NANOTECHNOLOGY REVOLUTIONIZING OF CELLULOSIC TEXTILES: OPPORTUNITIES AND CHALLENGES

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Nanotechnology has emerged as a revolutionary force in the textile industry, ushering in a new era of sustainable, intelligent, and functional fabrics. Nanomaterials have opened up new horizons across textile functionality, where they are used for UV protection, self-cleaning, superhydrophobicity, antioxidants, remarkable surface structure, high tensile strength, and electrical conductivity. Nanocellulose derived from renewable biomass has gained significant attention due to its biodegradability, high surface area, and tunable surface chemistry. Cellulose nanomaterials are being explored for applications in smart textiles, filtration fabrics, lightweight composites, and high-performance composites. Recent breakthroughs in surface functionalization, through carboxylation, phosphorylation, and sulfonation, enable nanocellulose to act as a platform for incorporating antimicrobial agents, sensors, flame retardants, and conductive nanoparticles. Nanotechnology empowers textiles by integrating nano-sensors, actuators, energy-harvesting components, and communication technologies, making them invaluable in fields as diverse as healthcare, sports, protection, and fashion. This paper explores the milestones of the nano revolution with and in cellulosic textiles and discovers the myriad ways that nanotechnology is transforming the world of textiles. However, while nanotechnology equips textiles with several desirable capabilities, the commercialization of nano-based materials faces challenges, such as high production costs, scale-up limitations, safety concerns regarding inhalable nanoscale fibers, and uncertainties in nano-waste management. Continuous research, collaboration, adherence to ethical principles, and consumer awareness are essential for navigating the challenges associated with nanotechnology in the textile industry and for ensuring a safe and sustainable transition toward the next generation of intelligent textiles.

Keywords: nanocellulose, nanoparticles, nano-waste, healthcare, textiles, sustainability

INTRODUCTION

Nanomaterials – building blocks of innovation

Nanomaterials possess distinctive characteristics owing to their nanoscale (10^{-9} meters) dimensions, offering exceptional properties compared to their counterparts in bulk. At the nanoscale, materials exhibit an increased surface area, providing enhanced reactivity and interaction with other substances.[1-3] This feature is particularly valuable in applications such as adsorption, catalysis, and superior mechanical properties that have propelled their widespread adoption in textiles.[3,4] Nanotechnology in textiles refers to the incorporation of nanoparticles or the creation of nanostructured surfaces and nanofibers in textiles to enhance their performance and properties. Many nanomaterials' lightweight and flexible nature ensures that their integration into textiles does not compromise comfort and flexibility.[5-7] These nanomaterials offer a wide range of benefits that contribute to developing functional, smart, and sustainable textiles.[8,9] Incorporating nanomaterials into textiles is an ongoing area of research and development, and it holds great potential for creating advanced, functional textiles with improved performance characteristics. The chronology of nanotechnology in textiles is shown in Figure 1, which also highlights significant advancements made throughout the nano-revolution. Notwithstanding their benefits, it is important to consider these nanomaterials' potential environmental and health impacts and ensure accountable disposal processes.[10] Responsible manufacturing practices and adherence to regulatory guidelines play a key role in the development and application of nanomaterials in textiles.

There are three segments into which the diverse applications of nanomaterials in textiles can be classified: nanoparticles, nanofibers, and nano-coatings (Fig. 2).

