent dirt particles from adhering, allowing fabrics to stay cleaner for longer.

Versatile Application: Nanomaterials can be applied to a wide range of fabrics, including delicate textiles that may not tolerate traditional water-repellent treatments well. The nanoscale application is less invasive, preserving the texture and appearance of different fabric types.

Nanomaterial-based water repellents thus combine effectiveness, durability, and eco-friendliness, making them an attractive alternative to traditional water-repellent chemicals.

Wrinkle repellence

Wrinkle-repellent textiles are designed to resist creasing and maintain a smooth, polished appearance even after washing or prolonged wear. This wrinkle resistance is especially valuable for apparel, home textiles, and professional garments, reducing the need for ironing and making fabrics more convenient and durable. Wrinkle resistance in textiles is typically achieved by chemical treatments, fiber modification, or nanotechnology, which impart flexibility and resilience to fabric fibers, allowing them to recover more easily from folding or compression. Cotton is a popular textile material due to its excellent wearing comfort and durability. Unfortunately, cotton cloth wrinkles easily when washed at home, causing significant inconvenience to users. Cotton's low resilience is due to the structure of the biopolymer-cellulose in its fibres, which includes hydrogen bonds as the primary intermolecular connection but no chemical cross-linkages [59]. To overcome winkles, wrinkle resistance to cloth and resin is often achieved using traditional methods where formaldehyde-based chemicals, primarily dimethylol dihydroxy

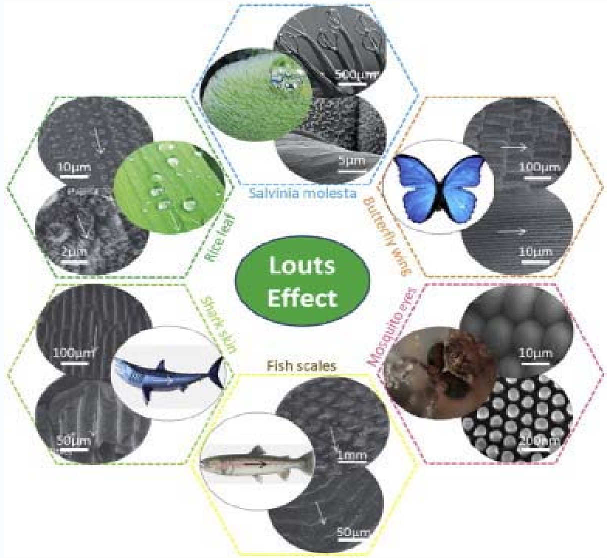

Figure 7: The mechanism is comparable to that of the lotus effect in nature (Reproduced with permission (M. Zhang et al., 2016). Copyright, 2015 Elsevier Ltd.).

Table 8: Nanomaterials used for Textile Effluent Treatment.

Nanomaterial	Function in Textile Effluent Treatment	Applications
Titanium Dioxide (TiO_2) Nanoparticles	Photocatalyst that degrades organic pollutants under UV light	Removal of dyes, organic contaminants, and pathogens
Zinc Oxide (ZnO) Nanoparticles	Photocatalytic and antimicrobial properties	Degradation of dyes, bacteria removal
Iron Oxide (Fe_3O_4) Nanoparticles	Magnetic properties for easy separation, adsorption of heavy metals	Removal of heavy metals and dyes, recovery of nanoparticles
Silver Nanoparticles	Antimicrobial properties to kill bacteria	Disinfection of textile wastewater
Graphene Oxide	High adsorption capacity for organic pollutants	Removal of dyes, organic and heavy metal contaminants
Carbon Nanotubes (CNTs)	High surface area and adsorption capacity	Removal of dyes, organic pollutants, and heavy metals
Silica Nanoparticles	Adsorption of dyes and heavy metals	Dye removal, adsorption of toxic metals
Copper Oxide (CuO) Nanoparticles	Antimicrobial and catalytic properties	Removal of pathogens, degradation of dyes
Zero-Valent Iron (ZVI) Nanoparticles	Reduces and degrades various contaminants, including dyes and metals	Removal of heavy metals, decolorization, pollutant degradation
Magnetic Nanoparticles	Facilitates separation of contaminants when combined with adsorbents	Efficient removal and recovery of nanoparticles after treatment
Manganese Oxide (MnO_2) Nanoparticles	Strong oxidizing agent that degrades organic pollutants	Decomposition of dyes and organic chemicals
Chitosan-Based Nanoparticles	Biodegradable, high adsorption capacity for dyes and metals	Dye removal, heavy metal adsorption, eco-friendly approach
Cerium Oxide (CeO_2) Nanoparticles	Catalyst for oxidation processes and dye degradation	Removal of dyes and organic pollutants
Aluminum Oxide (Al_2O_3) Nanoparticles	Adsorption of heavy metals and organic pollutants	Heavy metal removal, dye adsorption
Gold Nanoparticles	Catalytic degradation of organic pollutants	Dye removal, reduction of toxic compounds

ethylene urea (DMD-HEU), were used to crosslink cellulose. Since the 1950s, DMDHEU has been utilised in cotton finishing for its high wrinkle resistance. This methodology preserves fabric strength and integrity, making it a viable alternative to more demanding traditional methods.

However, there are limitations to its use in fibres and resin, such as a reduction in fibre tensile strength, abrasion resistance, water absorbency, dyeability, and breathability. Some scientists used nano-titanium dioxide and nano-silica to circumvent the limits of resin [121].

To create wrinkle-resistant textiles without compromising their quality, scientists have turned to nanotechnology. Some researchers are employing nano-titanium dioxide [124, 134] and nano-silica [90] to improve the wrinkle resistance of cotton and silk, respectively, to overcome the limitations of using resin. Traditionally, fabrics were treated with resins to reduce wrinkles, but this often weakened the fibers and made them less breathable and less colorfast. A promising approach involves using nanoparticles, such as titanium dioxide (TiO_2), to create cross-links between cellulose molecules in cotton and silk fibers. These cross-links help the fabric retain its shape and resist wrinkles, while preserving its softness and breathability [133].

Under UV irradiation, nano-titanium dioxide was used as a catalyst with carboxylic acid to catalyse the cross-linking reaction between the cellulose molecule and the acid. Nano-silica, on the other hand, was used as a catalyst with maleic anhydride, and the results showed that using nano-silica with maleic anhydride improved the wrinkle resistance of silk.

Clay NPs are resistant to heat, chemicals, and electricity, as well as wrinkle-free and UV light-blocking. Clay NPs can be used into textiles to improve tensile strength, modulus, and flexural strength. Clay NPs can be utilised to make flame-resistant, UV-resistant, and corrosion-resistant nanocomposite fibres. Although flame resistant coatings have been available since the 1970s, they are potentially hazardous due to the production of noxious gases when set ablaze. Clay NPs have been incorporated into nylon to provide flame resistance without the release of hazardous gases. Clay NPs have made it possible to colour polypropylene [94].

