Advances of Nanotechnology in Fabric and Clothing

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Advances of nanotechnology in fabric and clothing

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ABSTRACT

Nanotechnology is swiftly transforming the textile business by bringing innovative materials and treatments that improve performance, comfort, and usefulness. The integration of nanoscale elements, including nanoparticles, nanofibers, and nanocoatings, has endowed textile goods with enhanced characteristics such as antibacterial qualities, UV protection, stain resistance, water repellency, and self-cleaning capabilities. This research examines the diverse spectrum of nanomaterials—including metal oxides, carbon-based nanomaterials, clay, and silicon-based nanoparticles—and their utilization in textiles to address the changing requirements of fashion, healthcare, military, athletic, and protective apparel. It examines manufacturing techniques, including electrospinning and nanocoating technologies such as sol-gel, plasma polymerization, and layer-by-layer deposition, which provide great durability while maintaining comfort and aesthetics. The advent of smart and wearable textiles, which can detect and react to environmental or physiological alterations, represents a significant advancement in functional and intelligent apparel. Nanotechnology has several advantages; yet, it also poses obstacles, including expense, scalability, potential health risks, and environmental consequences. This study assesses the scientific, industrial, and practical progress in nano-fabrics and proposes avenues for further research and sustainable integration. The revolutionary promise of nanotechnology in textiles is unequivocal, heralding a new age of high-performance, multifunctional materials.

Abbreviations

Ag	Silver
Au	Gold
CNT	Carbon Nanotube
CQD	Carbon Quantum Dot
EEG	Electroencephalogram
EMG	Electromyography
L-b-L	Layer-by-Layer
MWCNT	Multi-Walled Carbon Nanotube
PVD	Physical Vapor Deposition
SWCNT	Single-Walled Carbon Nanotube
UV	Ultraviolet
SPF	Sun Protection Factor
LOC	Lab-on-Chip
NPs	Nanoparticles

1. Introduction

Nanotechnology is revolutionizing the textile business by facilitating the development of materials with enhanced functions that surpass conventional performance [1–2]. By manipulating materials at the nanoscale (often under 100 nanometers), researchers and producers may create lighter, stronger, more durable textiles, and more reactive to environmental stimuli [3–5]. These advancements are catalyzing the development of high-performance apparel intended for diverse purposes, including everyday usage and specialist fields such as healthcare, athletics, military, and fashion [6].

This revolution is fundamentally driven by nanomaterials, including nanoparticles, nanofibers, and nanocoatings [7]. These materials are integrated into textile substrates to improve attributes such as stain resistance, moisture management, UV protection, antibacterial characteristics, and thermal regulation [8–10]. Nanofibers can be utilized to produce breathable, water-resistant textiles, whilst nanocoatings may offer self-cleaning or odour-neutralizing properties. These innovations

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enhance comfort and wearability while also prolonging the durability and usefulness of apparel [11].

Nanotechnology has made it easier to create wearable and smart fabrics that can recognize, track, and react to changes in the body or environment. Recent developments include clothing with integrated nanosensors for health monitoring, temperature-adaptive materials, and textiles that collect energy [12–13]. However, the majority of previous reviews have tended to concentrate solely on particular materials (like silver or titanium nanoparticles) or application areas (like antimicrobial textiles), failing to provide a thorough perspective that encompasses the entire range of nanomaterial types, functionalization techniques, and practical textile applications [14].

The use of nanotechnology in textiles has several advantages, but there are also long-term drawbacks, such as high production costs, scaling problems, worries about environmental emissions of nanoparticles, and a lack of consumer safety data [15]. As nanotech textiles quickly move from laboratory-scale invention to commercial production, these concerns are becoming more and more pertinent. Furthermore, previous work has not adequately addressed more recent methods, like as sol-gel processing, layer-by-layer assembly, and plasma polymerization, as well as the emergence of wearable biomedical devices. Thus, there is an urgent need for a critical, updated appraisal that takes into account the numerous advancements, market significance, and sustainability concerns of nanotechnology in fabric and apparel [16].

There is a dearth of literature on nanotechnology in textiles, most of which concentrates on particular nanomaterials or discrete applications. Comprehensive studies that incorporate multifunctional uses, sophisticated production methods, and nanomaterials in industries including healthcare, sports, fashion, and the military are lacking. Understudied are cutting-edge technologies like intelligent drug-delivery textiles and wearable biosensors. To evaluate commercial growth and consolidate information, a comprehensive picture is required.

Therefore, the objective of this research is to provide a comprehensive and up-to-date overview of the application of nanotechnology in textile materials and clothing. The various types of nanomaterials (such as metal oxides, carbon-based, clay, and quantum dots), their production and coating techniques (such as sol-gel, layer-by-layer, and plasma polymerization), and their real-world applications in significant sectors like healthcare, the military, fashion, and sportswear are all carefully investigated. This study also critically examines the commercial trends, technological limitations, health and environmental concerns, and future research directions to link scientific knowledge with industrial scalability. By doing this, it encourages the ongoing transformation of textiles into multifunctional, sustainable, and intelligent materials.

2. Nanotechnology in textile fabrics

The enhancement and possible uses of nanotechnology in creating multipurpose and intelligent nanocomposite fibers, nanofibers, and other novel completed and coated textiles with nanotechnology-based concepts are the main emphasis of the current study. Additionally covered is the concept of employing nanoparticles to enhance product performance in textile finishing and processing. In the textile industry, nanocoating is a comparatively recent technique that is presently in the investigation and development phase. Nanoparticles are used in a variety of polymeric nanocomposite coatings. One extremely promising approach to creating multipurpose, intelligent, high-performance textiles is to spread them as polymeric media and use them for coating applications [17]. Nanotechnology's application in the textiles sector has greatly enhanced the quality, sanitary, durability, and comfort of textiles, thereby reducing the cost of manufacture. When compared to traditional methods, nanotechnology also has many advantages regarding environmental friendliness, economy, conservation, energy, packaging, controlling substrate release, separating and keeping substances in microscopic form for later use and release under regulated circumstances [18]. The innovative nature of nanotechnology and distinctive qualities have drawn scientists and researchers to the textile sector, which has led to a sharp rise in its application in this sector. This could be because one of the greatest fields for nanotechnology research is textile technology. When a significant amount of surface area is present for a specific cloth weight or volume, the textile materials provide the most appropriate materials. This wide space between surfaces is employed in the textile industry's synergy with nanotechnology. When a fiber changes from a moist to a dry state, different macromolecules or supermolecules nearby experience a sharp change in energy. Several studies have concentrated on using textiles to apply nanoparticles to generate final textiles with a range of functional capabilities. Because of their large surface area and high energy of the surface, which guarantees greater affinities for textiles and extends the duration of the targeted textile function, nanoparticles can offer treated fabrics excellent durability. Their adherence to the fibers is primarily determined by their size as well. It seems sensible to assume that the tiniest particles will firmly stick to the fabric matrix and penetrate deeper, whereas the biggest particle agglomerates will be readily removed from the fiber surface [19–20]. Fig. 1 illustrates the application of nanotechnology in textiles.

2.1. Types of nanomaterials used in textiles

i. Metal and Metal Oxide Nanoparticles [21]
ii. Carbon-Based Nanomaterials [22]
iii. Silicon-Based Nanomaterials [23]
iv. Clay Nanoparticles [24]
v. Quantum Dots [25]

2.1.1. Metal and metal oxide nanoparticles

Metal Nanomaterials:

a. Silver Nanoparticles (Ag)
b. Copper Nanoparticles (Cu)
c. Gold Nanoparticles (Au)

Silver (Ag) nanoparticles are frequently used in sportswear and medical textiles [26]. Copper (Cu) has antibacterial and antifungal properties [27]. Gold Nanoparticles (Au) are used in wearable electronics [28].

