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Review Paper

Application of Nanotechnology in Textiles: A Review

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Abstract

Nanotechnology has significantly transformed the textile sector, offering innovative solutions in both anticipated and novel ways. This review discusses the preparation of nanofibers using various methods, the types of nanofibers, and their wide-ranging applications in textiles. Among the preparation methods, electrospinning is the most widely used, alongside others such as melt-blowing, and phase separation. Nanofibers are categorized into four sources: polysaccharide-based, synthetic-based, carbon-based, and protein-based. The extensive application of nanotechnology in the textile industry is remarkable, encompassing areas such as water repellence, antistatic properties, wrinkle resistance, strength enhancement, UV protection, computing, odor control, optical displays, soil and stain repellence, anti-creasing, antibacterial properties, self-cleaning, thermal regulation, comfort, electronic textiles, medical dressings, home furnishings, food packaging, and cosmetics.

Keywords: Nanotechnology, Textiles.

Introduction

The field of study known as "nanotechnology" focuses on creating and using structures, devices, and systems by modifying atoms and molecules on a tiny scale, specifically on a scale of 100 nanometers (one hundred millionths of a millimeter) or less. Devices based on nanotechnology find many uses in fields like electronics, healthcare, energy, and textiles. The scale of these devices is usually less than 100 nanometers (nm). One billionth of a meter is equivalent to a nanometer, which is an extremely tiny unit of measurement. A piece of paper has a thickness of around 100,000 nanometers. In 1974, the professor Norio Taniguchi of University Tokyo coined the word "nanotechnology" to describe the capacity to manipulate materials on a nanometer scale. By using nanotechnology, textile technology may advance to the point where specialized textile products can be used in a variety of disciplines, such as medicinal, geo, and textiles for extreme environmental protection. The stages involved washing, dying, and finishing. A variety of Nano finishes and treatments may provide textiles with important and unique qualities, including wicking, flame retardancy, water resistance, dirt resistance, wrinkle resistance, breathability, and anti-static and UV protection . The use of nanotechnology in the textile industry has enhanced the value of textiles, establishing them as integral components of innovative smart technologies[1].

The ultra-fine solid fibers known as nanofibers are distinguished by their tiny pore sizes, high surface area per unit mass, and extremely small diameters (less than 100 nm)[2]. Nanomieties can give fibers anti-stain properties, anti-wrinkle properties, anti-static properties, and electrical conductivity without sacrificing their comfort and flexibility[3]. Numerous researchers are interested in nanofiber technology because it presents an intriguing way to address some of the pressing issues facing the biomedical profession today, including organ repair, burn and wound care, osteoporosis treatment, and other disorders. Nano-engineered functional fabrics represent an exciting new frontier in garment technology. The benefit of using nanomaterials is that they can be used to create function without changing the substrate's comfort level.

At 3 mg/ml, the dye-scavenging effectiveness rises to about 99% when the copolymers are transformed into 300–500 nm-sized nanofibers[4].

Source of Nanofibers

Nanofibers are mainly four types, such as synthetic sourced, polysaccharide sourced, carbon sourced, and protein sourced.

Polysaccharide sourced nanofibers: Cotton nanofibers*:* Cotton nanofibers are usually made from cotton. Cotton Nano fibers come in different colors. It is possible to make cotton nanofibers in different colors like brown, purple, yellow, etc. At 180°C in iso thermal, it was observed that colored cotton nanofibers can maintain better thermal stability than white cotton nanofibers[5]. Typically, cotton nanofibers are found to be 85–225nm in length and have a diameter of 6–18nm in morphological tests[5]

Jute nanofiber: Cellulose is a sustainable feedstock that is abundantly available; it has also been viewed as a polymeric raw material with potential as nanomaterials[6]. Extraction of Nano cellulose from the jute involves two steps. The first step is to remove non-cellulosic material such as lignin, hemicelluloses, etc. in the pre-treatment process. The next step is to produce Nano cellulose from cellulose fibrils using various extraction methods. Nano cellulose of jute fiber is shown on Figure-1A.

Wood nanofiber: Wood is primarily made up of lignin, cellulose, hemicellulose, extractives, and minerals. The wood is made up of around 40% cellulose, a semicrystalline, and an unbranched homopolymer made from glucose. Less than 1% of wood's composition is made up of organic materials, mostly calcium, potassium, sodium, magnesium, iron, manganese, and so on. Cellulose nanofibers are made from raw wood by following pulping, bleaching, and downsizing steps. This technique is a sustainable method with high efficiency in converting wood from micro to nanoscale (97wt%). Consequently, the amount of manufacturing waste generated by this process is negligible. This innovative kind of wood is used in several applications such as composites, paints, adhesives, packaging, and construction, among others.

Ramie nanofiber: Ramie is a significant natural fiber crop classified under the Urticaceae family. Ramie fibers are premium natural fibers that may be used to produce nanocellulose or nanofibers. Several mechanical methods, including homogenization, microfluidization, grinding, ball milling, cryocrushing, ultrasonication, extrusion, and steam explosions, may be used to produce cellulose nanofibers[7]. Using DES pretreatment, pretreated ramie fibers are made from raw ramie fibers. Using the ball milling process, cellulose Nano fibrils are made from pretreated ramie fibers. This process runs for around 6 hours. Raw ramie fibers and degummed ramie fibers are treated with a direct ball milling process for around 12 hours, and cellulose Nano fibrils are prepared. It is shown on Figure-2. Ramie fiber, with its abundant cellulose content, finds use in textiles, technical fabrics, industrial packaging, and reinforced composites.

Sisal nanofiber: Sisal fiber is made of sisal plant. To create nanocomposites, cellulose nanofibers are taken out of the sisal and mixed in varying amounts (0–5%) with cassava starch[8]. Delignified sisal is obtained by treating the sisal leaves with alkali. Bleached fiber can be obtained by treating Delignified sisal with bleaching. Cellulose nanofiber is obtained by treating the bleached fiber with acid treatment and homogenization. It is presented on Figure-1 B.

Synthetic sourced nanofibers: Poly-L-lactic acid (PLLA): Lactic acid is the source of the polymer known as poly-L-lactic acid (PLLA). Medical applications employ PLLA extensively. Because of its biocompatibility and biodegradability[9]. It doesn't hurt people or leave any harmful residue when used in biodegradable sutures, implants, scaffolds for tissue engineering, and drug delivery applications. PLLA is a useful substance in the medical industry because of its adaptability and environmental friendliness. Lactic acid (2-hydroxypropionic acid) is the source of poly lactic (PLA), a polymer having favorable mechanical, thermal, and barrier qualities. It's well-liked for being environmentally beneficial. PLA provides a sustainable substitute for conventional plastics in a number of applications, such as packaging, tissue scaffolding, 3D printing, and medical implants.