Because NPs have a big surface area and a high surface energy, they can provide great stability for treated fabrics, ensuring improved fabric affinity and increasing the endurance of the intended textile functionalities. Surface modification with NPs, including as TiO_2 NPs [66], SiO_2 NPs [19, 131], and nanoparticle mixes like SiO_2/TiO_2 NPs [36] and SiO_2 /Ag NPs [111], is one of the most common methods for modifying the hydrophilicity of fabrics. The Giannelis group [14, 32, 89] have developed nanoparticle fluids with tunable properties, allowing them to be used in various applications like water treatment and battery technology. By modifying the surface of silica or other metal oxide nanoparticles, scientists can create hydrophilic nanoparticles that can be attached to wrinkle-free fabrics. These nanoparticles repel water, preventing the fabric from getting wet. They adhere strongly to the fabric due to electrostatic interactions, resulting in a durable and resilient coating. By carefully controlling the treatment conditions, it's possible to create highly water-repellent fabrics that retain their wrinkle-free properties and soft feel [54].

Textile Effluent Treatment

So far we have discussed various applications of nanomaterials in manufacturing of fabric with desired properties. However, the role of

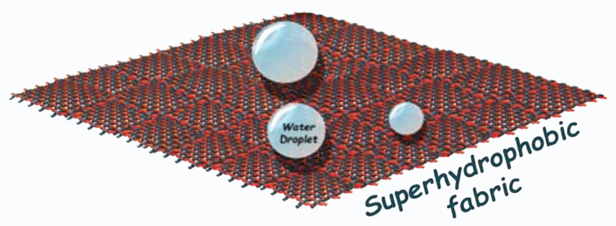

Figure 8: Water droplet on superhydrophobic fabric.

scientist and even industries do not end here. The textile industries consume high amount of water for various wet processes like mercerization, bleaching, dyeing and finishing. The textile effluent obtained at the end of process in generally discharged in the natural water reservoir like river, lake, etc. This creates severe problems from health, environment and ecological aspects. Although government and local bodies has imposed several rules and regulations from time to time to prevent such activities, but in the countries where law is not strictly enforced problem becomes more severe. The industrialists are always trying to adopt economical and feasible routes. The authors are happy to share that nanotechnology has played a key role in protection of natural sources of water. Dye is the natural or synthetic organic material having high molecular weight. The dye can be naturally degraded by the action of sun light. However, this process is very slow as the dye molecules cannot effectively absorb solar radiations. Whenever we are adding nanomaterials the efficiency of absorbing solar radiations becomes very high. Herein we are reporting several nanomaterials which are successfully used to degrade high molecular weight organic compounds. Table 8 shows nanomaterials used for textile effluent treatment.

UV-protection

UV protection refers to safeguarding skin and eyes from the harmful effects of ultraviolet (UV) radiation from the sun. Prolonged exposure to UV rays can cause skin damage, premature aging, sunburn, and even skin cancer. There are various ways to protect from UV-Visible radiations. Protection against UV-visible radiation can be ensured by apply a broad-spectrum sunscreen with SPF 30 or higher to all exposed skin, and reapply every two hours or after swimming or sweating. Wearing UPF-rated clothing, wide-brimmed hats, and sunglasses with 100% UVA and UVB protection is recommended to shield skin and eyes. It is advisable to be in shade especially in between 10.00 am to 4.00 pm when Sun emits maximum amount of UV-radiations. UV- blocking coating can be applied on the car. Also intake of some vitamins, especially Vitamin C and E can protect us and help to combat against the harmful UV-Visible radiations. With the emergence of nanotechnology, nanomaterials can be incorporated in the fabric. Nanoparticles, typically metal oxides such as zinc oxide (ZnO) and titanium dioxide (TiO_2), are incorporated into the textile fibers or applied as coatings on the fabric surface. Here's how this process works and its benefits:

UV Absorption: Nanoparticles such as ZnO and TiO_2 have the ability to absorb and scatter UV radiation. When incorporated into textiles, these nanoparticles can intercept and absorb UV rays, preventing them from reaching the skin beneath the fabric.

Broad Spectrum Protection: ZnO and TiO_2 nanoparticles offer broad-spectrum protection, meaning they can effectively block both UVA and UVB radiation. This helps to reduce the risk of sunburn, premature skin aging, and skin cancer caused by prolonged exposure

Table 9: Nanomaterials used for UV Protection.

Nanomaterial	Description	UV Protection Mechanism	Additional Benefits
Zinc Oxide (ZnO)	Nanoscale ZnO particles offer high transparency and effective UV-blocking abilities.	Absorbs and scatters both UVA and UVB radiation	Antibacterial, enhances durability
Titanium Dioxide (TiO_2)	Widely used in textiles for its effective UV-blocking and whitening properties.	Absorbs and scatters UV radiation	Self-cleaning, antimicrobial
Cerium Oxide (CeO_2)	Known for its stability and ability to block UV rays in harsh environments.	Absorbs and scatters UV radiation	Thermal stability, antioxidant properties
Silica Nanoparticles	Often used as coatings to improve UV protection in fabrics.	Scatters UV radiation	Increases durability and mechanical strength
Silver Nanoparticles	Primarily added for antibacterial properties but also contributes to UV protection.	Reflects and scatters UV radiation	Antimicrobial, odor-resistant
Carbon Nanotubes (CNTs)	Applied in textile coatings for enhanced mechanical properties along with UV protection.	Scatters and absorbs UV radiation	High durability, electrical conductivity
Graphene Oxide	Used for its lightweight, high-strength properties and potential for UV protection in fabrics.	Scatters and absorbs UV radiation	Improved fabric strength and breathability
Aluminum Oxide (Al_2O_3)	Acts as a UV barrier when integrated into textile fibers or coatings.	Scatters and reflects UV radiation	Increases abrasion resistance
Boron Nitride (BN)	Provides UV protection while enhancing the thermal management of textiles.	Reflects and scatters UV radiation	Thermal stability, soft hand feel
Fullerenes	Spherical carbon structures with strong UV-blocking properties.	Absorbs and neutralizes UV radiation	Antioxidant properti

to sunlight.

Uniform Distribution: Nanoparticles can be dispersed evenly throughout the textile matrix, ensuring uniform UV protection across the fabric surface. This distribution helps to maintain consistent sun protection properties even after repeated washing or stretching of the fabric.

Transparency and Comfort: Compared to traditional UV-blocking additives, nanoparticles can provide UV protection without significantly altering the appearance or texture of the fabric. Fabrics treated with nanoparticles remain lightweight, breathable, and comfortable to wear, making them suitable for a wide range of clothing and outdoor applications.

Durable and Long-lasting: Nanoparticles are resistant to degradation by UV radiation and exposure to environmental factors, ensuring long-lasting UV protection for the lifetime of the garment. This durability makes nanoparticle-treated textiles ideal for outdoor apparel, swimwear, sportswear, and other sun-protective clothing.