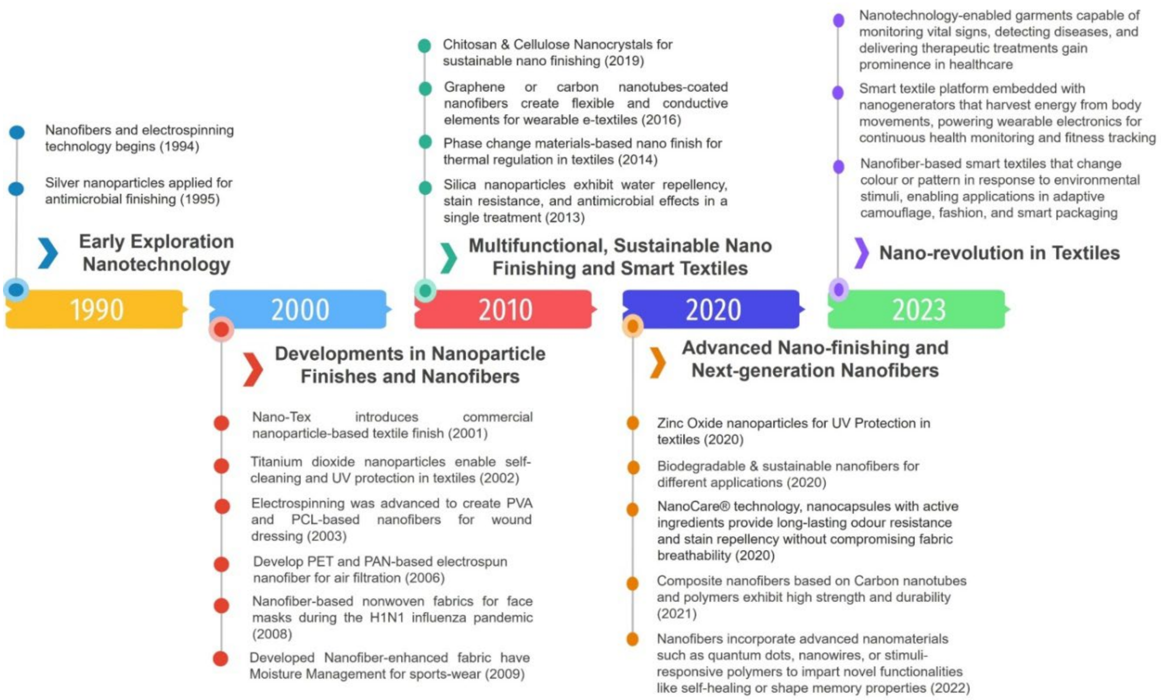

Figure 1: Chronology of the nano-revolution in textiles with important milestones