Polyglycolic acid (PGA): One of the most important biopolymers is polyglycolic acid, or PGA. It is a highly crystalline polymer that has a high melting point of 220-225°C and a glass-transition temperature (Tg) of around 35–40°[10]. As it is useful for medicinal applications such as suture in the area of surgery and the renewable energy sector due to its mechanical, thermal, and biodegradable qualities.

Polyaniline (PANI): Conducting polymer PANI (polyaniline) has distinct chemical, optical, and electrical characteristics[11]. PANI on its own, may be utilized to fabricate an electrode because of its high specific capacitance, high flexibility, low cost and it has demonstrated remarkable potential in the super capacitor area. It is widely used in sectors involving electronics and sophisticated materials because of its environmental stability, simplicity of synthesis, and versatility[11].

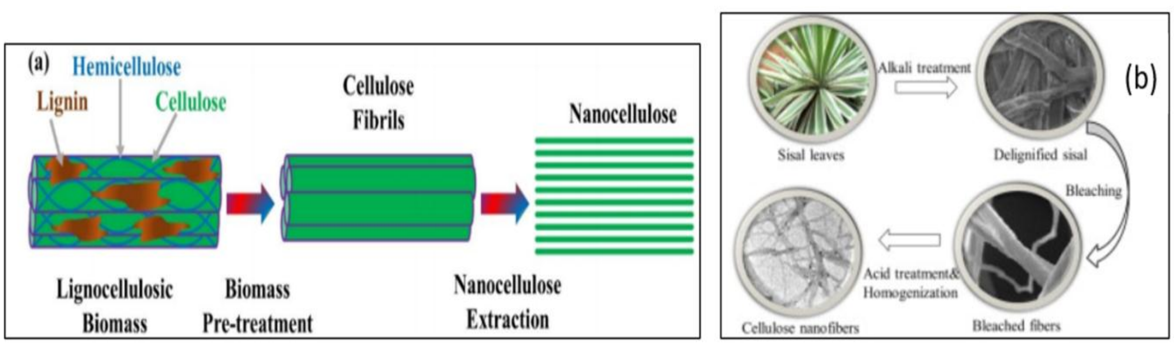

Figure-1: A. Jute nanofiber and B. sisal nanofiber preparation steps[6].

Polyacrylonitrile (PAN): With the linear formula $(CH_2CHCN)_n$, polyacrylonitrile (PAN) is a synthetic, semi-crystalline organic polymer resin. Despite being thermoplastic, polyacrylonitrile doesn't melt under ordinary circumstances. It breaks down before melting. When heated to a temperature of 50°per minute or higher. It melts at temperatures exceeding 300°C[12]. It has been widely employed in the production of carbon nanofibers (CNFs) because of its high mechanical qualities and stability.

Carbon sourced Nanofibers: Carbon nanofibers and nanotubes are produced by the passage of carbon via a metal catalyst (by the catalytic breakdown of carbon-containing gases or the vaporization of carbon from a discharge or laser ablation), followed by its precipitation as graphitic filament. The electro spinning and carbonization of polymers or the catalytic breakdown of carbon precursors. In theory, the catalytic breakdown of methane ($CH_4 \rightarrow C + 2H2$), in conjunction with the oxidation of the carbon deposited with CO_2 and O_2 (($(1/2)C + (1/2)CO_2 \rightarrow CO$, $(1/2)C + (1/2)O_2 \rightarrow (1/2)CO_2$), results in only one overall reaction (~H1073= −20 kJ/mol): $CH_4 + (1/2)O_2 \rightarrow 2H_2 + CO$[13]. Among the potential methods for processing hydrogen, catalytic breakdown of methane (CDM) satisfies these conditions Cellulose is one of the most abundant biopolymers in the world and is mostly derived from wood, plants, and microorganisms. Recently, there has been a lot of interest in the bacterial manufacture of CNFs, also known as bacterial cellulose (BC) The development of aggregated Nano fibrils in bundles with a high aspect ratio (7–8 nm) is what makes up bacterial cellulose. These naturally occurring biopolymers possess exceptional hydrophilicity, biodegradability, renewability, and mechanical characteristics. The produced cellulose has a significant functional surface area, low weight and density, and a highly interconnected pore structure due to its nanoscale dimensions .Carbon nanotubes (CNTs) are tubular structures made of carbon atoms, similar in appearance to rolled-up sheets of graphene .Carbon nanotubes (CNTs) are carbon structures with a length-to-diameter ratio that may exceed 1,000,000. These carbon molecules, which have a cylindrical shape, possess unique characteristics that have the potential to be valuable in many nanotechnology applications. Carbon nanotubes (CNTs) may be categorized according to the number of layers they possess: single-walled carbon nanotubes (SWCNTs) and multiple-walled carbon nanotubes (MWCNTs). It is shown on Figure-4. Furthermore, SWCNTs may be classified based on their crystallographic orientations as armchair carbon nanotubes, zigzag carbon nanotubes, and chiral carbon nanotubes. Each category of carbon nanotubes (CNTs) has various benefits, drawbacks, and exceptional qualities as a result of its distinctive features. Recent advances in nanotechnology have made carbon nanotubes (CNTs) an intriguing material with potential applications in biomedicine, energy storage and devices, high-strength composites, and many other fields. Ijima made the amazing discovery of carbon nanotubes (CNTs), which are 4 nm-diameter carbon nanotubes with many graphitic layers within. Regarding the topic of applications, it has been shown that CNFs and CNF-based nanomaterials have potential in the disciplines of energy storage and electrochemical sensing.

Protein sourced Nanofibers: Chitosan: Chitin is the source of chitosan. After cellulose, chitin is the biopolymer that occurs in nature most frequently. Chitosan is often more soluble in reagents than chitin due to its reduced crystallization. Because the chemical alteration of chitosan would not alter the protein's basic structure. It would preserve its initial physicochemical and biological characteristics while offering new or enhanced capabilities. It is an intriguing development. Chitosan's use is constrained, nonetheless. Because it does not dissolve in basic or neutral aqueous solutions[14].

Elastin: Many vertebrate tissues, such as the major arteries, the lung, ligaments, tendon, skin, and elastic cartilage, depend on elastin. An essential extracellular matrix protein, for their elasticity and durability .The application of pure elastin in biological investigations is greatly limited by the fact that it is still insoluble .Both transcriptional and post-transcriptional mechanisms control the expression of elastin[15].

Collagen: The process of electrospinning creates nanoscale threads by using electrical forces and polymer solutions. Its use in the production of nanofibers is more widespread than that of other methods. Both synthetic and natural polymers, such as polyurethane, polyvinyl alcohol (PVA), polyethylene oxide (PEO), polyamide, collagen, collagen/PEO, and polyvinyl pyrrolidone (PVP), may be used alone or in combination to create fibers[16]. Tropoelastin was combined using the electrospinning technique. It improved collagen, collagen/PEO, and polyvinyl pyrrolidone (PVP) cell migration and proliferation. Special emphasis is paid to popular proteins including keratin, collagen, silk, elastin, zein, and soy as well as modern fabrication techniques like electrospinning, wet/dry jet spinning, dry spinning, centrifugal spinning, solution blowing, phase separation, self-assembly, and drawing.