Environmentally Friendly: ZnO and TiO_2 nanoparticles are generally considered safe and environmentally friendly when used in textile applications. They are non-toxic, biocompatible, and do not release harmful chemicals into the environment during use or disposal.

Thus, overall, UV protection using nanoparticles in textiles offers an effective, versatile, and sustainable solution for mitigating the harmful effects of solar radiation on the skin. By incorporating nanoparticles into fabrics, manufacturers can create sun-protective clothing that helps to promote skin health and reduce the risk of sun-related skin damage and diseases. Technically, inorganic UV blockers are far more preferable to organic UV blockers as they behave like chemically stable and non-toxic under constant exposure to high temperatures and UV. It is said that, semiconductor oxides such as TiO2, ZnO, SiO2 and Al2O3 are usually Inorganic UV blockers. Among these semiconductor oxides, titanium dioxide (TiO2) [15-21] and zinc oxide (ZnO) [Saito 1993, Xiong et al. 2003, Yasuhide et al. 1997] are commonly used. It was observed that, nano-sized titanium dioxide and zinc oxide were more efficient at absorbing and scattering UV radiation than the traditional size and performs better to obstruct UV radiation. [Xin et al. 2004 and Saito 1993]. The main reason behind this, nanoparticles has a larger surface area per unit mass and volume than the conventional materials, which leads to the increase of the effectiveness of blocking UV radiation. Table 9 shows various nanomaterials used in UV-Protection (Table 9).

Sanitary Napkins

Menstruation: Menstruation, commonly referred to as a period, is a natural process that occurs in people with female reproductive systems. It involves the monthly shedding of the uterine lining (endometrium) that occurs in the absence of pregnancy. It is characterized by vaginal bleeding, which typically lasts for a few days to a week. On an average women lose 65 to 80 mL of fluid in a period. Menstruation is in fact a part of the menstrual cycle, which is controlled by hormonal changes in the body. The menstrual cycle typically lasts about 28 days, although it can vary from person to person. The cycle is divided into several phases, including the follicular phase, ovulation, and the luteal phase, leading up to menstruation. During menstruation, the uterus sheds its lining along with blood and tissue through the vagina. The flow of menstrual blood can vary in color, consistency, and volume from person to person and from one menstrual period to another. Many people experience symptoms before or during menstruation, collectively known as premenstrual syndrome (PMS) or premenstrual dysphoric disorder (PMDD). Common symptoms include mood swings, bloating, breast tenderness, headaches, and cramps.

Hygiene and Management: During menstruation, proper hygiene practices, such as using menstrual hygiene products like pads, tampons, menstrual cups, or period underwear, are essential to manage menstrual flow and prevent leaks. It's also important to change these products regularly to maintain cleanliness and prevent infections. Menstrual health is an important aspect of overall reproductive health. Issues such as irregular periods, heavy bleeding (menorrhagia), painful periods (dysmenorrhea), and absence of periods (amenorrhea) may indicate underlying health conditions that require medical attention.

Social and Cultural Perspectives: Menstruation is often surrounded by social and cultural beliefs, taboos, and stigmas in various societies. Efforts to promote menstrual equity, education, and access to menstrual hygiene products aim to address these issues and ensure that menstruating individuals can manage their periods with dignity and without barriers.

Understanding menstruation is essential for individuals with menstrual cycles, as well as for healthcare providers, policymakers, and society as a whole, to support menstrual health and well-being.

Gravimetric absorbency testing is particularly relevant for sanitary napkins, as it helps in assessing their effectiveness in managing menstrual flow. Here's how gravimetric absorbency testing contributes to the evaluation of sanitary napkins:

Absorption Capacity: Gravimetric testing measures the amount of liquid a sanitary napkin can absorb before reaching saturation. This is crucial in determining the overall effectiveness of the napkin in managing menstrual flow throughout the day or night.

Rate of Absorption: It's important for sanitary napkins to quickly absorb menstrual fluid to prevent leaks and maintain comfort. Gravimetric testing helps in assessing how rapidly the napkin absorbs liquid, providing insights into its performance during real-world use.

Retention Capacity: Once absorbed, the menstrual fluid should be securely retained within the napkin to prevent leaks and ensure dryness. Gravimetric testing helps in evaluating the napkin's ability to retain absorbed fluid under pressure, such as when the wearer moves or sits.

Surface Dryness: Gravimetric testing can also provide information about the surface dryness of the napkin after absorption. A napkin that quickly absorbs fluid and keeps the surface dry enhances comfort and reduces the risk of skin irritation.

Types of Sanitary Napkins

1. **Regular Pads:** Standard absorbency pads designed for light to moderate flow, often thinner for everyday comfort.

2. **Overnight Pads:** Longer and often more absorbent, these pads provide extra protection for overnight use.

3. **Maxi Pads:** Thick, high-absorbency pads suitable for heavy flow days.

4. **Panty Liners:** Very thin pads for light spotting, everyday freshness, or the days leading up to or following a period.

5. **Ultra-Thin Pads:** Slimmer pads with similar absorbency levels to regular pads, ideal for discretion.

6. **Reusable Pads:** Made from cloth and designed to be washed and reused, offering an eco-friendly alternative.

Layers of a Typical Sanitary Napkin

1. **Top Layer (Cover):** Soft, skin-friendly, and quick-absorbing to reduce moisture and provide comfort.

2. **Absorbent Core:** Made of materials like cotton, wood pulp, or superabsorbent polymers (SAP), this layer absorbs and retains fluid.

3. **Leak-Proof Barrier:** A waterproof layer, usually made from polyethylene or other synthetic materials that prevents leaks.

4. **Adhesive Layer:** Holds the pad in place on underwear for stability.

Comparative Analysis: By testing different types or brands of sanitary napkins, gravimetric testing allows for comparative analysis of their absorbency performance. This helps consumers and manufacturers make informed decisions about product selection and improvement.

Overall, gravimetric absorbency testing is an essential tool for evaluating the performance of sanitary napkins and ensuring that they meet the needs and expectations of users in terms of comfort, protection, and reliability during menstruation.