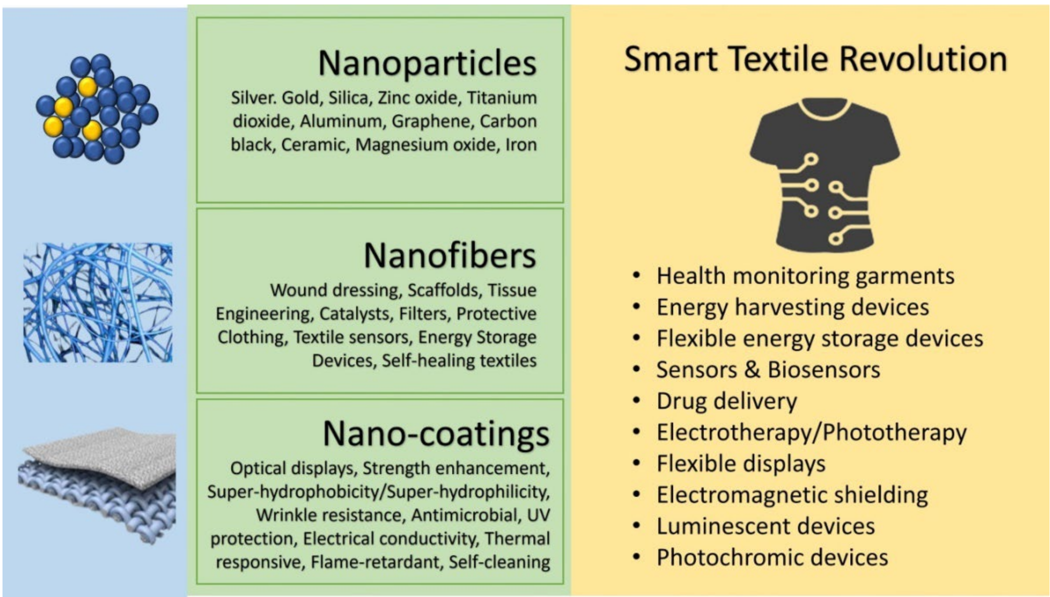

Figure 2: Applications of nanotechnology in textiles

Nanocellulose is a renewable, biodegradable, and high-performance material developed from natural cellulose sources. Recent breakthroughs in nanotechnology have permitted the extraction and exploitation of nanocellulose, which is classified into three types with unique structures and applications in the textile industry: cellulose nanocrystals (CNCs), cellulose nanofibrils (CNFs), and bacterial cellulose (BC).[11,12] CNCs are sometimes referred to as "nanowhiskers" or "nanorods", whereas CNFs, also known as "nanofibrils", "nanofibrillated cellulose", "microfibrillated cellulose", and "nanofibrillar cellulose", have fibril-like characteristics. Bacterial cellulose (BC) is also classified as nanocellulose and is distinguished by its great purity and crystallinity. Bacteria (such as *Acetobacter xylinum*) produce it extracellularly, while being cultured in an aqueous medium containing nitrogen and carbon sources, such as sugar.[13,14] The enormous potential of nanocellulose in the textile industry stems from its excellent mechanical performance and the possibility of chemical modification due to the high concentration of surface functional groups that may powerfully interact with diverse substrates. Nanocellulose is an effective adsorbent for textile dyes, both cationic and anionic, and has a significant application in textile wastewater treatment. In textile colouration, nanocellulose is important in more sustainable dyeing processes since it minimizes the use of dyes, water, chemicals, and dyes emitted in effluents.[13] Nanocellulose materials have several textile uses, including textile reinforcement, functional finishes, nanocoatings and nanocomposites.[14]

Nanoparticles: Power in miniature

Nanoparticles are perhaps the most recognizable nanomaterials due to their widespread use in textiles. These small structures provide a plethora of opportunities, and they can be created from a variety of materials, including metals, metal oxides, and polymers.[14] A notable characteristic of nanoparticles is their remarkably large surface area relative to their volume. This feature makes them perfect for interacting with other materials and surroundings. In textiles, nanoparticles are strategically incorporated into fibres, fabrics, and coatings to provide a range of benefits. Numerous organic and inorganic compound-based nanoparticles, including cellulose,[13,14] chitosan,[15,16] cyclodextrin,[17] alginate, tannic acid, gold (Au),[15] silver (Ag),[17,18] palladium,[16] titanium dioxide (TiO_2),[19] copper, copper oxide,[19] zinc oxide (ZnO),[19,20] aluminium oxide (Al_2O_3),[20] silicon dioxide (SiO_2),[21] graphene oxide (GO),[22] carbon nanotubes (CNT)[23] *etc.* can be applied directly by printing, spray coating, or impregnation methods in the finishing of textiles. The incorporation of these nanoparticles is employed to introduce a diverse range of functionalities, including antimicrobial, ultraviolet resistant, electrically conductive, optical, hydrophobic, flame-retardant, self-cleaning, and antioxidant properties into textiles.[20-23]

For instance, silver nanoparticles are renowned for their antimicrobial properties, making them invaluable in producing textiles with built-in resistance to bacteria and odor.[23-25] This innovation not only improves the functionality of sportswear, but also helps to reduce the water and energy consumption associated with regular laundry because the anti-odor and bacterial-resistant behavior avoids frequent laundering. Additionally, nanoparticles like titanium dioxide can be employed to create UV-protection and self-cleaning textiles.[26,27] Titanium dioxide nanoparticles on textile surfaces catalyze the degradation of organic pollutants when exposed to ultraviolet (UV) radiation. This self-cleaning system eliminates the need for chemical detergents and washing, aligning textiles with sustainability goals and conserving resources.[28] Textile surfaces can be reinforced with nanoparticles, such as alumina or silica, to increase their resistance to wear and abrasion. This kind of nano finishing is useful for garments like workwear and military uniforms, where textiles are frequently in contact with friction.[29,30] Gold, silica, zinc oxide,[31] carbon nanotubes (CNTs),[32] graphene,[33] and other nanostructures are often deposited on textiles to give them superhydrophobic, electrical conductivity, and antioxidant properties.[33-36] Nano-finishing offers a versatile approach for customizing textile properties to specific performance requirements.