Metal Oxide Nanoparticles:

a. Titanium Dioxide (TiO_2)
b. Zinc Oxide (ZnO)
c. Iron Oxide (Fe_2O_3)

Titanium Dioxide (TiO_2) has self-cleaning and UV-blocking qualities because of its photocatalytic activity [29]. **Zinc Oxide (ZnO)** combines antibacterial and UV protection properties, making it a textile nanoparticle with two uses [30]. Applications for iron oxide (FeO_3) include electromagnetic shielding, sensors, and magnetic fabrics [31].

2.1.2. Carbon-based nanomaterials

a. Carbon nanotubes (CNTs)
b. Graphene

Fig. 2 **shows** the structure of Carbon Nanotubes and Graphene

It is possible to add CNTs, a type of SWCNT (Single-Walled Carbon Nanotubes) or MWCNT (Multi-Walled Carbon Nanotubes), to textile preforms by either directly integrating with them or combining them with polymer matrices before applying them to textiles [32].

Wearable conductive e-textiles are in high demand for both personal healthcare devices and real-time health monitoring equipment used in

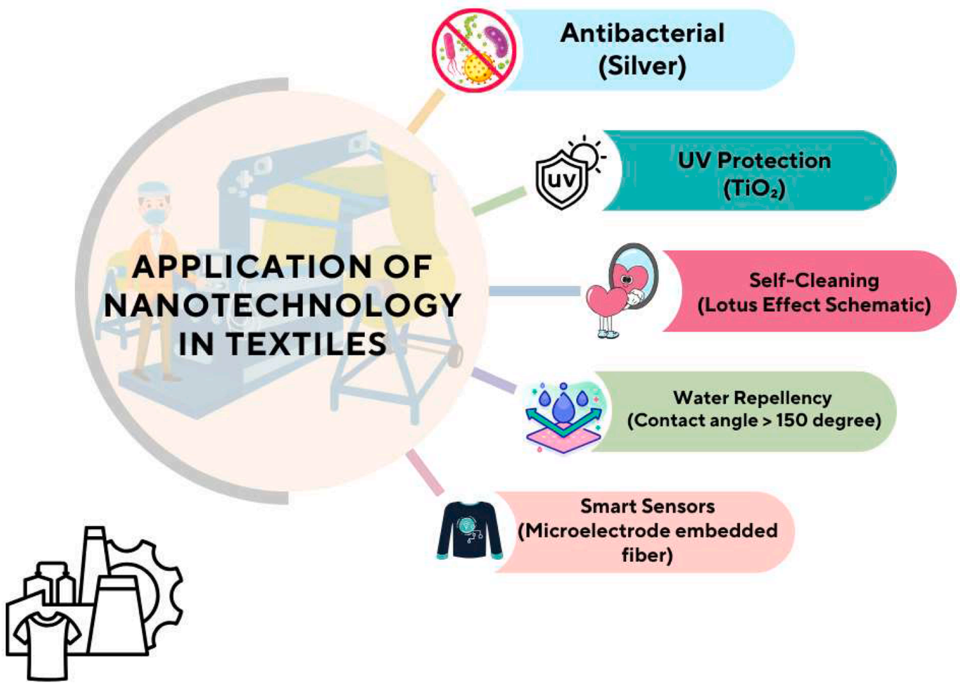

Fig. 1. Application of nanotechnology in textiles.

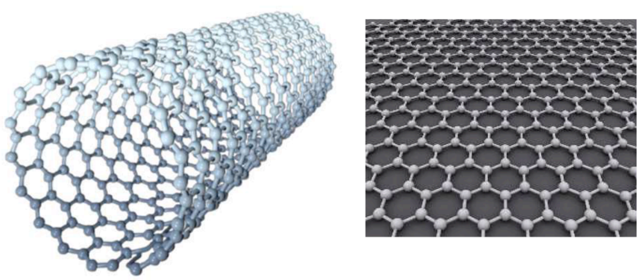

Fig. 2. Carbon nanotube, graphene.

hospitals [33]. Because graphene-based textile electrodes have greater skin contact, are more washable, and are stable over time, they are thought to be a perfect and innovative material for wearable sensors [34]. The textile-based electrodes coated with graphene are very effective and promising materials because of their increased hydrophobicity, stretchability, and bendability, which increases their skin contact [35].

2.1.3. Silicon-based nanomaterials

Silicone technology has revolutionized the textile industry since it is crucial to the process of making clothing. The new era of silicone invention discovery aids clothing producers in creating high-performance, smart, and useful textiles that meet consumer demands. Some beneficial qualities of silicones include their resilience to heat and sunshine, age, chemicals, dampness, and resistance. The majority of them are utilized in insulation, medical applications, adhesives, lubricants, sealants, and culinary utensils. It was adopted by the textile sector as well [36].

2.1.4. Clay nanomaterials

In addition to being resistant to heat, chemicals, and electricity, clay nanoparticles may block UV rays. Clay nanoparticles applied to a textile increased flexural modulus, tensile modulus, flexural strength, and tensile strength. It is possible to construct clay nanoparticle-based nanocomposite fibers to are flame, UV light, and anti-corrosive resistant. To give nylon flame-retardant qualities without emitting toxic gases, clay nanoparticles have been introduced. Polypropylene has been treated with clay nanoparticles to enable dyeing. ZnO, Al_2O_3, TiO_2, and MgO metal oxide nanomaterials have the power to photocatalyze, conduct electricity, absorb ultraviolet light, and oxidize chemicals and biological materials. The primary areas of study about the usage of metal oxide nanoparticles have been antibacterial, self-decontaminating, and UV-blocking uses for both civilian health products and military protective gear [37–39]. Kaolinite, Illite, Bentonite, Chlorite, and Montmorillonite are significant clay particles. Montmorillonite is the most common clay used in textile coating: Chemically (Na, Ca) $6(SiO_{10})_3(OH)$ (Al, Mg) 6-nH_2O, Staying hydrated, Calcium, and Sodium Aluminium. The mineral magnesium Hydroxide of Silicate [40]. In many coating applications, the ability to combine hardness, scratch resistance, and flexibility is greatly desired. This can be accomplished by mixing unaltered clay and montmorillonite (Na+MMT) with a polymer resin made of various textile materials. When the clay was added, all coatings showed exceptional chemical resistance and adhesion, while conventional coating characterization techniques showed an improvement in surface hardness, scratch resistance, and flexibility [41].

2.1.5. Quantum dot nanoparticles

The materials used to make military textiles need to be easy to clean, comfortable, and come with handy maintenance instructions. It is also important to take into account their sterilization or disinfection, as well as their washing durability [42]. High-temperature resistance, exceptional electrical and thermal conductivity, high plasticity, corrosion resistance, UV blocking, high adsorption rate, and high catalytic performance are just a few of the beneficial properties of carbon quantum dots (CQDs), which are spherical nanoparticles with a particle size of 1–10 nm [43–44].

2.2. Nanofibers and nanocoating

A novel type of nanomaterial, nanofibers have lengths in the micron or millimetre range and diameters in the submicron region (50–500 nm). They have certain special qualities because of their extremely large surface area, which makes them viable options for a variety of uses, including filtration, barrier textiles, protective gear, wipes, and biological uses like scaffolds for tissue engineering [45]. Nanofibers are extremely thin fibres that have dimensions between one and one hundred nanometres. Their small pore size, high surface area-to-volume ratio, and increased flexibility provide them with special mechanical, chemical, and physical characteristics. These qualities provide nanofibers with great value in a range of textile applications [46]. Fig. 3 shows Potential applications of electrospun nanofibers

Table 1, Table 2, Table 3

Fig. 4 shows the Manufacturing process of nanofibers.