The essential properties of sanitary napkin is as below:

- Protection against leakage
- Comfortable to wear and stay in a place
- Hygienic and environmentally friendly
- Odorless

Sanitary napkins are a member of disposable hygiene products those belong to technical textiles as they contain functional textile materials. Sanitary napkins have a big market [1] because almost the half of the world population consists of women and every woman have menstrual bleeding during their fertile periods [1, 2]. The sanitary napkin market will maintain its size until new techniques, which are easier to use, accessible, hygienic and more comfortable, will be emerged. Sanitary napkins are produced as layered structures as they have to fulfill different properties such as absorption, leakage prevention, comfort, etc. at the same time. These layers contain textile and film structures. The uppermost layer which contacts with the body is the top sheet. The material of top sheet can be polyethylene film or polypropylene spun bond nonwoven fabric. An acquisition-distribution layer (ADL) is under the top sheet and it distributes the menstrual fluid along the sanitary napkin and transfers it to the absorbent layer below. The ADL and absorbent layers are made up of nonwoven fabrics. It is advantageous to use nonwoven fabrics as they are easy and fast to produce, they absorb high amount of fluid and they provide comfort to the user. ADL can be made of air laid wood pulp nonwovens or multicomponent structures composed of wood pulp and man-made fibers. Absorbent layer is usually made of wood pulp and superabsorbent polymer. It can be produced by air laid technology and with different configurations. The bottom layer namely back sheet is usually an impermeable film.

The most common material used for commercial sanitary pads is superabsorbent polymer (SAP). This material was first utilized for sanitary pad and diaper manufacture in high-income countries (Japan and the US) in the 1970s. The challenges regarding SAP are that it is expensive, and the production is more technical, requiring a high level of capital and complex machinery. In contrast to SAP, natural plant fibers are cellulose-based and attract water which make them highly absorbent. The structure of plant fibers changes dimensions with changing moisture content because the cell wall contains hydroxyl and other oxygen containing groups that attract moisture through hydrogen bonding. Moisture swells the cell wall, and the fiber expands until the cell wall is saturated with water. Beyond this saturation point, moisture exists as free water in the void structure and does not contribute to further expansion. Superabsorbent polymer can absorb water up to 200-fold of its own weight [17]. Cotton fibers, from cotton plants, typically hold water up to 24–27-fold their own

Table 10: Nanomaterials used in Sanitary Napkins.

Nanomaterial	Function in Sanitary Napkins	Benefits
Silver Nanoparticles	Provides antibacterial and antimicrobial protection	Reduces odour and risk of infections
Zinc Oxide Nanoparticles	Has antimicrobial and anti-inflammatory properties	Protects against irritation and infections
Silica Nanoparticles	Increases absorbency by improving fluid distribution	Enhances overall absorbency and dryness
Graphene Nanoparticles	Used for thermal regulation and antimicrobial effects	Keeps the pad cooler, reduces odour
Titanium Dioxide (TiO_2)	Acts as a whitening agent and provides antimicrobial benefits	Adds brightness and controls odour
Activated Carbon Nanoparticles	Improves odour control and absorbency	Reduces odour and keeps pad feeling fresh
Superabsorbent Polymer Nanoparticles (SAP)	Increases absorption capacity for long-lasting dryness	Keeps moisture away from the skin
Cellulose Nanofibers	Used for structure and improved absorbency in eco-friendly pads	Enhances natural absorbency and comfort

weight [18]. Linen fibers, which are obtained from the flax plant, have less absorbency than cotton fibers [19]. Cotton terry cloth, where cotton fibers are woven in loops, is more absorbent than standard cotton. The surface area of the loops is designed to absorb liquids and the ability of absorption is driven by fabric weight, thickness, and pile yarn twist [20]. Hemp is a natural fiber from a variety of the Cannabis sativa plant. Hemp has goods antibacterial properties and good absorbency [21, 22]. Hemp is more water absorbent than cotton [23]. Bamboo fiber or bamboo textile is another highly absorbent material. Bamboo fiber is also more absorbent than cotton [24]. A study in cloth diapers, comparing bamboo diapers, cotton diapers and blended fabrics found that pure bamboo has the strongest antibacterial activity and a bamboo cotton blend had greater absorption capacity than pure cotton [25]. The cross-section of the bamboo fiber is filled with numerous micro-holes and micro-gaps. Bamboo fibers' cellulose composition consists of crystalline and hierarchal structures which differs from the other natural materials. Bamboo is found to contain a unique anti-bacterial and bacteriostatic bio-agent called 'Bamboo Kun'. This feature of bamboo fiber makes it useful for sanitary products, as it will not gather as much bacteria as other alternatives, when worn for extended periods. Bamboo fiber appears to be an excellent alternative to SAPs, as it is highly absorbent, biodegradable and has excellent ventilation and several anti-bacterial properties. However, processing of bamboo fiber and sealing it into a sanitary pad is expensive, which in turn increases the user cost. In view of that, direct usage of bamboo wadding fabric instead of bamboo fibers is becoming popular. Bamboo wadding fabric has been used previously only inside quilts and children's coat. Table 10 describes various nanomaterials used in sanitary napkins.

Surgical Gowns

Surgical gowns are personal protective garments worn by healthcare professionals during surgical procedures to prevent the transfer of infectious agents, protect against bodily fluids, and maintain a sterile environment. The major uses of gowns are two-fold. Firstly, gowns are used in surgery while performing invasive procedures, both to decrease the transmission of skin flora from the healthcare staff and to protect the staff against contact with potentially infective material, such as blood. Secondly, gowns are used when caring for patients with certain infectious disease to aid in preventing cross-transmission. Surgical garments used to protect the patient and the surgical team during surgery must have a number of features. Pore size in the surgical garment, liquid repellency, liquid-tightness, air permeability and the other properties need to be analyzed. Liquid repellent feature of surgical clothes is very important to prevent the growth of bacteria in moist environments. Fluid-repellent surgical clothing is specifically designed to minimize the risk of contamination during procedures involving bodily fluids. These garments are suitable for a wide range of surgeries, including those with minimal fluid exposure, such as eye surgery and microsurgery. In surgeries involving patients with infectious diseases like Hepatitis B, Hepatitis C, or HIV, the use of liquid-repellent surgical gowns is critical to protect both the patient and the surgical team from cross-contamination. Air permeability of surgical clothes varies according to its raw material. Surgical gowns that allow moisture to evaporate are more suitable to provide the heat balance of the body easily. Surgical gowns that are made from fabric with better air permeability and water vapor transfer rate, have the ability to provide a wider comfort. A surgical gown that does not allow enough evaporation and transfer can cause discomfort to the body. Materials used in surgical gowns must prevent the penetration of bacteria and viruses by linking liquids. But the same material must allow water vapor to escape to ensure protection of body's heat balance.

They are typically made from non-woven materials, which provide a balance of protection, comfort, and breathability. Gravimetric absorbency test also plays a role in assessing the effectiveness of surgical gowns, albeit in a slightly different context compared to absorbent products like sanitary napkins. Here's how gravimetric test contributes to the performance evaluation of surgical gowns: Table 11 shows various nanomaterials used in surgical gowns.

Liquid Barrier Performance: Surgical gowns are designed to provide a barrier against fluids such as blood, bodily fluids, and other contaminants during medical procedures. Gravimetric test helps in evaluating the gown's ability to repel liquids and prevent them from penetrating through the fabric.