Gelatin: Since gelatin is naturally biocompatible, biodegradable, and non-toxic, it has been extensively investigated for use in biomedicine. The average molecular weight of the components of gelatin is shown by the bloom value of gelatin, also known as gel strength or stiffness. It typically ranges from 30 to 300 blooms, with less than 150 being a low bloom, 150–220 being a medium bloom, and 220–300 being a large bloom[17] Gelatin has a greater bloom value when it is stronger. Various gelatin boom values are used, depending on the kind and purpose of the final product. The kinetics of drug administration and gelatin breakdown has been optimized by adjusting parameters such as cross linking density and isoelectric point.

Zein: Zein is a maize byproduct that is a prospective biopolymer for use in food and nutrition applications because of its renewable resources, distinct hydrophobic/hydrophilic nature, and ability to form films and fibers, and antioxidant qualities. The reported average size of zein nanoparticles is between 50 and 200nm[18]. Zein nanofibers were made both alone and in combination with plasticizers (polyethylene glycol, glycerol, and casein) ethanol, acetic acid, and water mixtures. Because of their low toxicity, good water penetration qualities, sustainable manufacture, and biodegradable nature, zeins have found widespread use as a flexible industrial polymer in the food, textile, and, more recently, pharmaceutical industries.

The formation method of nanofibers

The discovery of nanofibers has revolutionized the textile industry. Nanofibers can be prepared by various methods. Here is a detailed discussion of four methods by which we can enrich our knowledge by studying them. They are electrospinning, melt-blowing, freeze-drying, phase separation.

Electro spinning method: The most famous and most widely used method for making nanofiber is electro-spinning. In 1934, Formhals invented and published a patent for the manufacture of artificial yarn using the electro-spinning method[19]. Electro-spinning is the process of making nanofibers that have several uses and its making process is cost efficient. It's needed a syringe pump, syringe, spinneret, polymeric jet, high voltage supplier, and collector for preparing nanofiber. Electrospinning is a method of spinning that takes use of a high-voltage electrostatic field to propel the whole spinning process. To apply an external electric field to the spinneret, the electrostatic charges are assembled at the tip of a liquid droplet[20]. As a consequence of this, the electrostatic repulsion that exists between the surface charges acts in opposition to the surface tension, which causes the droplet to be deformed and reshaped into a stretched cone that is referred to as a Taylor cone. When a threshold voltage is achieved, a jet is then released from the Taylor cone. This jet first moves on a linear trajectory and then undergoes a complicated oscillating motion caused by bending instabilities. During the motion, the solvent evaporates, and the polymeric jet is extended into a smaller diameter. Eventually, this process generates nanofibers which are then deposited onto a predetermined collector (Figure-2 A). Polymeric jet that is electrically charged and has an effect on the creation of nanofibers during the electrospinning process[21–23]. The axisymmetric varicose instability known as the Rayleigh instability seeks to fragment the polymeric jet into tiny droplets. Because of a strong electrostatic field already in place, surface charges of polymeric jets electrostatically repel one another, causing non-axisymmetric mixing and whipping instability. Typically, the electrospinning method gathers the nanofibers as low thickness (often less than 1 mm) meshes with dense packing densities.

Phase separation method: Another technique for creating nanofibers is phase separation. Phases in this manner will distinct due to the outward asymmetry. Owing to the outward asymmetry, the solvent eventually gives up after going through many residue phases[24,25]. This process basically consists of five steps, and represents on Figure-2 B: i. The dissolving of polymers in a solvent at either room temperature or higher. ii. In order to manage the nanofiber shape (porosity), gelation is the most challenging phase. Temperature and polymer concentration both affected how long the gelation took. iii. Utilizing water to remove the solvent from the gel. iv. Freezing. v. Vacuum assisted freeze drying[24,25].

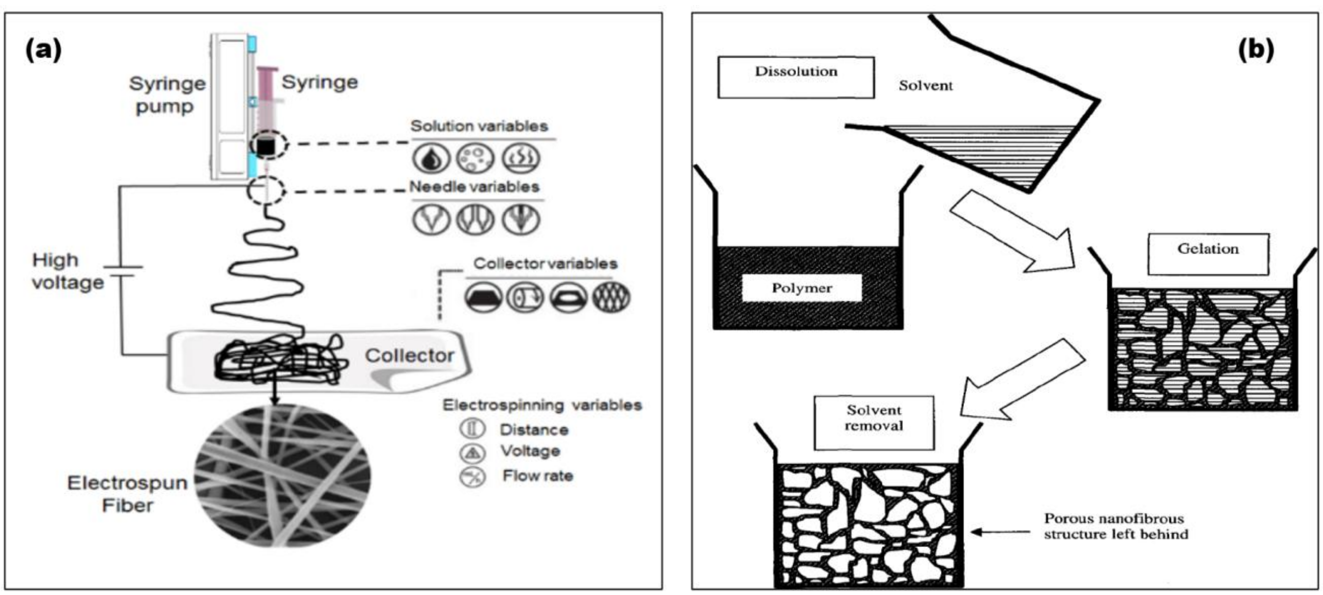

Figure-2: A. Schematic representation of electrospinning. B. Phase separation diagrams used generally to create nanofibrous structures.