Furthermore, nanoparticles can be used as catalysts in conjunction with crosslinking agents for sustainability, such as nano zirconia (ZrO_2), titanium dioxide, silver, and silica, which have all been explored as crosslinking agents in nano finishes.[37,38] Titanium dioxide nanoparticles are widely employed due to their photocatalytic activity, which promotes the crosslinking of crosslinking agents with substrates.[39] These nanoparticles have not been utilized alone to give wrinkle resistance; rather, they have served as co-catalysts in several wrinkle-resistant treatments.[40-42] Certain metals, such as gold, silver, platinum, palladium, copper, and quantum dots, exhibit colours due to Surface Plasmon Resonance (SPR) when their particle size is in the nanometer range.[43,44] These nanoparticles may be utilized to make textiles that change colour in response to pH, temperature, or light.

Cellulose nanocrystals (CNCs) are renewable, biodegradable nanomaterials derived from biomass or agricultural waste, offering an abundant and cost-effective source of raw material. Characterized by their high crystallinity (typically above 90%), CNCs exhibit several desirable properties, including low density, high mechanical strength, large surface area, transparency, and biodegradability. Rich in hydroxyl groups, CNCs can be chemically modified with functional groups, such as sulfates, carboxyls, or others, to enhance their application potential. These nanocrystals can be blended with synthetic textile fibers (*e.g*., PVA, PLA), incorporated into nanofibers for nonwoven fabrics, applied as surface coatings, or used to create composite films for textile lamination.[12] Beyond their structural and environmental advantages, CNCs also exhibit unique structural coloration, making them promising candidates for use as photonic materials in optical sensors, inks, and display technologies. The iridescent nature of cellulose nanocrystal (CNC) films, resulting from their chiral nematic (cholesteric) self-assembly, has garnered significant attention for applications in optical sensing. This unique structural coloration, which changes with viewing angle and environmental conditions, has been extensively explored for detecting solvents, monitoring pH levels, sensing humidity, and identifying acid vapors, as documented by numerous studies.[45] A number of investigations have highlighted the synergistic combination of CNCs with polyvinyl alcohol (PVA), which not only enhances the mechanical strength, but also improves moisture barrier properties. This CNC-PVA composite has been effectively utilized in the development of optical fiber-based humidity sensors[46] and has shown promise in the fabrication of self-healing electronic skins,[47] capable of mimicking the tactile and responsive functions of human skin. Owing to their outstanding mechanical integrity, tunable optical features, and chemical versatility, CNC-based materials offer a broad spectrum of potential applications, ranging from functional clothing for everyday use to advanced textile systems tailored for healthcare monitoring, athletic performance enhancement, and protective gear in defense environments.

Nanofibers: Strength in scale

Another class of nanomaterials that have significantly impacted the textile sector is nanofibers, which are distinguished from conventional fibres due to their extremely small diameter, large surface areas, and high aspect ratios. These characteristics give exceptional properties to the nanofibers that make them suitable for a wide range of applications.[48] Nanofibers can be produced using a wide range of materials like polymers, carbon materials, and natural biomaterials. Synthetic polymers include polyurethane (PU), polylactic acid (PLA), polylactic-co-glycolic acid (PLG/PLGA), polyethylene-co-vinyl acetate (PEVA), polycaprolactone (PCL), polyacrylonitrile (PAN); natural polymers include proteins, like keratin, collagen, silk fibroin, gelatin, and polysaccharides, like cellulose, alginate and chitosan, as well as lignin, which gives them a tremendous range of versatility. Electrospinning is the most commercially viable method for producing nanofibers; in addition to that, several other techniques are also available to produce these nanofibers, which provide flexibility and adaptability for several application areas.[49,50] 3D nanofibrous structures with required porous characteristics, surface interaction, and mechanical properties can be easily tailored for specific applications like noise acoustics, filter media, tissue scaffolds, and medical devices.[51,52]