Fluid Resistance: In addition to providing a barrier, surgical gowns should resist fluid penetration under varying levels of pressure. Gravimetric testing assesses the gown's resistance to liquid penetration, which is crucial for protecting healthcare workers from exposure to potentially infectious materials.

Durability: Gravimetric testing can also provide insights into the durability of surgical gowns under simulated usage conditions. This includes assessing how well the gown maintains its liquid barrier properties after repeated use, laundering, or exposure to other stress factors.

Comparative Analysis: Similar to other applications, gravimetric test allows for comparative analysis of different types or brands of surgical gowns. This helps healthcare facilities select gowns that offer the optimal balance of protection, comfort, and cost-effectiveness.

Table 11: Nanomaterials used in Surgical Gowns.

Nanomaterial	Function in Surgical Gowns	Benefits
Silver Nanoparticles	Provides antimicrobial and antibacterial protection	Reduces risk of infections and contamination
Copper Nanoparticles	Offers antimicrobial and antiviral properties	Inhibits bacterial and viral growth
Graphene Oxide	Enhances strength and provides antimicrobial protection	Increases durability, reduces pathogen spread
Titanium Dioxide (TiO_2)	Used for antimicrobial properties and UV resistance	Protects against bacteria and environmental UV
Silica Nanoparticles	Improves liquid repellency and enhances fabric durability	Provides fluid resistance and structural integrity
Zinc Oxide (ZnO) Nanoparticles	Known for antimicrobial and anti-inflammatory properties	Helps protect skin, reduces microbial load
Carbon Nanotubes (CNTs)	Adds mechanical strength and enhances flexibility	Increases tear resistance, improves durability
Chitosan Nanoparticles	Naturally derived antimicrobial agent	Provides biocompatibility and antibacterial effects
Polymeric Nanoparticles	Creates barriers and enhances fabric flexibility	Adds fluid repellency and wear comfort
Fullerenes	Acts as antioxidants and enhances microbial resistance	Reduces oxidative damage and microbial risks

Nowadays two categories of materials are used to manufacture surgical gowns: Reusable and single-use material. Reusable surgical gowns are manufactured from woven fabrics and are subjected to washing and sterilization process before each use. But disposable surgical gowns are manufactured from nonwoven fabrics and are designed for a single use.

Types of Surgical Gowns

1. **Standard Surgical Gowns**: Basic gowns providing essential protection against low levels of fluid exposure, used in general surgical settings.

2. **Reinforced Surgical Gowns**: Reinforced in high-risk areas (chest and sleeves) to provide additional protection during procedures with moderate to high fluid exposure.

3. **Disposable vs. Reusable Gowns**: Disposable gowns are single-use, often made from synthetic materials like polypropylene. Reusable gowns are made from washable, durable materials such as polyester and are designed for multiple uses.

Protective Standards

Surgical gowns are typically rated according to their protection levels:

• **Level 1**: Minimal barrier protection, ideal for low-risk situations.

• **Level 2**: Provides a barrier for low to moderate fluid exposure, used for minimally invasive surgery.

• **Level 3**: Moderate barrier protection against larger volumes of fluid exposure, suitable for longer surgeries.

• **Level 4**: High barrier protection for procedures with high fluid exposure and high risk of infection.

Materials Used

1. **Non-Woven Polypropylene**: Provides strength, flexibility, and fluid resistance.

2. **Polyethylene Film Coatings**: Enhances the impermeability of the gown against liquids.

3. **Spunlace and SMS (Spunbond-Meltblown-Spunbond)**: Combines breathability with barrier properties; SMS materials are commonly used in surgical gowns (Table 11).

With modern technology, it is possible to obtain surgical gowns and drapes using many different materials. The choice of using single-use or reusable gowns depends upon rules relating to the barrier and comfort properties of gowns, safety of patient and staff and the risk of bacterial contamination.

Self-cleaning fabrics

Self-cleaning fabrics are advanced textiles that use nanotechnology to repel dirt, stains, and other contaminants. They leverage special coatings and structures that mimic natural phenomena like the lotus leaf effect, where water and dirt easily roll off, leaving the surface clean. Here's how they work and what makes them effective: The nanomaterials used in self-cleaning textiles is shown below in Table 12.

How Self-Cleaning Fabrics Work

Self-cleaning fabrics typically employ two main mechanisms namely Hydrophobic Mechanism and Photocatalytic Mechanism.

Hydrophobic (Water-Repellent) Mechanism: These fabrics have a highly water-repellent (hydrophobic) surface, often using nanomaterials to create tiny peaks and valleys on the fabric surface. This texture significantly reduces the area that water droplets can stick to, causing them to bead up and roll off, taking dirt and other contaminants with them. This effect is inspired by the lotus leaf, which remains clean because dirt particles are carried away by rolling water droplets.

Photocatalytic Mechanism: Some self-cleaning textiles incorporate photo catalysts like titanium dioxide (TiO_2) nanoparticles. When exposed to sunlight or UV radiation, these particles generate reactive oxygen species (ROS) that can break down organic matter, such as stains or bacteria, into harmless components. This is particularly useful for fabrics in medical or outdoor settings, where fabrics need to stay clean without frequent washing.

Benefits of Self-Cleaning Fabrics

Reduced Need for Washing: By repelling water and breaking down dirt particles, self-cleaning fabrics reduce the need for frequent washing, which saves water and energy.

Enhanced Durability: Self-cleaning coatings, particularly nanomaterial-based ones, are often highly durable and resistant to washing and abrasion.

Eco-Friendly: Reducing wash frequency also reduces detergent use and water pollution, making these fabrics more sustainable.

Antibacterial Properties: Many self-cleaning textiles naturally

Table 12: Self-Cleaning Nanoparticles.

Nanomaterial	Type/Composition	Mechanism	Properties	Applications
Titanium Dioxide (TiO_2)	Metal oxide	Photocatalytic under UV light	Breaks down organic matter; antibacterial	Medical textiles, outdoor wear
Zinc Oxide (ZnO)	Metal oxide	Photocatalytic, especially under UV	Stain degradation, antimicrobial, UV-blocking	Sportswear, outdoor fabrics
Silica Nanoparticles	Silica-based compounds	Hydrophobic surface structure	Durable water repellency, transparency	Clothing, outdoor gear
Silver Nanoparticles	Metal-based	Antibacterial action	Antimicrobial, inhibits odour-causing bacteria	Medical, sportswear, uniforms
Copper Oxide (CuO)	Metal oxide	Photocatalytic and antibacterial	Antimicrobial, durable	Healthcare, industrial uniforms
Graphene Oxide	Carbon-based	Hydrophobic and antimicrobial	Water repellency, thermal stability	High-performance fabrics, outerwear
Carbon Nanotubes (CNTs)	Carbon-based	Superhydrophobic properties	Extremely durable, enhances water repellency	Outdoor clothing, industrial fabrics
Fluorinated Nanoparticles	Fluoropolymer-based	Superhydrophobic	High water and stain repellency, durable	Outerwear, high-end fabrics
Aluminium Oxide (Al_2O_3)	Metal oxide	Hydrophobic and UV-blocking	Increases durability and stain resistance	Uniforms, workwear, outdoor fabrics
Silicon Dioxide (SiO_2) Gel	Silica-based	Creates nanoscale roughness	Enhances water beading, self-cleaning	Upholstery, home furnishings
Gold Nanoparticles	Metal-based	Catalytic properties in sunlight	High durability, stain-resistant	High-end fabrics, outdoor wear
Molybdenum Disulfide (MoS_2)	Inorganic compound	Photocatalytic, antimicrobial	Repels water, prevents microbial growth	Medical, outdoor fabrics

resist bacterial growth, thanks to the photocatalytic activity of nanoparticles, which can inhibit or kill bacteria on contact.