The characteristics of nanofiber are influenced by the concentration of polymer. An increase in polymer concentration results in a decrease in fiber porosity and an improvement in the mechanical properties of the fiber. The process begins with dissolving the polymer at room temperature to create a homogeneous solution. Next, the gel is extracted, and the matrix is dried to produce nanofibers. This process continues until the gelation temperature is maintained. At which point phase separation produces nano-fibrous matrixes (Figure-1)[24]. A minimal set of equipment is needed for the procedure. By varying the concentration of the polymer, it may directly create a nanofiber matrix whose mechanical characteristics can be customized. Few polymers have been converted into nanofibers. Thus far utilizing the phase separation technique, including polylactide (PLA) and polyglycolide[26]. The usage of the phase separation approach is limited. Because it needs gelation capacity, which prevents all polymers from undergoing phase separation and producing nanofibers. Additionally, lengthy continuous fibers cannot be created using this process.

Melt blowing method: Melt blowing is a simple, flexible, one-step method for transforming polymeric raw materials into nonwovens, as seen in Figure-3A. Five components make up the MB process: extruder, die assembly, web creation, metering pump, and winding[27].

The melt blowing technique involves the continuous injection of a molten polymer stream into an area with high-velocity air. Fibers are created by the elongation of the molten stream that emerges from the die hole and is then collected on an appropriate collector. The average fiber diameter is at least 1-2 µm, increasing the processing temperature may reduce the melt viscosity of a polymer. However, there is a limit to how high the temperature can be raised before the polymer starts to degrade[28].

The melt blowing tests are conducted by using a horizontal extruder with a length-to-diameter (l/d) ratio of 40/1. The system comprised of a polymer feeder (hopper), 10 heating zones, pressure transducers, a single hole die with a 0.5 mm orifice diameter, and vent apertures as seen in Figure-2. The heating zones' temperatures are individually adjusted and monitored using thermocouples. The polymer comes from the hopper is progressively heated as it passes through the heating areas, following the principles of progressive melt theory .A specific feed rate of the polymer is supplied by gravity from the hopper to the extruder in the form of pellets, granules, powder, or chips[27,29]. The feed rate is low because higher feed rate is the reason for making coarser fiber. The pressure within the extruder is measure using pressure transducers mounted at various places along the extruder length. The hot air at a high velocity is then used to pull the molten polymer out of the rotating head. After that cold air is applied to form web as shown in Figure. The newly formed web passes through the calendar roller guided by winding rollers and wound on the collector roller as roll. A rotating drum collector assembly (Figure-3 B, C) is employed for the collection of aligned fibers for the mechanical characterization, which is also set up at distances of 200, 300 and 400 mm from the die output. Rotating drum collector assembly used to: (A) collect nanofibers and (B) dumb-bell-shape of the specimens on figure 10 used for tensile testing[28].

In addition to having a large specific surface area of microfibers, micro-nanofiber nonwovens also have a porous structure that facilitates the passage of continuous fluids via the inter-fiber gaps, including water, oil, and air. We have described a novel method for creating melt-blown fiber-in-fiber polymer mixes into nanofibers.

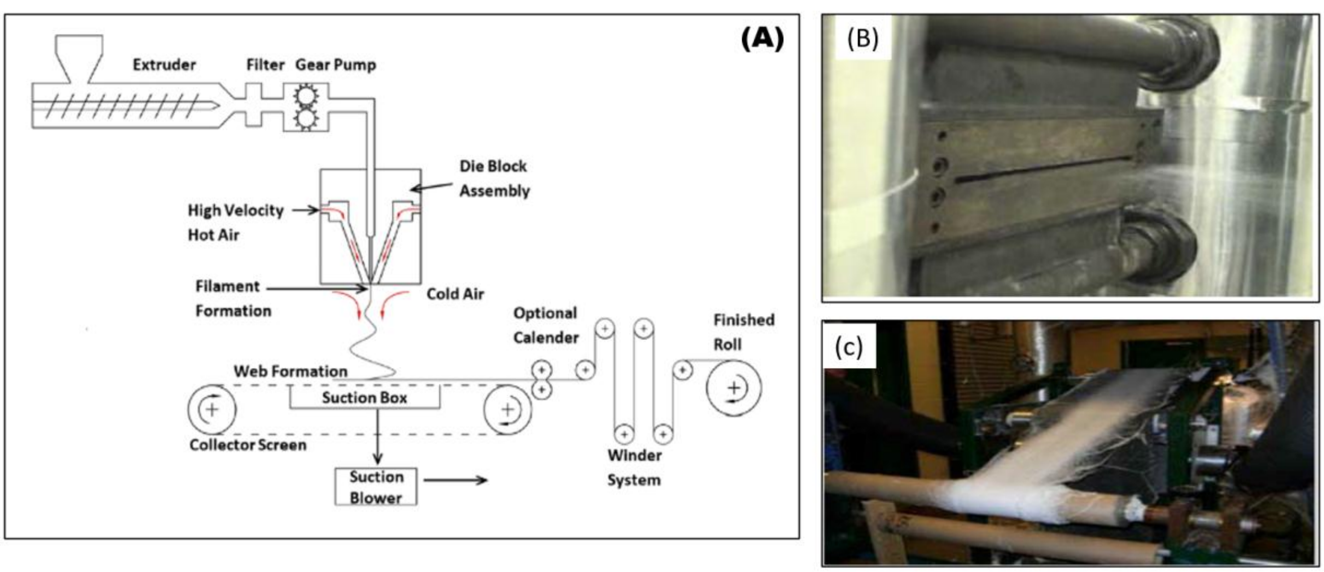

Figure-3: (A) melt blown line. (B) Typical Sketch of the melt blown die[30], (C) Continuous production of nanofiber webs[30].

Application of nanotechnology in textiles

Nanofibers have become a significant innovation in the textile industry due to their unique properties like high surface area-to-volume ratio, small pore size, and flexibility in surface functionalities. Their adaptability to a wide range of applications—from medical to smart textiles and protective apparel—makes them a crucial part of textile technology going forward. The properties of textile nanofibers or materials are water repellence, antistatic properties, wrinkle resistance, strength enhancement, UV blocking, computing, odor control, optical display, soil repellent, stain repellent, anti-creasing, anti-bacteria, self-cleaning, protection from heat and cold, comfort, electronic textile, medical dressing, home furnishing, food packaging, cosmetics and many more, which are represented on Figure-4 bellow:

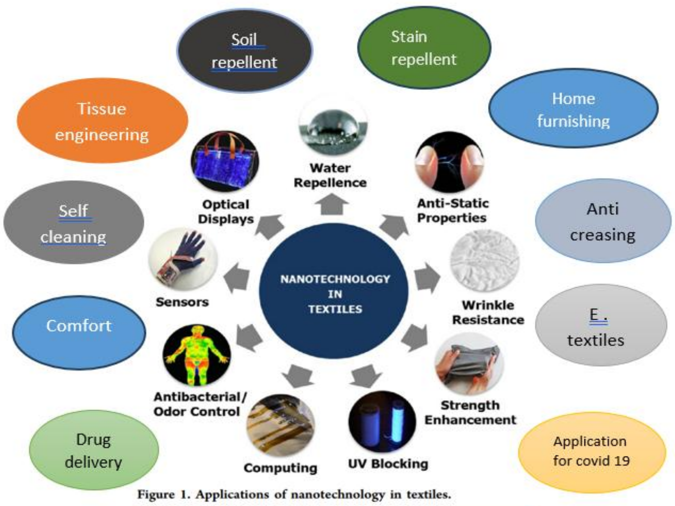

Figure-4: Application of nanotechnology in textile.