The textile sector has enormous commercial potential thanks to nanotechnology. This is mostly because conventional techniques for giving textiles new qualities frequently fail to provide long-lasting results and can lose their usefulness after several washings or wearing. Thus, developments based on nanotechnology have created a plethora of opportunities for textile finishing methods, leading to both innovative new finishes and novel application strategies. The most crucial is to apply different types of nanoparticles or create structured surfaces based on nanotechnology to make chemical finishing more manageable, long-lasting, and substantially more functional. Numerous technical textile applications, including protective apparel, medical textiles, sportswear, automotive textiles, etc., can benefit from the remarkable level of textile performances in Nano finishes, such as stain resistance, antimicrobial, controlled hydrophilicity/hydrophobicity, antistatic, UV resistant, wrinkle-controlled, and shrink-proof properties. Finishing methods that use nanotechnology in the form of Nanoemulsions also allow for more intelligent applications on textile surfaces. More significantly, finishing based on nanotechnology can give fabrics high durability because nanoparticles have a high surface energy and a large surface area-to-volume ratio, which improves their affinity for fabrics and increases the function's durability. Therefore, a coating and nanoparticles on a fabric's surface won't change how it feels to the touch [49]. Coatings can make a substance biocompatible, improve a material's mechanical, thermal, or chemical stability, increase wear resistance, durability, or lifetime, reduce friction or prevent corrosion, or alter the material's overall physicochemical and biological characteristics. An ancient technique for adding particular surface qualities, such as shine, wear, hydrophobicity, water and gas barrier, conductive, antistatic, and antibacterial, is to apply a polymeric layer to a wood, metal, textile, or leather substrate. However, traditional coating has some issues, including poor abrasion resistance, poor adhesion, strength loss, and reduced durability [50–51]. Higher coat-to-weight ratios are frequently needed to obtain the necessary level of surface quality. Scientists concentrate their efforts on reducing the coat-to-weight ratio to solve

Table 1
Products based on nanofibers that are sold commercially [48].

Serial No.	Company Name	Product name	Type of product
01	Beauty Cloth International	Beauty Cloth ExfoliaTM facial cloth	The skin's dead scale is removed by the nanoscale threads without harming the lower layers.
02	Donaldson Company Inc. USA	Industrial filters	Air, oil, and hydraulic nanofiber-based filters
03	eSpin Technologies	SIMWYPESTM	Super dusting cloths that can eliminate dangerous pollutants that are undetectable.
04	Hollingsworth & Vose	Nanoweb	Air and liquid filter.
05	Mempro	Filterhot	Air filters made of catalyzed ceramic nanofibers are used in coal-fired power stations to cut down on pollution.

Table 2
Advantages and disadvantages of plasma polymerization-assisted nano-coating.

Advantage	Disadvantage
Solvent-free, one-step coatings [59]	Demands RF generators and exact control for vacuum or atmospheric plasma systems, which raises the cost and complexity of operations [63].
Coatings without pinholes (ranging in thickness from around 100 pm to 1 μm) that adapt effectively to a variety of substrate geometries [60]	Precursors are randomly fragmented by plasma, making it difficult to regulate or replicate their final composition and functionality [64].
The resulting coatings have high cross-linking, which makes them mechanically strong, chemically stable, and long-lasting [61].	Behavior that is dependent on the system [65].
Surface functionality that can be adjusted [62].	Limitations of the multifunctionality of films [66].

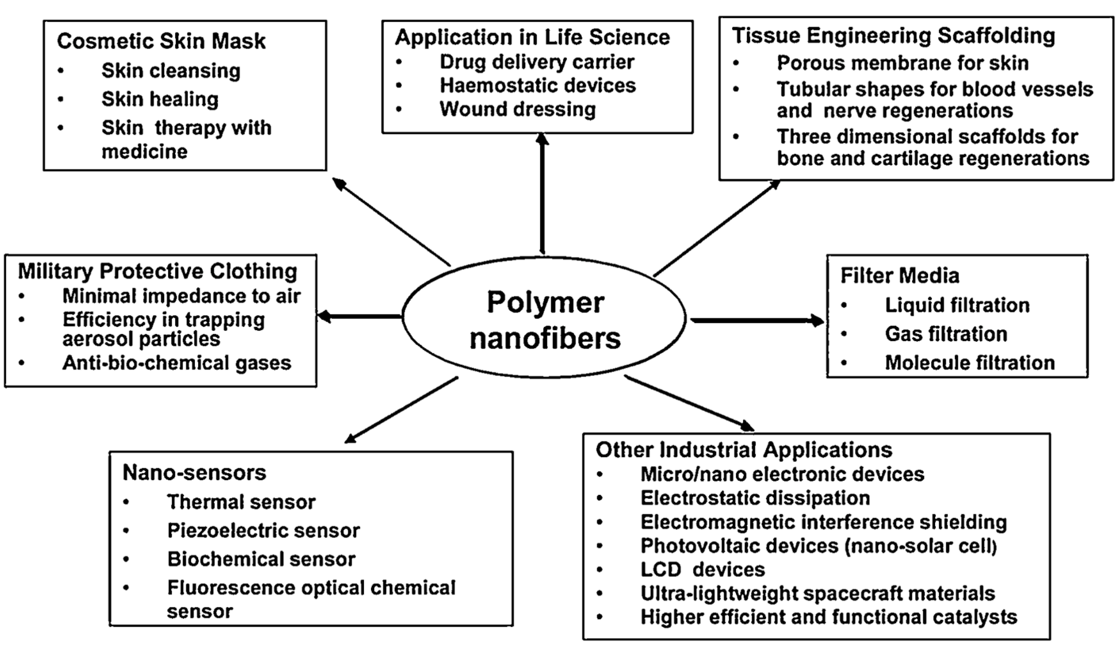

Fig. 3. Potential applications of electrospun nanofibers [47].

Table 3
Advantages and disadvantages of sol-gel.

Advantage	Disadvantage
Superior molecular homogeneity and purity [69]	Monoliths frequently crack or shrink as a result of the delicate and time-consuming processes of drying, ageing, and thermal densification [73].
Processing at low temperatures [70].	Less bonding and generally less wear resistance than other coatings, which restricts use in high-wear situations [74].
Economical for nanotechnology and small-scale [71].	Challenging to adapt to large-scale production, particularly for intricate or thick coatings; expensive and moisture-sensitive metal-alkoxide precursors [75].
Ability to create a variety of morphologies, including films, coatings, fibres, and monoliths, with adjustable porosity and hybrid organic-inorganic composites [72].	Precursor purity, pH, solvent, and catalysts all have a significant impact on product quality; side reactions can introduce contaminants [76].