Applications of Self-Cleaning Fabrics

Self-cleaning textiles have applications in various fields:

Clothing and Apparel: Active-wear, sportswear, and outerwear benefit from staying cleaner and fresher longer.

Medical Textiles: Self-cleaning and antibacterial properties make these fabrics ideal for uniforms, bedding, and curtains in healthcare settings.

Home Furnishings: Upholstery, curtains, and carpets treated with self-cleaning coatings require less maintenance and cleaning.

Industrial and Outdoor Use: Tents, awnings, and work uniforms in industrial settings benefit from reduced cleaning needs and durability in harsh environments (Table 12).

Smart Textile to Warm up and Cool Down

Smart textiles, equipped with innovative materials and responsive technologies, can now actively adjust body temperature, ensuring optimal comfort in any climate.

Types of Smart Cooling and Heating Textiles

Phase Change Materials (PCMs)

Phase change materials absorb and release thermal energy by changing their physical state (e.g., from solid to liquid or vice versa). When the temperature rises, the PCM absorbs heat, cooling the fabric and wearer. When it cools down, the PCM releases the stored heat, providing warmth. Common PCMs include paraffin wax, fatty acids, and specially formulated polymers, which are microencapsulated in the fabric. They are highly Used in sportswear, outdoor gear, and adaptive clothing for individuals in varying climates or environments.

Thermoelectric Fabrics

Thermoelectric fabrics generate a temperature gradient using the Peltier effect, which creates heat or cooling by passing an electric current through two dissimilar conductors. This process can either release or absorb heat, depending on the direction of the current. Typically, these fabrics use thermoelectric materials like bismuth telluride in conjunction with flexible, conductive fabrics that carry the electric current. They find applications in military and emergency response clothing, as well as garments for extreme weather conditions where on-demand heating or cooling is essential.

Electro-thermal Textiles

By embedding heating elements (like conductive yarns or carbon fibers) into fabrics, electro-thermal textiles can warm up when a small electrical current is applied. Some advanced systems integrate thermal sensors to detect ambient temperatures and regulate heat output accordingly. They make use of conductive yarns (e.g., carbon, silver-coated fibers) woven into fabrics, which can be powered by small, portable batteries. They are commonly found in heated jackets, gloves, and socks, especially for winter sports, outdoor work gear, and healthcare settings to provide warmth in cold environments.

Cooling Textiles with Nano-porous or Microfiber Structures

Fabrics with nanoporous structures and high moisture-wicking capabilities allow sweat to evaporate quickly, promoting cooling. Some fabrics also have the ability to reflect sunlight, reducing heat absorption and keeping the wearer cooler. These textiles often use polyester, nylon, or cellulose-based fibers combined with nanoporous coatings that enhance moisture transport and evaporation. They are most commonly found in active-wear, summer wear, and outdoor work clothing designed for hot climates.

Hydrogel-Based Cooling Fabrics

This type of fabric can be rehydrated periodically, providing prolonged cooling without additional energy. Hydrogels are integrated within layers of fabric or encapsulated in microcapsules that release moisture as temperature rises. They are commonly used in sportswear, military clothing, and industrial uniforms where prolonged cooling is needed without a power source.

Infrared-Responsive Fabrics

These textiles use advanced polymers that respond to the wearer's body temperature, either retaining or releasing infrared radiation to modulate warmth. When the body temperature rises, the fabric

Table 13: Nanoparticles used in Biocompatible coating.

Nanomaterial	Function in Biocompatible Coating	Applications
Hydroxyapatite (HA) Nanoparticles	Mimics bone minerals, promotes bone cell attachment	Orthopedic and dental implants for bone integration
Titanium Dioxide (TiO_2) Nanoparticles	Enhances corrosion resistance and biocompatibility	Implants, stents, dental devices
Silver Nanoparticles	Provides antimicrobial properties to prevent infections	Catheters, wound dressings, surgical tools
Gold Nanoparticles	Known for biocompatibility and anti-inflammatory properties	Drug delivery systems, biosensors, implants
Zinc Oxide (ZnO) Nanoparticles	Antimicrobial, enhances wound healing	Wound dressings, skin grafts, anti-bacterial coatings
Chitosan Nanoparticles	Biocompatible, antimicrobial, promotes cell adhesion	Wound healing, tissue engineering, suture coatings
Graphene Oxide	Adds strength, flexibility, and biocompatibility	Implants, tissue engineering scaffolds
Silica Nanoparticles	Increases surface roughness for cell adhesion, enhances durability	Bone implants, tissue scaffolds
Diamond-Like Carbon (DLC) Nanoparticles	Provides wear resistance, smooth surface, and biocompatibility	Heart valves, orthopedic implants, stents
Calcium Phosphate Nanoparticles	Promotes osseointegration and bone regeneration	Bone implants, dental coatings
Magnesium Oxide Nanoparticles	Biodegradable, supports bone formation	Orthopedic implants, bone tissue engineering
Cerium Oxide Nanoparticles	Antioxidant, reduces oxidative stress on cells	Implants, wound dressings, skin protection
Polyethylene Glycol (PEG) Nanoparticles	Reduces protein adsorption, prevents immune response	Catheters, vascular grafts, drug delivery
Heparin Nanoparticles	Prevents blood clotting, adds anticoagulant properties	Cardiovascular stents, blood-contacting devices
Collagen Nanoparticles	Promotes cell adhesion and tissue integration	Wound dressings, implants, tissue scaffolds

releases infrared energy to cool down. When it drops, it reflects infrared energy back to the body, providing warmth. They are made up of Polymers and fibers that respond to infrared, often combined with heat-retaining materials like metallic coatings (e.g., titanium or silver). They are primarily designed for sportswear, outdoor wear, and clothing for environments with wide temperature fluctuations.

Smart Fabrics with Temperature Sensors and Control Systems

Embedded sensors detect temperature changes and trigger heating or cooling mechanisms as needed. These fabrics are often part of a larger system, connected to a smartphone or wearable device, allowing users to adjust temperature settings on demand. These systems integrate temperature sensors, conductive fabrics, and small control units, typically with Bluetooth or other wireless connectivity. They are used in high-tech clothing for wearable healthcare, smart work-wear, and fashion with adjustable temperature control.