UV blocking: In textile materials, UV protection refers to the fabric's capacity to either absorb or filter ultraviolet (UV) light from the sun, shielding the skin from damaging exposure. The goal of textiles with UV protection is to limit the quantity of UV rays that reach the skin. When a dye, pigment, diluting, or ultraviolet absorbance is fully absorbed and the absorbed UV radiation prevents the skin from being exposed to the UV radiation via a fabric, the UV-protective characteristic of a textile nanomaterial is enhanced. Varied varieties of human skin need varied amounts of skin protection, and this relies on the distribution of the skin with respect to time of day, place, strength of UV radiation, and season. SPF (Sun Protection Factor) is the term used to describe this UV defense. Nanofiber is improved for the protection property of UV. It absorbs total ultraviolet radiation and interrupts the transmission through the fabric to the skin[31]. When the high protection factor (SPF) value is higher, its protection against UV radiation is more than others[31]. The UV blockers must be nontoxic and stable. When the temperature is higher than it works. TiO_2 and ZnO (semiconductor oxides) exploited and dispersed UV radiation[31]. It is mainly dependent on the size of NP and wavelength[32].

Anti-coronavirus textile equipment: The Coronavirus first appeared in Wuhan, China in December 2019 and has gradually spread around the world very quickly. Initially, no vaccine could be discovered for this virus, so it was decided to use different types of textile fabrics such as PPE, gloves, masks, surgical cap, surgical gown etc. It is shown on Figure-5, that are made by nanofibers as a preventive measure[33]. To reduce the risk of getting infected with the coronavirus, masks must be used, which are considered textile products[33]. By wearing the mentioned garments during the treatment of people infected with coronavirus, the medical personnel are protected by not having direct contact or touching the patient with the doctor[33] Ventilator bags made of high-density polyethylene are used to treat respiratory problems in patients with coronavirus, which is considered as textile material that are made by nanofibers or manmade fiber. Medical shoe cover is made of heavy-duty non-woven fabric, very comfortable soft, and eco-friendly made in a textile factory. Blood, various fluids, and viruses cannot penetrate the shoe cover and cannot come into contact with the doctor, thereby protecting the doctor[33].

Figure-5: COVID-19 protective cloth PPE, hand gloves, surgical cap, mask, textile surgical sleeve cover, surgical shoe protector, textile medical ventilator, textile DBS[33].

Anti-static properties: Antistatic properties refer to the ability of a material or substance to prevent the buildup or discharge of static electricity. Static electricity is the result of an imbalance of electrical charges within or on the surface of a material. It can cause various problems, including dust attraction, sparks, or damage to sensitive electronic components. Two methods of finishing are used to bestow antistatic qualities onto the fibers, for example: non-durable finish, and durable finish. The primary processes of antistatic finishes are enhancing the conductivity of the fiber surface, which effectively decreases the surface resistance, and minimizing frictional forces by applying lubrication. Surface resistivity is a material characteristic that quantifies the relationship between the voltage gradient and the current density of a substance. Resistivity refers to the inherent resistance of fiber to the passage of electricity. They enhance conductivity resulting in less charge accumulation and faster dissipation, while more lubricities diminish the initial charge buildup. An intermediate layer is formed on the surface by antistatic chemicals that boost the conductivity of the fiber surface. Usually, this layer is hygroscopic. Greater conductivity is a result of the greater moisture content. For there to be more conductivity, mobile ions must be present on the surface. The humidity of the surrounding air during real usage has a significant impact on the efficacy of hygroscopic antistatic coatings; lower humidity causes poorer conductivity (higher resistance) and more issues with static electricity. Due to their low water absorption, synthetic fibers like nylon and polyester often accumulate static charges. As synthetic fibers have low antistatic qualities, nanotechnology is employed to give antistatic properties to such fibers or increase their antistatic capabilities[34]. The hydroxyl and amino groups in silane Nano sol may absorb moisture and water from the environment; they lessen the possibility of static charge buildup, which enhances the antistatic ability of synthetic fibers. Because silane gel particles on fiber absorb water and moisture from the air via amino and hydroxyl groups in water, silane Nano sol enhances anti-static characteristics[35]. To provide polyacrylonitrile antistatic qualities, commercial materials called poly (tetrafluoroethylene) (PTFE) (W. L. Gore) created an antistatic membrane made of electrically conductive nanoparticles embedded in fibrils (PAN) fibers[36,37]

Nanofiber-containing drugs: The therapeutic approach to wound healing was formerly the only method available, modern medications that are combined with polymers and spun into nanofibers may release pharmaceuticals more effectively than those used in conventional treatment[38]. As-prepared core/shell nanofiber have a wound healing ratio over 99% but the centella triterpene cream treatment has a rate of 99.2% and cumulative drug release of centella triterpene cream-treated wound and coaxial nanofibers were 82% within 24 hours[39]. The environmentally friendly method of treating wounds using silver nanoparticle-embedded chitosan/polyvinyl alcohol (PVOH) was presented by Abdelgawad et al. Glutaraldhyde was used to crosslink the nanofibers. The seven-day immersion test drug release investigation demonstrates that an increased crosslinking time causes the Ag+ ion release to decrease. According to an antibacterial test, PVA/CS/AgNPs fiber effectively resists E. coli, and it also showed that adding more chitosan to the system (above 20%) decreased the number of bacterial colonies[40] Although the cosmetic use of medicinal substances on the skin is a significant challenge, formulations based on nanofibers have shown some encouraging results. In a full thickness wound model, Uppal et al. investigated the healing efficacy of electro spun hyaluronic acid using deionized water as the solvent and cocamidopropyl betaine, Vaseline gauze, and antibiotic dressing. In comparison to other materials, hyaluronic acid fibers had a higher healing potential, achieving full epithelialization and wound healing in only 12 days.

Home Furnishing: Mattresses, bed sheets, and furniture covers made of nanofibers are used in home beds. The use of nanotechnology in the manufacture of textile products has resulted in antibacterial, stain, and water resistance, antistatic properties, moisture wicking, and wrinkle resistance properties in textile products[41]. Products made of electro spun nanofibers using nanotechnology are being patented and applied in the market due to the synergistic effect of Nano-dispersible fillers[41]. Electro-spun nanofibers are used as lightweight but dense and sound-absorbing alternatives. It converts sound energy into heat energy, making the sound much less audible or disappearing. Nanofibers bring down loud noises to a less distracting level and make them audible[41]. Nano dream electro spun nanofiber layers are much denser and act as a natural barrier to dust that is much stronger than microfiber fabric.