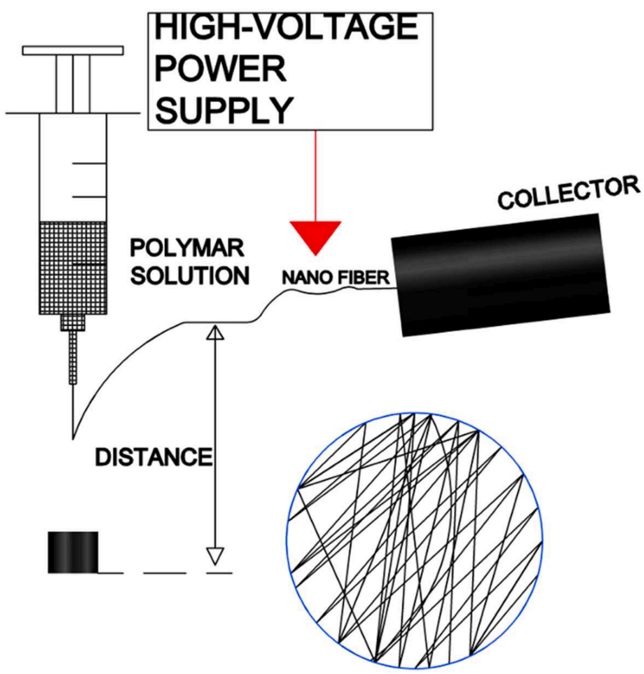

Fig. 4. Manufacture of nanofibers.

these issues. Since the development of nanotechnology, a new field of extremely thin (about 50 nm) textile nanocoating has emerged. Coating is only the process of applying a layer to a material; therefore, nanocoating is the application of a layer that is as thick as a nanometer or the application of a nanoscale entity to a surface. Developing nanostructured surfaces with greatly improved or optimized characteristics is one of the new strategies. Nanostructures can form during the coating process or by arranging the constituents into the appropriate coating configuration [52–54]. These nanostructures provide characteristics that significantly affect the strength, durability, corrosion resistance, and coating reactivity [55]. Vapor deposition, chemical reduction, pulsed laser deposition, mechanical milling, magnetron sputtering, self-assembly, layer-by-layer coating, dip coating, sol-gel coating, electrochemical deposition, and plasma-assisted/ion-beam-assisted techniques are some of the widely used nanocoating techniques. Planar substrates are preferred for coating by most of these methods. The most crucial methods for determining application compatibility on a textile substrate's uneven surface include layer-by-layer, sol-gel, plasma polymerization, and self-assembly.

2.2.1. *Self-assembly-based nano coating*

To bring out more advanced functionalities in textile processing, Toray Industries, Inc. has successfully developed a "nano-scale processing technology" that enables the formation of molecular arrangements and assemblies [56]. Each of the monofilaments that make up the fabric (woven or knitted fabric) has a functional material coating (10–30 nm) created by this "nano-scale processing technology" called "Nano-MATRIX." Fig. 5 represents Nanomatrix Technology from Toray for nanocoatings on textiles through self-assembly

The idea of "self-organization" is the foundation of the "nano-matrix," which regulates variables including temperature, pressure, magnetic and electrical fields, humidity, and additives.

By managing the interactions and reactions between the functional material to be coated and the fiber material (polymer), it is feasible to accurately regulate the state of molecular arrangement and/or assembly of functional materials on each of the monofilaments at the nanoscale. Without sacrificing the texture of the fabric, the use of this technology is anticipated to result in the creation of new features as well as notable enhancements to the current ones (quality, durability, feel, etc.).

2.2.2. *Plasma polymerization-assisted nano-coating*

Comprising highly excited atomic, molecular, ionic, and radical species with free electrons and photons, plasma is a partially ionized gas. Plasma is produced when gases receive enough extra energy from an electric field. There are a large number of simultaneous recombination mechanisms because the reactive species of plasma, which are produced by ionization, fragmentation, and excitation processes, are strong enough to dissolve a broad range of chemical bonds. The benefits of altering the surface characteristics of inert materials are demonstrated by plasma surface treatments. The primary benefits of plasma polymerization techniques are as follows:

(1) They can be applied to nearly all organic, organometallic, and heteroatomic organic compounds.
(2) They can modify surface properties without changing the bulk characteristics.
(3) They require little energy because they only require small amounts of monomeric compounds [58].

2.2.3. *Sol-gel*

The innovative method of creating highly active surfaces with UV-blocking, antibacterial, and self-cleaning qualities, as well as remarkable durability and low coat weight, is nanocoating textiles and apparel. Numerous fields, such as biomedical engineering, electronics, material science, and catalysts, apply the sol-gel method, a popular method for coating surfaces with nanoscale entities [67]. The sol-gel nanocoating process typically uses the dip coating method [68].

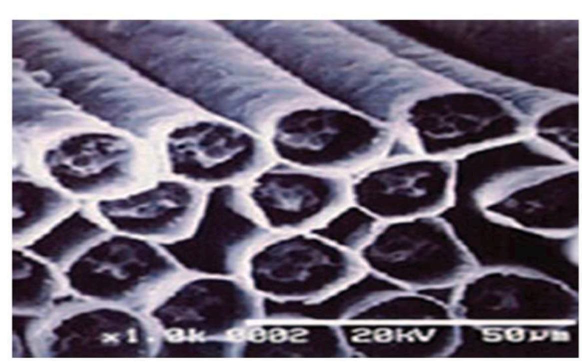

Fig. 5. Nanomatrix technology from Toray for nanocoatings on textiles through self-assembly [57].

Thermal densification and drying can cause cracking or shrinking in sol-gel coatings, which can lead to poor mechanical durability, particularly in thicker or porous layers [77]. The mechanical durability of plasma polymer films is increased by their excellent cross-linking, chemical stability, and wear resistance [78]. In a basic lab setting, sol-gel is less expensive, but it requires solvents, catalysts, and potentially dangerous byproducts that need to be treated [79]. Waste remediation expenses are decreased by plasma technologies' elimination of solvents, but the cost is significantly increased by the capital expenditure and specialised gases or RF equipment [80]. Although inert in bulk, nanomaterials from sol-gel processes can leak or shed nanoparticles; ecotoxicity varies depending on the material (e.g., TiO_2 or ZnO); these can be harmful to aquatic creatures [81]. Environmental safety profiles are impacted by repeatability; plasma polymers might inadvertently include pollutants from ambient or feed gases while avoiding solvent dangers [82]. Usually batch-based, sol-gel techniques are sensitive to environmental factors and challenging to scale consistently, raising serious questions about repeatability and quality control [83]. Potential for industrial scalability is provided by plasma polymerisation, particularly in atmospheric-pressure roll-to-roll systems. However, maintaining uniformity over wide regions and intricate shapes is still a difficult technical task [84].

2.2.4. Layer-by-layer

With molecular-level control over film thickness and chemistry, layer-by-layer (L-b-L) nanocoating techniques can be used to manufacture thin film coatings. The l-b-L procedure doesn't require any specific equipment, and mild physicochemical conditions can be used to create nanocoatings. Any surface that is suitable for the water-based layer-by-layer adsorption method used to create poly-electrolyte multi-layers, including the interior surfaces of complicated objects, can have this kind of coating applied to it [85]. The l-b-L assembly process creates multi-layer coatings (or films) with nanometer-thick layers by sequentially adsorbing oppositely charged polyelectrolytes on a charged solid support. Fig. 6 represents a Schematic of l-b-L nanocoatings through self-assembly.

3. Key advancements in nanotechnology for fabrics and clothing

Enhancing fabric qualities without appreciably increasing weight, thickness, or stiffness is possible when clothing and fabric are made with nanoparticles or nanofibers. For instance, adding nanowhiskers to pants' fabric creates a lightweight textile that resists stains and water [87–90]. The last few decades have seen many different applications and scopes in the textile industry due to the growth of nanotechnology in the production of fibers and yarns, including the creation of fabric finishes. The development of nanotechnology has been significantly aided by the recent improvements in fabric treatments. The surfaces of textiles treated with abrasion-resistant, water-repellent, ultraviolet (UV), electromagnetic, and infrared protective finishes can be significantly altered by mixing the nanoparticles with organic and inorganic chemicals. Recently, nanoparticles of titanium dioxide (TiO_2) have been used to protect against UV rays. Cotton textiles are more resistant to wrinkles when nanoengineered cross-link agents are used during the finishing process. The textile sector uses the recently created microencapsulation method for fire or flame-retardant chemicals. Silver nanoparticle-based microcapsules (Silver Cap) have been created to reduce odour and have antimicrobial properties [91]. Table 4 shows nanotechnology's application area

3.1. Functional fabrics

Advanced textiles known as "functional fabrics" are made to offer particular qualities or functions that go beyond the typical uses of clothing, such as insulation and covering. To improve their performance in areas including comfort, durability, protection, and flexibility, these textiles use specific technologies, materials, or treatments [97].