Biocompatible coatings

Biocompatible coatings are materials applied to medical devices, implants, and other biomaterials to improve their compatibility with human tissues and reduce the risk of adverse reactions. These coatings are designed to interact harmoniously with biological tissues, enhance device integration, and minimize immune responses or infection risks. Table 13 shows various nanomaterials used in biocompatible coating.

Key Functions of Biocompatible Coatings

1) **Prevent Immune Reactions**: Minimize inflammation and rejection of implants by the body.

2) **Enhance Device Integration**: Promote cell adhesion and tissue compatibility for better integration with bone, skin, or organ tissues.

3) **Antimicrobial Properties**: Reduce the risk of infection around the device or implant.

4) **Corrosion and Wear Resistance**: Improve durability and performance of the device or implant

5) **Orthopaedic Implants**: Coatings like hydroxyapatite and titanium promote bone integration and increase implant durability.

6) **Cardiovascular Devices**: Antithrombogenic (anti-clotting) coatings such as heparin are applied to stents and vascular grafts to prevent clot formation.

7) **Catheters and Wound Dressings**: Silver nanoparticles and chitosan provide antimicrobial properties to reduce infection risk.

8) **Dental Implants**: Coatings like titanium and calcium phosphate help in Osseo integration (bone bonding).

Nanoparticles can be used to create biocompatible coatings on medical textiles, enhancing their performance and functionality. These coatings may improve properties such as water repellency, stain resistance, and durability while maintaining biocompatibility with the skin (Table 13).

Invisible Cloth

The concept of "invisible cloth" refers to materials or technologies that can render objects or people partially or fully "invisible" or blend seamlessly with their surroundings. Though true invisibility is still largely in the realm of science fiction, significant advances in optics, materials science, and nanotechnology have enabled some real-world progress.

Metamaterials

Metamaterials are engineered materials with structures smaller than the wavelength of visible light. By controlling these structures, scientists can manipulate how light interacts with the surface, bending it around objects rather than reflecting it back to the viewer. This effect, called "negative refraction," can theoretically render objects invisible. Common materials used in metamaterials include metal-dielectric structures, where precise arrangements of metals like gold, silver, or copper are layered with dielectrics to create a unique light response. Currently, most metamaterial cloaking devices work with specific wavelengths, such as microwave or infrared light, so they're not yet functional in the entire visible spectrum. They are being developed for military and stealth applications, as well as in telecommunications and advanced optics.

Thermal Camouflage Using Adaptive Fabrics

Some "invisibility" systems focus on thermal invisibility rather than optical invisibility. Adaptive fabrics with thermoelectric or phase-change materials can control thermal emissions, making objects "disappear" from infrared cameras. These fabrics can actively adapt to surrounding temperatures, blending an object's thermal signature with the environment. These fabrics often uses graphene or thermoelectric materials like bismuth telluride, which can change heat output in response to electric current. They are used in military gear to avoid detection by thermal imaging and they have potential applications in wildlife research and surveillance.

Quantum Stealth Technology (Optical Camouflage)

Quantum Stealth, developed by a company named Hyper stealth, uses a material that bends light around a person or object. Although details are proprietary, it likely combines aspects of optical camouflage with light-bending techniques that distort the viewer's perception, effectively "erasing" the object from sight. Specific details about the materials used are not public, but it likely uses transparent polymer sheets or layered lenses to bend light. They are primarily used for military and defense applications, including camouflage for soldiers, vehicles, and equipment.

Electrochromic and Thermochromics Materials

Electrochromic materials change color or transparency when an electric current is applied, while thermochroic materials do so in response to temperature changes. These materials could theoretically match surrounding colors or even change to a clear state, blending the wearer with the environment. Common electrochromic compounds include tungsten trioxide, while thermochroic materials use liquid crystals or leuco dyes. Not yet used for full invisibility, but widely applied in smart windows and wearables that adjust transparency or color. Researchers are exploring applications for adaptive camouflage.

Augmented Reality (AR) Camouflage

In environments where people use AR glasses or displays, digital camouflage can make objects or people "invisible" by overlaying their surroundings in real-time. Sensors and cameras capture background imagery and project it onto the person or object, blending them into the scene. This approach relies on cameras, sensors, and augmented reality systems, rather than specific textiles. Cameras capture the background image, while AR displays alter the view. Their potential applications include privacy technology, security, and entertainment. Though not true invisibility, it can create a similar effect in digitally enhanced environments.

Reflective and Refractive Cloaking

Reflective cloaking uses mirrors or lenses to direct light around the object. A cloaking device, often constructed from carefully arranged lenses, refracts light so that it appears to travel in a straight line, effectively "bending" around the object. This approach often uses lenses, mirrors, and transparent materials like glass or acrylic. They are primarily used for small-scale invisibility demonstrations in labs. Practical applications are still under research, as this method currently works best with static viewpoints.

Challenges in Achieving Full Invisibility

Creating a fully "invisible" fabric is challenging due to the complexity of manipulating light across the entire visible spectrum, viewing angles, and dynamic backgrounds. Many existing technologies are limited to specific wavelengths or rely on bulky equipment not yet suitable for wearable fabrics. Additionally, real invisibility requires adaptive, real-time light manipulation, which remains a significant scientific and engineering hurdle.

Diagnostic textiles

Nanoparticles can be functionalized with biomolecules or antibodies to create diagnostic textiles for detecting specific biomarkers or pathogens. By integrating nanoparticles into textiles, wearable diagnostic devices can be developed for monitoring health parameters, such as glucose levels, pH, or biomarker concentrations, in real time. Diagnostic textiles are a fascinating intersection of textile technology and medical diagnostics. They involve the integration of functional materials and sensors into textiles to monitor physiological parameters, detect diseases, or provide therapeutic functionalities. Let's see how they work and some examples:

- **Integration of Functional Materials:** Diagnostic textiles incorporate materials with specific properties, such as conductive fibers, nanoparticles, or biomolecules, into the fabric. These materials can interact with biological samples or physiological signals.

- **Sensing Mechanisms:** The functional materials integrated into the textile can serve as sensors to detect various biological signals, such as temperature, humidity, pH, or specific biomarkers indicative of health conditions.

- **Signal Transmission and Processing:** Once the sensors detect signals, such as changes in temperature or biomarker concentrations, the data needs to be transmitted and processed. This can be achieved through embedded electronics or wireless communication systems integrated into the textile.

- **Monitoring and Analysis:** The data collected by the sensors can be monitored in real-time or stored for later analysis. This information can provide valuable insights into an individual's health status, allowing for early detection of diseases or monitoring of chronic conditions.