Tissue engineering: Different types of nanomaterials, or nanofibers, are used in the medical sector, such as collagen nanomaterials. It is used in tissue engineering. Tissue engineering has revolutionized the field of the medical sector. By using tissue engineering, to regenerate damaged organs or tissue in a body that is shown on Figure-6(A)[42]. To regenerate injured tissue, follow two methods: one is a cell-based method, and the other is a scaffold-based method[42]. Scaffolder-based tissue engineering is widely used in bone regeneration, neuroscience, and skin reconstruction. Collagen nanomaterials are used in bone morphogenetic proteins for biocompatibility (human morphological stem cells[42]. Gelatin-methacryloyl (GelMA) is used in calcium phosphate nanoparticles (CaPs) for bone regeneration accelerated[42].

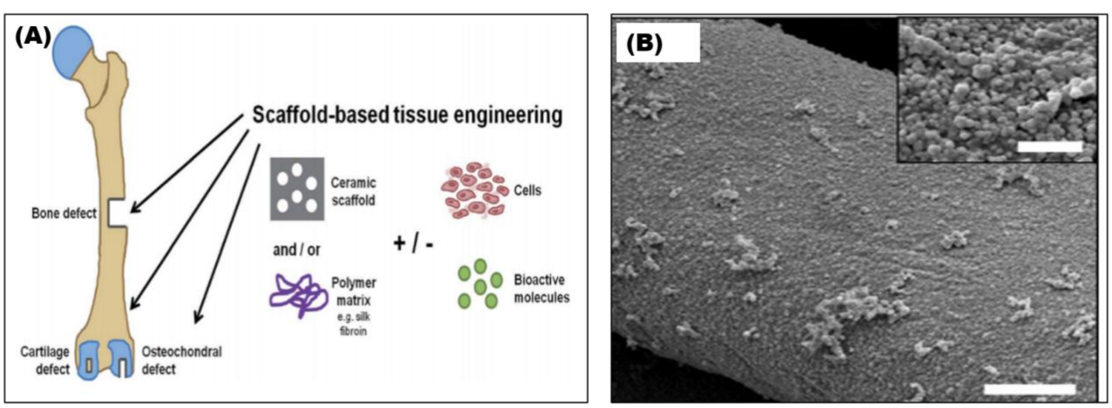

Figure-6: (A) Scaffold-based tissue engineering strategy (Skeletal tissue). (B) Cotton fibers coated with silver nanoparticles provide antibacterial qualities[32].

Anti-bacterial clothing: Antibacterial properties in textile materials refer to the ability of the fabric to inhibit or kill bacteria, preventing the growth of harmful microorganisms on the surface. These properties are crucial in various applications, including medical textiles (e.g., bandages, surgical gowns), sportswear, socks, and everyday clothing. Cotton antibacterial fabric is shown on Figure-6 (B). Apparels are shielded from a variety of germs and offensive smells, which helps to keep fibers from deteriorating or breaking down. Sportswear and socks were manufactured using chitosan fiber textiles, which have antimicrobial, fungicidal, and moisture-controlling qualities. A variety of organic metals, quaternary ammonium compounds, and organic silicones are used for finishing textile products like antibacterial sports apparel, sports shoes, and insoles. Zinc oxide nanoparticles have been used in certain instances to make antibacterial sportswear. Since more nanoparticles are being used per unit area, the antibacterial properties of these particles may also be amplified[34,43].

Enhancement of Comfort Properties: Whereas there are additional approaches for creating nanofibers, electro spinning provides a multitude of management factors. Superior coverage area-to-volume proportions tiny pores, and enhanced pore collaboration may all be accomplished with consistent homogeneity using electrically spun Nano webs[44]. After multiple washings, the synthesized nanofiber web composites were capable of continuing to retain their comfort, water proofness, and the thermal qualities that are required to shield the body of an individual from outside contaminants[45]. The incorporation of nanofibers within apparel components could offer new avenues for enhancing temperature control capabilities and comfort[46]. During protection of the breathing system, the comfort attributes encompass humidity administration, air transparency, and resistance to thermal expansion[47]. A comfortable temperature is an ambiguous phrase that corresponds more precisely to thermo hemodynamic comfort. Where in the equilibrium of temperatures are attained when transpiration of heat is equal to heat formation. Hence, the body sustains an ongoing temperature.

Application in Cosmetics: Electro spinning nanofibers featuring the potential to contain chemicals that are active renders. This method viable for cosmetic services[48]. In comparison with pre-moistened cotton coverings on the marketplace, masks (Figure-7) for the face with their dryness nature have more longevity and greater rigidity[49]. Chitosan and its related compounds constitute some of the organic substances that are attractive for usage in cosmeceuticals, because of recent improvements in the advancement of biotechnology and nanotechnology for instance. The aforementioned compounds have the ability to function as Nano transporters for the active components in cosmetics and other personal care goods or as representatives for maintaining good dental health. Because of its possible a youthful appearance benefits, chitosan's associated capacity for antioxidants is beneficial for dermatological skincare items

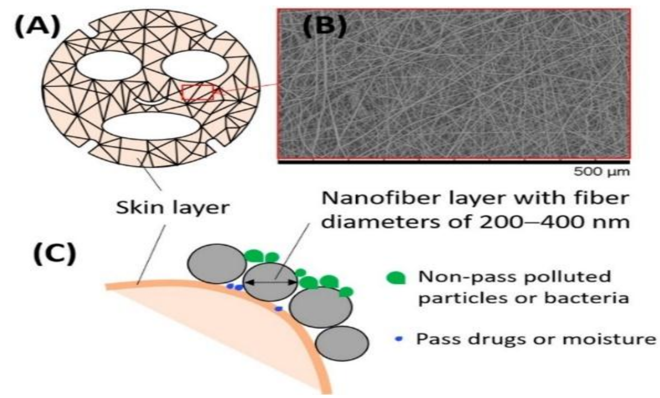

Figure-7: A cosmeceutical defensive mask for post-burn personal grooming utilized on the surface of the skin based on (B) a chitosan nanofiber barrier; (C) an exploded visualization of the skin's nanofiber the subsequent layer.

The nanofiber masks for facial protection can have a variety of utilizes. Such as enhancing interaction with the skin area, shielding the skin from microscopic pollutants and microorganisms and preserving skin's hydration and adaptation. Necessitated by the components and components that are used in the production phase.

Optical displays: Consumer gadgets today almost always include electrically powered transparent liquid crystal displays. However even more effective "electrophoretic ink and electro drenching" exhibits[50] have recently been manufactured for the market. As nanoscience and nanotechnology sophisticated quickly, crossing nanowires. That grows started to serve as the fundamental building blocks for multicolored light-emitting semiconductor devices[51]. Core/multi shell nanoscale complex structures were also employed concurrently to create multicolored, highly efficient diodes that produce light (LEDs). Research on visually powered color displays, or all-optical full-color displays, constructed from different substrates is very desirable and vital. In order prevent using an electrically generated technique. Many studies are currently conducted on polymer-based substances, which show promise for full-color displays because of their inexpensiveness, great flexibility, and advantageous process ability.