3.1.1. Functional fabric feature

1. Self-cleaning
2. UV protection
3. Antimicrobial properties
4. Textiles as Sensors
5. Smart textile
6. Wrinkle resistance

Table 4
Nanotechnology advancements and their application.

Advancement	Application	Reference
Antimicrobial Nanocoating	Improves cleanliness, lessens odor, and stops bacteria from growing in sportswear.	[92]
Conductive Nanofibers	Makes wearable sensors and electronics possible through smart textiles.	[93]
Thermoregulating Fabric	Keeps body temperature stable; utilized in outdoor gear and sportswear.	[94]
UV protective Nano fabrics	Protects against damaging UV radiation; it is utilised in outdoor apparel.	[95]
Color-changing Nano fabrics	Both fashion and military camouflage use it.	[96]

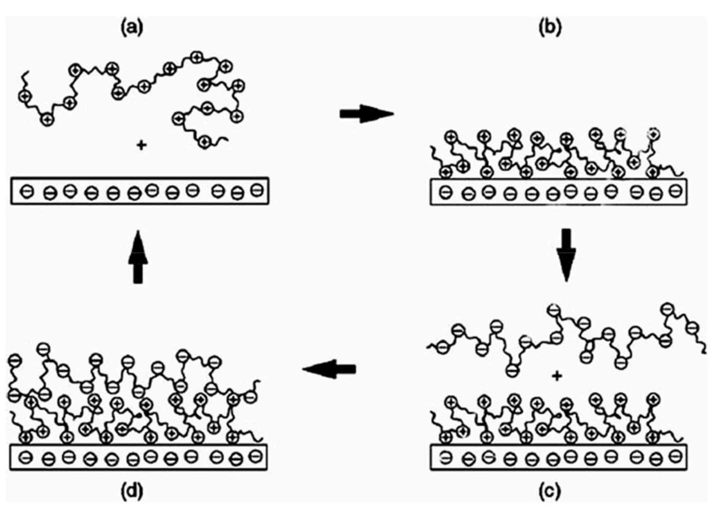

Fig. 6. L-b-L nanocoatings through self-assembly [86].

7. Waterproof.

3.2. Smart and wearable textiles

The phrase "smart textiles" describes a wide range of research and goods that increase the practicality and usability of everyday textiles. Textile goods that can interact with the environment or user, such as fibers, filaments, yarns, and woven, knitted, or non-woven structures, are referred to as smart textiles. The creation of smart materials that can perform a wide range of tasks, which are now present in rigid and non-flexible electronic goods, may be impacted by the convergence of textiles and electronics, or e-textiles. In addition to improving social well-being, smart textiles may result in significant welfare budget savings. They fall into one of three groupings and combine a high degree of intelligence:

- **Passive smart textiles:** only dependent on sensors to sense the user or surroundings;
- **Active smart textiles**: combining a sensing device with an actuator function to sense environmental stimuli reactively;
- **Advanced smart textile**: Very intelligent fabrics that can feel, respond, and change their behaviour depending on the situation.

The presence of sensors is crucial in passive smart materials since they give a nervous system the ability to detect signals. Together with the sensors, the actuators are a crucial component of active smart materials. They can respond to the detected signal on their own or through a central control unit [98]. Fabrics with thermocouples can be used to sense temperature [99], luminescent elements integrated into fabrics can be used for biophotonic sensing [100], shape-sensitive fabrics can sense movement, and EMG sensing can be combined with fabric sensors to determine muscle fitness. Fabric sensors can be used for electrocardiogram (ECG) [101], electromyography (EMG) [102], and electroencephalography (EEG) [103–104].

3.2.1. The smart bra

The Smart Bra was created in Australia and is intended to adapt its characteristics to the motions of the breasts. To avoid breast soreness and droop, it can loosen and tighten its straps or relax and stiffen its cups [105]. A stretchy bra for early diagnosis of breast cancer. Palpreast, an inflatable bra, aids in the early detection of cancer [106]. Fig. 7 shows a smart bra that prevents early breast cancer

3.3. Enhanced durability and comfort

Every day, living depends on textiles, and user happiness is greatly impacted by their performance qualities. Conventional techniques for improving fabric qualities frequently require sacrificing comfort for durability. Nanotechnology, on the other hand, provides solutions that simultaneously solve both issues. This essay examines how nanotechnology might increase the comfort and durability of textiles while highlighting innovative and useful uses [108].

3.3.1. Enhancing comfort

Memory for shapes. Materials with a form memory function that is woven or otherwise treated into textiles are known as textiles. Shape memory, high deformation recovery, good shock resistance, and flexibility in the face of external factors like temperature, mechanical force, light, pH level, etc., are only a few of the remarkable properties of textiles. An Italian company called Corop Nove invented the "lazy shirt." The shirt's sleeves can self-heal and even iron in cold weather, and they will instantly roll up from the wrist to the elbow in a matter of seconds in hot weather [109]. Fig. 8 represents the Shape-Memory Foam Applications.

4. Applications of nanotechnology in clothing

The contemporary textile business must contend with a steady flow of new and increasingly inventive products and unrelenting consumer demand for creative uses of emerging technologies. Nanotechnology allows for the creation of innovative, multi-functional textiles with revolutionary applications in health, pharmaceuticals, military, fashion, sports, protection, and transportation [111–112].

4.1. Healthcare

Nanotechnology effectively advances diagnostics, regenerative medicine, disease treatment, gene therapy, dentistry, oncology, medication delivery, aesthetics, and therapeutics.

4.1.1. Utilization of nanotechnology in diagnostic procedures

Medical diagnostics stand to benefit significantly from the increased speed, sensitivity, and precision made possible by nanotechnology [113]. Nanoparticle-based diagnostic imaging improves MRI, CT, and PET scan sensitivity, accuracy, and specificity by attaching nanoparticles to biomarkers [114]. Nanotechnology-enabled point-of-care diagnostic tests can quickly and accurately diagnose infectious diseases, cancers, and other illnesses. Timely therapy and avoiding these disorders are possible [114–115]. For early identification and therapy, nanotechnology enables sensitive biosensors to detect low biomolecule quantities in blood and urine. Sickness management [116–117]. Nanomaterial-based microfluidic technologies separate and analyze cells, proteins, and genetic material for fast and accurate disease diagnosis [114,118]. Nanopore sequencing, a new technology, may swiftly and reliably diagnose cancer and hereditary disorders by detecting DNA or RNA sequences [119]. Nanomedicine improves in vitro diagnostic efficiency and reliability [120]. This uses subcellular nanodevices, human tissue, cell culture, and physiological fluid samples [114, 121–122]. Nanomedicine devices are being developed for in vivo diagnostics to detect bodily irregularities that could cause toxicity or tumors [118,123]. Diagnostics use paramagnetic nanoparticles, nanocrystals, quantum dots, nano shells, and nanosomes [124–125].

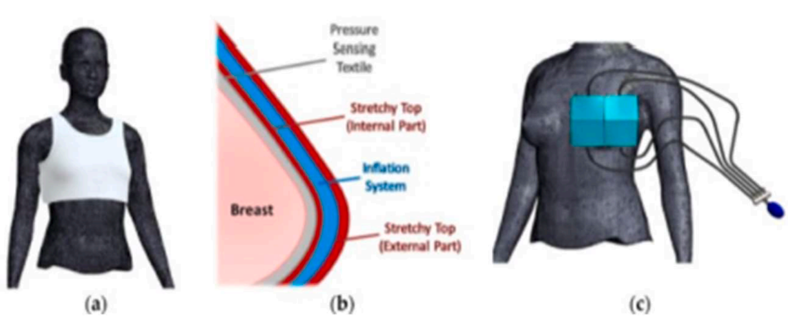

Fig. 7. (a) Shows a stretchable bra for an early breast cancer diagnosis; (b) shows four separate air chambers positioned around the breast, and (c) shows a pressure-sensitive textile sensor [107].