Examples of diagnostic textiles include:

Smart Garments: Clothing embedded with sensors to monitor vital signs like heart rate, respiration rate, or body temperature. These garments can be particularly useful for athletes, patients with chronic conditions, or elderly individuals living independently.

Wound Dressings: Textiles incorporated with sensors or antimicrobial agents to monitor wound healing or detect infections. These dressings can provide real-time feedback on the condition of the wound and alert healthcare providers to any complications.

Biomedical Implants: Textiles used as implantable devices for drug delivery, tissue engineering, or monitoring physiological parameters inside the body. These implants can be designed to degrade over time or to be biocompatible with the surrounding tissues.

Environmental Monitoring Textiles: Fabrics embedded with sensors to detect environmental pollutants, toxins, or pathogens. These textiles can be used in protective clothing for workers in hazardous environments or for monitoring air and water quality in public spaces.

Overall, diagnostic textiles offer a non-invasive, comfortable, and potentially cost-effective way to monitor health parameters and improve healthcare outcomes. They represent a promising area of research and innovation at the intersection of textiles, electronics, and medicine

Therapeutic textiles

Therapeutic textiles are specialized fabrics designed to provide various health benefits and promote well-being through their interaction with the body. These textiles often incorporate functional materials or technologies that offer therapeutic properties. Nanoparticles with unique properties, such as magnetic nanoparticles or nanoparticles with photo-thermal properties, can be incorporated into textiles for therapeutic applications. For example, magnetic nanoparticles embedded in textiles can be used for targeted hyperthermia treatment of cancerous tumors, while photo-thermal nanoparticles can be employed for localized heating therapy. Here we will discuss some common types of therapeutic textiles and their applications.

Compression Garments: These garments exert pressure on specific areas of the body to improve circulation, reduce swelling, and alleviate symptoms associated with conditions like lymphedema, varicose veins, or deep vein thrombosis. Compression garments are commonly used in medical settings and sports performance.

Far-Infrared Emitting Textiles: Far-infrared (FIR) emitting textiles contain fibers or coatings that emit FIR radiation when exposed to body heat. FIR radiation is believed to improve blood circulation, enhance tissue oxygenation, and promote relaxation. These textiles are used in clothing, bedding, and accessories for therapeutic purposes such as pain relief and stress reduction.

Antimicrobial Textiles: Antimicrobial textiles are treated with substances that inhibit the growth of bacteria, fungi, or other microorganisms. They are used in healthcare settings, personal protective equipment, and everyday clothing to reduce the risk of infections and maintain hygiene.

Moisture-Wicking Fabrics: Moisture-wicking fabrics are engineered to transport moisture away from the skin to the outer surface of the fabric, where it can evaporate more easily. These textiles help regulate body temperature, keep the skin dry, and prevent discomfort and irritation caused by sweating.

Aromatherapy Textiles: Aromatherapy textiles are infused with essential oils or microencapsulated fragrance molecules that are released upon contact with the skin or through mechanical stimulation (e.g., rubbing or pressure). These textiles can provide therapeutic benefits such as stress relief, relaxation, and mood enhancement.

Biomechanical Textiles: Biomechanical textiles are designed to support specific body movements or postures to prevent injuries, alleviate pain, or promote rehabilitation. Examples include orthopedic braces, support belts, and athletic tape.

Photochromic and Thermochromics Textiles: These textiles change color in response to light (photochromic) or temperature (thermochromics), offering visual feedback on environmental conditions or body temperature changes. They can be used for monitoring purposes or as a form of therapy for conditions like Raynaud's disease.

Therapeutic textiles continue to evolve with advances in material science, textile engineering, and medical research. They offer a non-invasive, comfortable, and often cost-effective approach to improve health and well-being, both in clinical settings and everyday life.

Barrier textiles

Nanoparticles can be used to create barrier textiles with enhanced properties, such as impermeability to fluids and airborne particles. By coating or embedding nanoparticles into textile fibers, medical textiles can be engineered to provide protection against biological and chemical hazards in healthcare settings. Barrier textiles are fabrics designed to provide a physical barrier against external agents such as liquids, chemicals, microorganisms, or particles. These textiles are engineered to prevent the penetration or transfer of substances, thereby protecting the wearer or the environment. Here are some common types of barrier textiles and their applications:

Waterproof Textiles: Waterproof fabrics are treated or coated with substances that repel water, preventing it from penetrating the material. These textiles are used in rainwear, outdoor gear, medical garments, and protective clothing to keep the wearer dry and comfortable in wet conditions.

Chemical Protective Clothing: Chemical barrier textiles are designed to resist penetration by hazardous chemicals, acids, solvents, and other corrosive substances. They are used in industrial settings, laboratories, and emergency response situations to protect workers from chemical exposure and skin contact.

Medical Barrier Textiles: Medical barrier textiles are used in healthcare settings to prevent the transmission of infectious agents such as bacteria, viruses, and blood-borne pathogens. These textiles include surgical gowns, drapes, masks, gloves, and other personal protective equipment (PPE) worn by healthcare professionals to minimize the risk of contamination and infection transmission.

Particle Barrier Textiles: Particle barrier textiles are engineered to block the penetration of airborne particles, dust, pollen, and other allergens. They are used in respiratory protection equipment, cleanroom garments, filtration systems, and environmental control applications to maintain air quality and protect individuals from respiratory hazards.

Radiation Shielding Textiles: Radiation barrier textiles are designed to attenuate or block ionizing radiation from sources such as X-rays, gamma rays, and radioactive particles. They are used in medical imaging, nuclear medicine, radiation therapy, and nuclear industry applications to protect workers and patients from radiation exposure.

Fire-Resistant Textiles: Fire barrier textiles are treated with flame-retardant chemicals or made from inherently fire-resistant fibers to prevent ignition, inhibit flame spread, and minimize heat transfer. They are used in protective clothing for firefighters, industrial workers, and military personnel, as well as in home furnishings and building materials to enhance fire safety.

Insect Repellent Textiles: Insect barrier textiles are treated with insect repellent chemicals or infused with insecticidal substances to deter mosquitoes, ticks, and other biting insects. They are used in outdoor apparel, camping gear, and mosquito nets to reduce the risk of insect-borne diseases such as malaria, Zika virus, and Lyme disease.

Barrier textiles play a critical role in protecting human health, safety, and comfort across a wide range of industries and applications.

Their development and use continue to advance with innovations in material science, textile engineering, and regulatory standards for safety and performance.

Conclusion

Nanotechnology is an exciting and rapidly growing field that has found its way into many industries, including textiles. It offers incredible potential for innovation, especially in cotton and other textile production, by enhancing the properties and value of fabrics in a cost-effective way. With the help of nanotechnology, specialized fabrics designed for medical, military, and industrial use can be developed more efficiently. Unlike conventional methods, nanotechnology allows textiles to gain advanced features like antibacterial protection, water resistance, and improved durability, making it a game-changer for the industry.

Conflict of Interest

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