Optical magnifications of the combined colors at the connecting point of the physical structure. Zoomed in (10 views) perspectives of the sites at crossroads are displayed in the indents. The signs indicate how the light travels in its diffusion patterns. The dimension of the blocks in the screen's c-f the indents are 10µm[52].

Anti- creasing: Considering cotton has strong permeability and dyeing characteristics, it is a suitable material for utilizing for clothes that are comfy[53]. Despite the fact of the fragility of the hydrogen bonds that exist among the linkages of cellulose molecules. Fabrics made from cotton are considered to have an intrinsic issue of becoming rapidly wrinkled following repetitions of washing[54]. Furthermore, cotton fibers have minimal fiber condensation, which ends up in a considerable reduction in the coupling force between cellulose molecules while they acquire water. This reduction in connecting force promotes expansion. As a result, the cell wall polysaccharides in cotton fabrics endure swelling and migrate whenever they are knotted or scraped during washing or wearing. As a result of these changes, the fabric creases and compresses. The main strategy for reducing wrinkles in cotton garments. After washing or wear is to interconnect the fragments of cellulose in the material using the right chemicals. The following keeps the fragments of cellulose in cotton fibers from moving closer to one another while washing or wearing[54].

Stain repellency: When an item of clothing has been ruined, it means that substances such as grease, dry particles, oil-borne streaks, or water-borne streaks have locally affected it; in contrast, spotting signifies the general infection or uneven coloration of a textile substance. Tea, oil, or a condiment mark on clothing are just several varieties of stained areas. The capability of a fabric to withstand fluid soil absorption during stationary conditions. When the fluid is not pushed onto the fabric by factors apart from the force of capillary contraction and the actual weight of the fluid drop—is known as stain repellency[55]. This is among the most technologically effective potential uses for the field of nanotechnology for textiles that are available today[56]. Particularly for coverings, upholstery, festival gowns, and other kinds of textiles and clothing, stain repellency must be maintained.

Odor control: The entire human digestive tract emissions from the glands that sweat, feces, urine, skin, and genitalia are responsible for odor. The lateral geographical area, sternum, tangential area, scalp, feet in order and hands contain eccrine and apocrine sweat glands. Which are one of the main biological causes of odor in the body. Eating foods like onions and garlic, drinking alcohol, and taking certain prescription medications can amplify the smell that the body generates. Odor accumulation and discharge from textiles are intricate and multidimensional processes. Numerous scents, especially those originating from the bodies of people, are caused by microbes. Data indicates that a particular kind of fiber can affect the retention and proliferation of bacteria. Therefore, an antibacterial coating can stop these. To stop odor, cyclodextrins can be applied to a fabric accomplish. Taiwanese nanotech company "Green sheild" has used nanotechnology to make anti-odor undergarments .A combination of infrared radiation and invisible ions that are negative created by the undergarment's fiber. Remove microorganisms that contribute to odor. To eliminate unpleasant odors, tiny capsules carrying scents may additionally be inserted into cloth and released gradually over a period of time.

Electronic textile: A vital element of the wearable electronics category is wearable energy-generating gadgets that fit comfortably into clothing. To promote flexible self-powered systems, energy harvesting from ambient mechanical sources such as body movements—such as pushing, stretching, bending, and twisting—air flow, transportation movement, and sound waves have garnered a lot of interest[57]. By including BT nanoparticles in the polymer matrix, the voltage, and current outputs of the P(VDF-TrFE) nanofibers could be increased by up to 200 percent[58]. Near-field communication (NFC) rings and smart watches are two examples of electronic jewelry that bring technology closer to our bodies than it has ever been. These fibers, which are self-contained and contain CdS, are intended for use in optoelectronic devices or sensors[59].

To achieve a very robust and highly conductive elastic conductor that can be included in skin-tight wearable electronic textiles, a material design idea that can inhibit fracture propagation in metal-filled elastomers is needed. We have successfully constructed a multimodal sensing skin-tight electronic shirt and a highly reproducible strain sensor using extremely robust and soft metal-elastomer composites[60]. In polo shirt, some sensor such as EMG, ECG, Elbow's strain sensor are placed for collecting body information. That is shown on Figure-8. Electronic textiles have attracted massive attention in the past decade due to their potential applications in wearable electronics and portable devices[61,62], like medical detectors[63,64], transportable electricity[65], and employment as well as military garb[66,67].

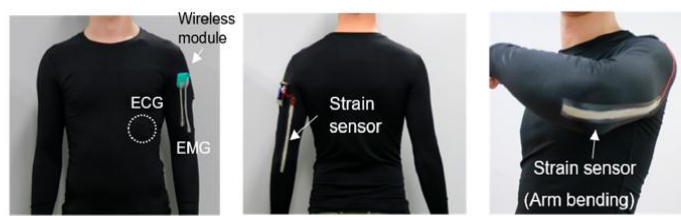

Figure-8: The volunteer is wearing a multimodal sensing suit that includes strain, EMG, and ECG sensors (left). View from the middle of the back. The elbow's strain sensor is where the arm bends to the right[60].

Strength enhancement: The mechanical strength and structural integrity of the as-spun Nano fibrous membrane were improved by adding 300 nanometers of tiny polyvinylidene fluoride (PVDF) particles[68]. The majority of these uses need certain resilience and mechanical characteristics. An increase in the fiber content did not considerably change the final strength. While no negative strength condition has been detected, indicating that nanofibers may have a minor function in strength increase, a direct boost of tensile strength has not been reported for these composites, which may be related to a more brittle matrix state. The extensively distributed nanofibers in thermoplastic polymers of the VGCF-reinforced PP composites and conducting polymers using the other polymers in this work have the potential to be multifunctional materials for strength and electrical conduction[69]. To increase poor productivity, Nano fibrous styrene–acrylonitrile (SAN) membranes were created using electro blowing, a modified electrospinning technique, and the use of a low-toxic dimethyl sulfoxide (DMSO) solvent [70,71]. The SAN nanofiber membranes' mechanical strength, elongation, and pore size range were then improved for MD applications by the use of cold pressing, hot pressing, vapor welding, and dilute solvent welding procedures. It looked at how the length of solvent exposure time at a certain temperature affected the final vapor welding process parameters. The ANFs may be thought of as fillers that create heterogeneous nanocomposites with concurrently improved strength and fracture resistance, so resolving the conflict between strength and toughness. The coated nanofiber composite showed a significant improvement in strength in tensile test results, but the uncoated composites had a negative effect; the former displayed shear yielding because of improved interfacial bonding, while the latter shattered brittlely.