Fig. 8. Shape-memory foam applications [110].

Nanotechnology could improve healthcare diagnostics and tailored medicine.

4.1.2. Lab-on-chip technologies and nanotechnology

Nanotechnology and Lab-on-Chip Technology revolutionized disease detection, personalized treatment, and medicine delivery [126]. These technologies have led to faster, more accurate, and cost-effective diagnostic tools than older methods [127]. Virus and cancer treatments using Lab-on-Chip technology are being investigated [126,120]. The entire process requires cellular genetic data analysis [126]. Gene sequencing and body fluid collection have progressed nanotechnology, enabling treatments for untreatable diseases. The combination of these technologies created Lab-on-Nanoparticles, miniature devices that can diagnose, administer drugs, and monitor health [127–128]. Nanoscale materials enable real-time monitoring and personalized treatment [122]. Nanotechnology and Lab-on-Chip Technology aid cancer diagnosis [116–117]. Nanoparticles can identify and cure cancer early [129]. Lab-on-chip detects genetic, metabolic, and viral disorders [128, 130]. Medicine uses nanoscale and Lab-on-Chip Technology for drug delivery [128]. Nano-liposomes address particular cells or tissues, improving treatment efficacy and decreasing adverse reactions [114, 131]. In addition, nanoscale diagnostics can identify infections. These sensors monitor organ medication release, improving therapy [132].

4.1.3. Utilization of nanotechnology in medicinal sciences

Nanotechnology applications in pharmaceutical sciences are briefly discussed in the next section, with a graphic in Fig. 9.

Nanotechnology has transformed the pharmaceutical sector by

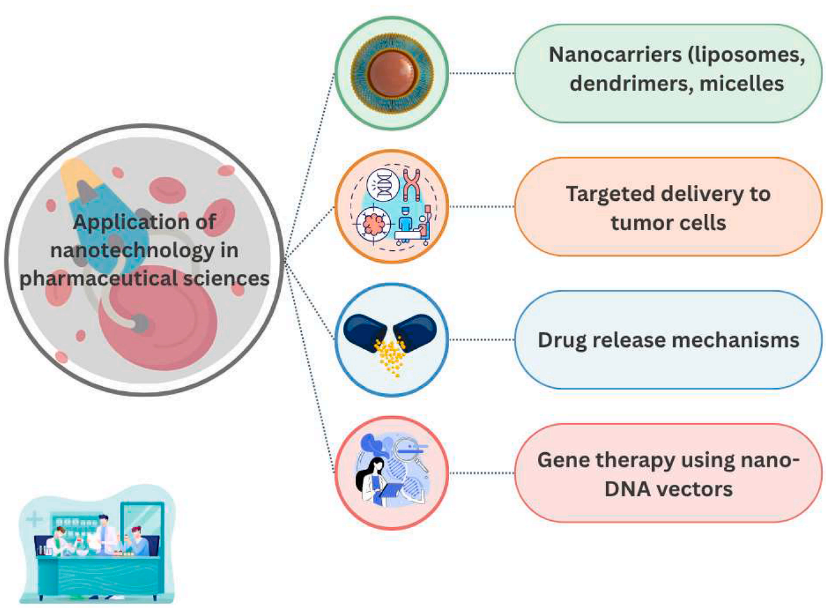

Fig. 9. Application of nanotechnology in pharmaceutical sciences.

enabling the creation of more effective and less harmful medications. Nanoparticles optimize medication pharmacokinetics by enhancing solubility, stability, and bioavailability [133]. Targeting specific tissues and cells can improve efficacy and reduce adverse effects [121]: Nanoscale and unique physicochemical properties. Nanoparticle characteristics necessitate precise drug dosage and administration requirements [134–135]. The dose of nanoparticles varies on factors such as size, shape, surface qualities, and administration route [135]. Due to differences in absorption and distribution in the body, oral delivery may require a higher dose than intravenous treatment [135–136]. Nanorobotics can oxygenate tissues 200+ times better than red blood cells [137–139]. Nanotechnology may be used for diagnosis and future blood-linked disease treatment [138]. DNA strands are infused into patients' cells to repair broken or missing genes in gene therapy [140]. Nanoparticle-based gene therapy delivers remedial genes to targeted cells [136,141]. Nanocarriers prevent DNA degradation and increase cell membrane penetration to improve genetic therapy efficacy and safety [139,142].

4.1.4. *Other applications of nanotechnology in the medical field*

They can cross cell membranes and the blood-brain barrier, making them advantageous for delivering medicines and therapeutic substances to cancer cells. They can also detect cancer cells and pinpoint illness sites and types [143]. Nanotechnology plays a promising role in cancer diagnostics by developing tailored nanoparticles. Special nanoparticles cling to cancer cells, making them easy to use. Commodity fibers, including synthetic (polyester, polypropylene, polyamides, and PTFE) and natural (cotton, silk, and viscose), are frequently utilized in dressings and personal hygiene products because of their comfort, absorbency, and durability [144]. Spunbond, meltblown, and air-laid non-woven textiles are distinguished by their high porosity, absorbency, and filtration capacities. Fabrics that are knitted or woven based on the needs for reusability and structure [145]. Alginate dressings made from seaweed alginic acid salts absorb exudate to create hydrophilic gels that are naturally conformable and biodegradable, making them perfect for wounds that exude a lot [146]. Sodium carboxymethylcellulose-based hydrofiber dressings absorb a lot of liquids and reduce maceration by forming gels [147]. Dry gauze, lint, plasters, bandages (natural or synthetic), and cotton wool are examples of traditional wound dressing materials that are used as main or secondary dressings to prevent contamination of the wound [148]. A certain level of protection against bacterial infection is provided by gauze dressings consisting of cotton, rayon, and polyester woven and nonwoven fibers. Using the fibers in these dressings, certain sterile gauze pads are utilized to absorb liquids and exudates from an open wound. To prevent healthy tissues from macerating, these dressings need to be changed frequently. The cost of gauze dressings is lower. Too much wound drainage causes the dressings to get wet and stick to the wound, which makes taking them off painful. The purposes of synthetic bandages made of polyamide materials and natural bandages made of cotton wool and cellulose are different. For example, high compression bandages and short stretch compression bandages offer prolonged compression in the event of venous ulcers, whereas cotton bandages are utilized to retain mild dressings. Petrolatum gauze containing 3 % bismuth tribromophenate is used as a non-occlusive dressing (XeroformTM) for wounds that do not exude or just slightly exude. Commercially available tulle dressings that are saturated with paraffin and appropriate for superficial clean wounds include Bactigras, Jelonet, and Paratulle. Conventional dressings are typically used as secondary dressings or for clean, dry wounds with low exudate levels. Modern dressings with more sophisticated formulas have supplanted conventional dressings because the former are unable to offer a moist environment for the wound [149]. Instead of merely covering the wound, modern wound dressings are designed to help the wound function. The purpose of these dressings is to prevent dehydration and encourage healing of the wound. There are several products on the market depending on the form and origin of the wound, which makes choosing one extremely challenging. The majority of contemporary wound dressings are made of synthetic polymers and fall into one of three categories: passive, interactive, or bioactive. Gauze and tulle dressings are examples of passive products, which are non-occlusive and are applied over the wound to restore function beneath. Interactive dressings come in films, foam, hydrogel, and hydrocolloid forms and can be either semi-occlusive or occlusive. These dressings serve as a barrier to prevent bacteria from entering the wound environment [150–153]. High porosity, ECM-like structure, huge surface area, and controlled drug release nanofibers are made possible by electrospinning and are perfect for wound healing applications because they improve cell adhesion and biocompatibility [154]. Broad antibacterial and UV protection is provided by CuO or Ag–TiO_2 coatings on cotton or polyester [155]. A multipurpose dressing is created by integrating electrospun silk fibroin membranes with nano diamonds (NDs) that contain nitrogen-vacancy (NV−) centres: Helps cells repair (silk imitates extracellular matrix). Allows for the non-removal monitoring of wound inflammation and infection by optical nanoscale thermometry using fluorescence. Demonstrates antibacterial properties and in vivo biocompatibility against *Escherichia coli* and Pseudomonas aeruginosa [156]. Dip-coating Ti_3C_2Tx MXene nanosheets onto cellulose nonwoven fabrics produces electrically conductive textiles, or "M-fabric," which provide localized Joule heat (∼4 V) for wound therapy and pain reduction as well as bacterial ablation [157].