Water repellence: Water repellency, dirt resistance, wrinkle resistance, anti-bacteria, anti-static, UV protection, flame retardancy, improved dye-ability, and other qualities are added to textiles by the use of nanotechnology[72]. When the contact angle increased from 105° to 120°–155°, the CF4 plasma provides the PET (polyethylene terephthalate) surface a structure similar to Teflon with extremely strong water repellence. Fluorocarbons have strong hydrophobic and oleophobic properties, especially on synthetic fibers[73]. Water contact angle measurement was used to assess the water repellency of coated and uncoated cotton fabric (OCA15EC model, Data physics, Filderstadt, Germany). Samples of fabric were cut into rectangles of about 1.5 by 10 cm, then carefully put on top of the black Teflon surface and grasped. The air between the gaps between the microstructures created a cushion at the contact between the leg and the water, potentially enhancing the artificial water strider leg's ability to repel water Textile manufacturers used various perfluoro aliphatic chemicals, polymers, and zirconium/aluminum salt to adhere the compounds to the fabric during the creation of Nano whiskers fabric. These substances demonstrated promising results in terms of water repellence; nevertheless, because of their higher weight and size, the treated cloth ultimately became heavy[75]. Furthermore, the enormous size caused light rays to scatter, which somewhat altered the color of the treated cloth.

Self-cleaning Textiles: The 20th century researchers have been motivated by self-cleaning devices[76]. The ability of smart textiles to self-clean against different types of contamination would improve their performance. However, the methods previously employed to give these functional fabrics this ability have usually been costly and constrained by unpredictable polymer thicknesses and morphologies. They have produced a range of materials solar panels[77], window glass, vehicle mirrors[78], furnishings and comprising textiles having self-cleaning surfaces. In water, these two polymers have almost identical lower critical solution temperatures (LCST), ranging from 30 to 32^{O}C [79]. The significance of these fabric surfaces and self-cleaning substrates lies in their unique characteristics and wide range of applications in the domains of smart textiles, self-disinfecting surfaces, and contamination-free surfaces. Nanoparticle finishes may be applied using an electrostatic and technological method to pass through specific areas of fabrics.

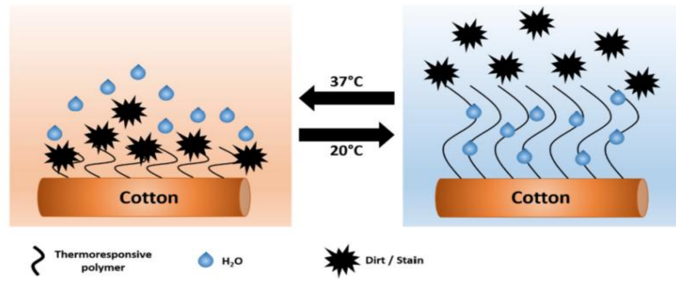

Figure-9: Diagram illustrating how a thermo responsive polymer-grafted cotton fabric self-cleans[80].

Protection from heat and cold: The term "thermo-physiological comfort," which more precisely refers to the state of thermal balance reached when heat production and loss are equal, is a complicated idea that maintains the body's temperature constant. Breathable and waterproof materials are used to create comfortable protective clothing that is intended to shield wearers from harsh weather and certain job situations[81]. Wearers should be shielded from the effects of heat and cold. Waterproof breathable materials should efficiently transfer perspiration from the skin of the body and shield users from the elements to provide a consistently pleasant garment microclimate in a variety of weather situations. Wearing the fabric is what makes one human. Human skin has to be protected from elements such as heat, cold, and rain. Humans utilize clothes as a social tool to display their culture. Once the essential requirement for clothes was met, the human mind began to move toward using fabrics for purposes other than clothing[82]. The methods of heat transmission via fibrous insulation where the diameter of the fiber is smaller than one micrometer is the subject of our discussion[83]. In low-density fiber insulation at moderate temperatures, 40–50% of the total heat transfer may be attributed to thermal radiation. The assumption used by modeling tools considers radiative transfer, if the fibers emit, absorb, and scatter heat radiation.

Wrinkle resistance: Wrinkle-freeness may be achieved using nanomaterials .These advanced finishes add some novel properties to several textile surfaces, such as flame retardancy, microbial resistance, stain resistance, antistatic, hydrophilic, shrink-proof abilities, wrinkle resistance, high durability, and self-cleaning properties. They also give an unpredictable suitable candidate textile an unpredictable performance in coloration, high surface energy, and large surface area-to-volume ratio[84]. These Nano engineered textiles range from protective apparel to smart apparel, hygienic apparel, bulletproof or antiballistic vests, and functionally completed apparel like wrinkle-resistance or water-repellent apparel. During the fabric finishing process, it is possible to enhance wrinkle resistance in cotton textiles by using cross-linking agents with nanotechnology. In addition to its ability to resist wrinkles, this kind of finishing may also get rid of harmful substances while keeping cotton's intended level of comfort[85]. However, when maleic anhydride and Nano-silica were used as a catalyst, the outcomes showed that silk's ability to withstand wrinkles could be effectively increased. Water repellence, dirt resistance, wrinkle resistance, anti-bacteria, anti-static, UV protection, flame retardation, improved dye-ability, and more qualities are added to textiles by nanotechnology. Traditionally, resin is used to provide cloth resistance to wrinkles.

Conclusion

In the rapidly advancing modern world, the integration of nanotechnology into various industries is reshaping the way we innovate, and nanofibers are at the forefront of these advancements. As one of the remarkable discoveries of modern science, nanofibers are created using various sophisticated methods, each tailored to produce fibers with specific properties for diverse applications. This study has explored several fabrication techniques, including electrospinning, phase separation, and melt-blowing, among others. Of these, the electrospinning method stands out as the most versatile and widely adopted due to its efficiency and ability to produce high-quality nanofibers. Nanofibers are categorized into different types based on their sources, such as polysaccharide-based, synthetic-based, carbon-based, and protein-based fibers. These categories reflect the diverse material compositions and the broad spectrum of applications they enable. The unique properties of nanofibers, such as their high surface area-to-volume ratio, superior mechanical strength, and functional adaptability, make them invaluable in addressing challenges across multiple fields.

The transformative potential of nanofibers is particularly evident in the textile industry, where they are driving the development of smart textiles—materials that exhibit advanced functionalities like self-cleaning, moisture-wicking, and temperature regulation. Beyond textiles, nanofibers have found revolutionary applications in aerospace engineering, where they contribute to lightweight yet durable materials, and in aromatic engineering, where they are utilized for filtration and sensory systems. This study also highlights the significant contributions of nanofibers to other scientific and industrial sectors. Their exceptional properties make them indispensable in the medical field, where they are used for wound dressings, drug delivery systems, and tissue engineering. Additionally, nanofibers play a critical role in environmental engineering, enabling advancements in water filtration and air purification technologies. The demand for nanofibers continues to grow exponentially as researchers and industries unlock new possibilities for their application. Their versatility and multifunctionality are paving the way for groundbreaking innovations in science, engineering, and technology. It is evident that nanofibers will play a pivotal role in shaping the future of material science and engineering, making them a cornerstone of modern technological progress.

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