4.2. *Wearable diagnostics & smart fabrics*

High flexibility, adjustable conductivity, and robustness are provided by CNT-embedded textiles for health sensor platforms, particularly for oxygenation, pulse, and ECG monitoring [158]. Coatings, infusions, weaving yarns infused with carbon nanotubes, and printable inks are examples of fabrication techniques [159]. Cotton, polyester, Gore-Tex, or neoprene can be made into highly conductive, electrochemical sensor substrates by applying graphene and Ag nanoparticle/Ag nanowire coatings. Applications include biosignal monitoring and DNA/protein detection [160]. With an exceptionally high strain sensitivity (gauge factor $\sim 6.3 \times 10^7$), a wearable accessory that combines a graphene nanosheet and laser-patterned gold electrode efficiently monitors vital signs, including temperature, hydration, movement, and heart and breathing rate [161]. Sweat sampling using thread- and fabric-based microfluidics, frequently combined with conductive threads or colorimetric detection, allows for real-time metabolic or ionic (sodium, glucose) monitoring [162]. Examples include battery-free textiles with NFC capabilities for wound healing or monitoring of hyperthermia, and graphene-coated bra sensors for arrhythmia [163]. The device was worn on the wrist and included a state-of-the-art plasmonic nanowire (Ag/SiNW) optical sensor functionalized with glucose-binding chemistry (4-MPBA). It has dual-mode detection (SPR shifts + Raman scattering) and can detect glucose in sweat as low as 0.12 mM. verified by human testing using the output of mobile apps [164].

4.3. *Sportswear*

Nanotechnology has enabled the manufacturing of functional sportswear with improved performance and efficiency, addressing the long-standing yearning for such products. This document provides an overview—nanotechnology applications in sports, focusing on flooring, clothes, and shoes. Key elements of nanotechnology in sports gear are also extensively covered. The nanotechnology breakthrough will soon impact all sports gear, reflecting the current trend. Nanotechnology in textiles, such as nanofibers, composite fibers, and nano-finished fabrics, offers many qualities for use in sportswear. Scholler, a Swiss company, uses nano-technology to create clothes with maximum comfort, wind and water resistance, air permeability, and self-cleaning properties for cold-weather sports like mountaineering and skiing. Rain- and snowrepellent features are also included in the sportswear [165]. JR Nanotech, a UK-based company, developed "SoleFreshTM" socks using silver nanoparticles to reduce athlete's foot odour. Hyosung, a Korean corporation, produces nano silver-containing nylon fibers for daily activities, sportswear, backpacks, and running shoes [166]. Nanotechnology significantly improved the anti-slip qualities of footwear soles [167]. Nanotechnology enables improved wicking in sportswear, shielding mountaineers from freezing rain and monitoring individual temperatures in harsh climates [168]. The first waterproof, breathable fabric was created using densely woven fabric or polymeric and resin coating, but nanotechnology has opened new avenues for development [169]. Waterproof polyester cloth covered with nanosilicate. These swimsuits remain dry after 2 months of immersion due to lower water-fabric resistance, increasing their popularity [170–172]. Table 5 illustrates the properties of sportswear and shoes.

4.4. Military and defense

Nanomaterials have unique physical and chemical properties, enabling great strength and lightweight, optical, electromagnetic, and chemical adjustability. Nanotechnology is now a reality for controlling water pollution, energy storage and generation, healthcare, defence, and other uses. Employing nanotechnologies in pads, coatings, or fabrics like nanocomposites offers exciting prospects for modifying composite function. Enhancing matrix properties with nanoscale polymers increases compressive strength, while tangled nanotube networks improve tensile strength and elastic modulus, especially in ceramic nanomaterials with high-temperature resistance [173–174]. Fig. 10 illustrates the application of nanotechnology in defense.

Nanorobotics is a new technical field focusing on nanoscale robotic components and machines for space and military applications [175]. In general, nanorobotics has two parts. The initial topic is robot design and control. Nanorobots should possess three key abilities: self-assembly, swarm intelligence, replication, and power and maintenance through a nano or macro interface architecture [176]. Nanomaterials for automotive applications aim to reduce engine emissions and promote healthy driving, quiet cars, self-healing bodies, and windshields [177–178]. Military applications of nanotechnology aid defense in the following ways: Protection (armour-like fabric body armor and vehicle shields), temperature tolerance garments, waterproof uniforms, self-cleaning, anti-degradant military uniforms, drug dose diagnosis chips, Auto control, invisibility ware, surveillance improvements, smaller cameras, robots, effective weapons, anti-scratching surfaces, stronger glass, faster medical assistance, fuel-efficient aircraft, vehicles, ships, and electromagnetic camouflage for radar undetected planes and submarines [179].

Carbon nanofibers and carbon black nanoparticles effectively reinforce composite fibers. Both nanomaterials exhibit excellent chemical resistance and electrical conductivity in composite fibers. Composite fibers with nano-sized clay particles or flakes (hydrated aluminum silicate) are flame-retardant, chemical-resistant, and UV-blocking [180–181]. A UV-protective cloth shields against UV rays and reduces skin injury risk [182]. The treated cotton fabric is coated with a thin coating of TiO_2 nanoparticles, providing UV protection and durability up to 50 home launderings [183].

Table 5
Characteristics of sportswear and shoes incorporated with nanotechnology [172].

Properties	Sportswear and Shoes
Ultraviolet radiation protection	Clothing for outdoor sportswear
Self-Cleaning	Mountaineering tents
Protection from heat and cold	Skiing, diving, snowboarding, mountaineering, canoeing, and cycling clothes
Water-proof	Swimsuit, canoeing, diving, and sports shoes
Recovery of muscles and enhanced blood circulation	Therapeutic elbow bands, knee bands, and back belts, esp. for weightlifting
Electronic textiles	Mountaineering, clothes, running and fencing, referee gadgets
Antibacterial	All categories of sportswear and shoes
Comfort	All categories of sportswear and shoes

4.5. Fashion

Today, nano textiles are widely used in various fields, including technology clothing, protective occupational attire, waste reduction, and functional clothing. Nanotechnology in textiles offers enhanced qualities for innovative applications, materials, and goods [184]. Nanotechnology can reduce water usage by using dry processes to imprint nanostructure and surface functionality on textiles [185]. The procedure is eco-friendly and has a significant impact. Conductive yarns and fibers combine conductive materials with pure metallic or natural fibers [186]. Adding carbon nanotubes to polypropylene eliminates the "die-swell" effect, which causes polymers to swell during electrospinning. This improves fiber strength against high voltage between the capillary tube and collector [187].

Technology, buried in coatings and fibers, can transform the look of textiles and create stunning effects. Light-emitting clothing appears on couture catwalks, indicating a future trend in technology apparel. Consider the T-shirt. Nano technology-enhanced T-shirts are being researched to monitor heart rate, breathing, sweat, and chill you on hot summer days [188].

5. Challenges and prospects

Nanotechnology may revolutionize diagnosis, therapy, and prevention. Nanotechnology controls materials' chemical, physical, and biological properties, offering accurate oversight. Innovative medicines, tailored drug distribution structures, and sensitive diagnostic devices are possible. Nanoparticles enhance drug solubility, stability, bioavailability, delivery, targeted distribution, pharmaceutical quality, dosage limits, and systemic side effects. Nanotechnology-based sensors and devices can monitor patient health quickly for early detection and personalized treatment. Nanorobots could attack cancer cells or deliver medicinal payloads via bloodstream navigation with future nanotechnology [189].

A recent nanotechnology study suggests that nanoparticles may prevent cancer. Genetic nanobodies protect fragile cells against UV mutations. Nanoparticles are also being researched to inhibit cancer cell feeding. Nanoarrays, nanosensors, liposomes, monoclonal antibodies, and nanoparticles (dendrimers, diamondoids, gold-based, magnetic, and optical dots) aid cancer research. Nanoparticles for cancer prevention are promoted by cancer nanotechnology research. Genetic nanobodies protect sensitive cells against UV-induced mutations. Nanoparticles are also being researched to inhibit cancer cell feeding. Nanoarrays, nanosensors, liposomes as monoclonal antibodies, and nanoparticles (dendrimers, diamondoids, gold-based, conductive, and quantum dots) improve cancer research [190].

Recent sportswear advances prioritize performance, quality, and design, growing the market. Sportswear with utility and style will cost more, making it more competitive. To improve performance products, future designs will prioritize multifunctional requirements like controlling temperatures, contact reduction, moisture management, superior durability, elastic resiliency, brightness, wind, and water opposition, wear comfort, and other sport, climate, and tangible activity-specific features. Consider how nanoparticles harm the skin and the environment. Unfortunately, nanoparticle safety, healthcare, and ecological research are sparse [191]. Nanoproducts' health and environmental implications are still debated. Future research will prioritize nanomaterial safety for high-performance sportswear, minimizing health, safety, and environmental risks [192]. Minimal concerns surround nanofibers and nanocomposite fibers. Nanoparticle therapy

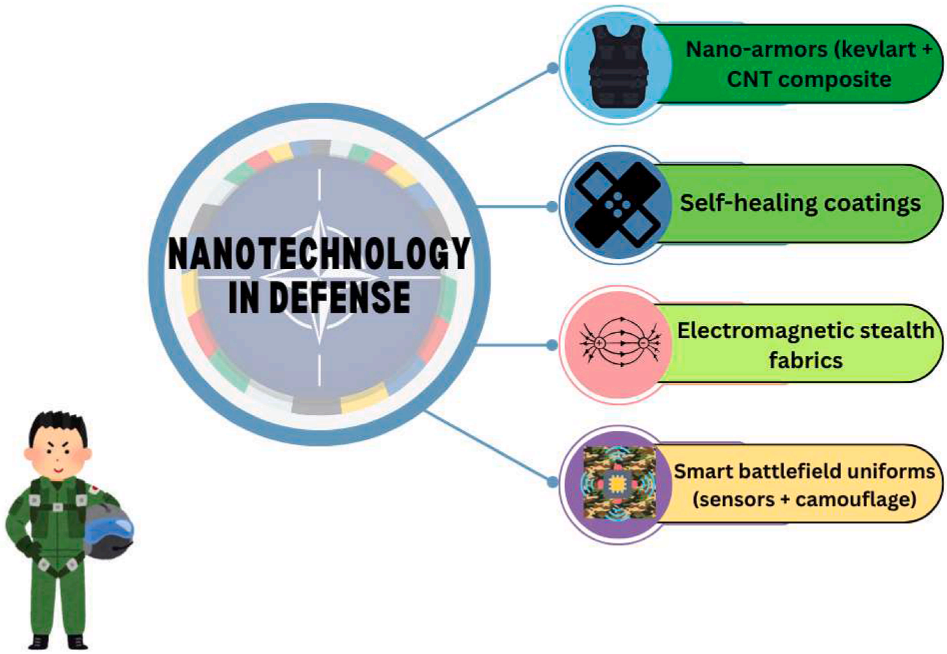

Fig. 10. Application of nanotechnology in defense.

textile surface coating may be more dangerous after nano-finishing. The garment business needs nano-treatment durability. Sustainable nano-finishing lowers textile nanoparticle health and environmental risks. In-situ nanoparticle production on textiles improves particle adsorption and product durability [193].

Research suggests that nanotechnology in body armor can enhance protection without reducing mobility. The assessment highlights using lighter, more substantial materials to increase military safety and operational effectiveness. Additionally, nanotechnology research highlights medicinal advancements, including real-time monitoring and customized medicine delivery. These innovations boost medical responses to injuries, potentially lowering mortality and long-term health consequences for soldiers. Nano-enabled biosensors for vitals monitoring could revolutionize combat first-response protocols. Additionally, the report acknowledges ethical concerns and potential obstacles in integrating nanotechnology into warfare. Although nanoparticles have significant benefits, concerns about their unexpected effects, such as environmental damage and their abuse in warfare, are crucial. When deploying these technologies, strict restrictions and ethical considerations are essential [194].

Despite advances, technical, production, and scalability issues remain. These technologies need more study to improve, sustain, and overcome limitations. Researchers, designers, and manufacturers must collaborate to develop innovative materials for popular fashion [195].

6. Conclusion

The textile industry is now at the forefront of innovation thanks to the substantial advancements in fabric design and functionality brought about by the application of nanotechnology. The use of nanoscale materials has transformed textiles from passive clothes into active, responsive systems with many functionalities. Nanoparticles and nanofibers boost durability, breathability, antibacterial efficacy, UV protection, water resistance, and temperature regulation—attributes that prolong the lifespan and functionality of textiles in several industries, including healthcare, military, fashion, and sports.

The development of smart and wearable textiles, which incorporate nanosensors for real-time monitoring of health and environmental variables, is one of the most transformational advances. These advanced textiles hold significant potential in medical diagnostics, athletic performance monitoring, and military uses. Nanocoating techniques, including sol-gel, plasma polymerization, and self-assembly, allow the creation of functional surfaces without compromising the tactile characteristics of textiles, thereby preserving comfort while augmenting usefulness.

This technical advancement presents significant problems. Elevated manufacturing expenses, challenges in large-scale production, environmental apprehensions with nanoparticle discharge, and ambiguities surrounding long-term health implications persist as significant obstacles to wider adoption. Furthermore, guaranteeing the safety and sustainability of nano-enhanced textiles is crucial for customer confidence and adherence to regulations.

To mitigate these issues, multidisciplinary research initiatives should concentrate on the development of sustainable nanomaterials, the enhancement of manufacturing efficiency, and the execution of thorough safety evaluations. Sustainable nano-finishing methods, including in-situ nanoparticle synthesis and bio-derived nanomaterials, provide intriguing opportunities for reducing environmental impact.

In overall, although nanotechnology presents extraordinary potential to transform textiles, its efficacy depends on ethical innovation, environmental stewardship, and collaborative engagement among scientific, industrial, and regulatory sectors. Through balanced development, nanofabrics will persist in influencing the future of textiles—providing more intelligent, safer, and sustainable clothing solutions for many applications.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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