Due to their unique properties, including their electrical conductivity, mechanical strength, and large surface area, carbon nanofibers have many applications in energy harvesting/storage, sensors, biomedicine, and catalysis.[50] Biomaterials, such as collagen, gelatin, chitosan, fibrinogen, hyaluronic acid, and silk, are frequently employed as scaffolds due to their biocompatibility and bio-functionality.[51] Electrospun matrices can have body-mimicking structures, which makes them useful in tissue engineering and wound care applications, where they promote the regrowth of damaged tissue and accelerate the healing process.[52,53] Incorporating medicines or bioactive substances is also possible with these electrospun matrices. Wound care often benefits from sustained controlled release, since it reduces or eliminates the burst effect of conventional medicine injection, and incorporating the medication into a fibre matrix also enables very specific and local drug delivery, reducing the amount of drug necessary to have the desired effect.[54-56] Using biodegradable nanofiber matrices adds benefit to electrospun wound care products since painful removal of the product is unnecessary. Additionally, by selecting an appropriate material, the nanofibers facilitate the healing process and simultaneously degrade and leave behind only waste compounds that the body can naturally eliminate.[57] Also, the degrading behavior of the fibers, and hence drug release, may be altered depending on material choice and the morphology of the fibres.[58] Thus, tissue engineering, smart/responsive wound dressings, scaffolds for regenerative medicine, and target drug delivery systems are the most promising applications of nanofibers in the biomedical field.[37,54,55]

Filtration is another noteworthy use of nanofibre structures, and they are used for adsorption of pollutants, removal of contaminants, and filtering of water and air.[48,59] Nanofiber-based textiles can serve as highly efficient filters; their large surface area and small pore sizes enable the capture of even the smallest particles, including airborne pollutants and bacteria.[60] Such textiles are not only important for enhancing indoor air quality and safeguarding public health, but they also help to promote environmental sustainability by lowering pollution and the need for throwaway filters. Nanofiber materials are also used in automotive air filters to enhance filtration efficiency. Additionally, they can be incorporated into fuel filtration systems to capture particles and improve fuel quality.[61,62]

Nanofiber-based textiles and apparel are used to improve breathability, moisture management, and antimicrobial qualities.[63] The nanofibers can enhance the moisture-wicking properties of sportswear, keeping athletes dry and comfortable. For instance, nanofiber-based fabrics can be used for advanced sportswear or military uniforms.[48,51,64] Nanofiber-based conductive materials can be used to create wearable sensors,[65] flexible displays, and electronic textiles.[66] They have found extensive uses in the fashion sector, and these developments are being explored for greater usage in defense, healthcare, and on-body energy-harnessing applications.[67-69] Additionally, nanofibers are used in fuel cells, photovoltaic materials, and energy storage devices, including batteries and supercapacitors.[70-72] Nanofiber-based electrodes can provide more surface area and improved charge/discharge kinetics, increasing the overall efficiency of energy storage systems.

Cellulose nanofibres (CNFs) have been effectively processed via electrospinning using a variety of natural and synthetic polymer matrices. They significantly enhance the mechanical performance of polymer composites, and beyond that, they impart application-specific functionalities to electrospun nanofibers.[11] CNFs have demonstrated high biocompatibility in biomedical contexts and have been associated with improved cell adhesion, proliferation, and migration, without causing cytotoxic effects. For instance, electrospun vascular scaffolds were developed from cellulose acetate (CA) containing both microcrystalline cellulose (MCC) and CNFs, where CNFs facilitated enhanced cellular attachment, and a synergistic interaction with MCC yielded improved biocompatibility and cell viability.[73]

In another study, a 20-fold and 22-fold increase in oxygen and carbon dioxide permeability, respectively, was reported in chitosan–polyethylene oxide (PEO) electrospun mats upon incorporation of CNCs. This elevated gas permeability is critical for wound dressing applications, where efficient gas exchange promotes tissue regeneration and suppresses anaerobic bacterial growth. CNCs have also demonstrated promise in wearable electronics.[74]

Furthermore, CNCs have shown efficacy in membrane technologies, where the incorporation of CNCs enhances salt rejection efficiency of PVDF-HFP-based membranes, demonstrating their potential to substantially improve membrane separation performance.[75]

Nano-coatings: a protective shield

Nanocoating is another aspect of nanotechnology's influence on textiles, where ultra-thin coatings are applied on textile surfaces to impart specific properties or functionalities.[76] Nano-coatings incorporating phase change materials (PCMs) can be employed in textiles for thermal regulation. These coatings allow textiles to absorb, store, and release heat in response to temperature fluctuations, which improves comfort. Applications encompass outdoor apparel and military uniforms.[77,78] Nano-coatings can also provide flame resistance, UV protection, and stain repellency, hence increasing the durability and longevity of textiles.[79,80] These coatings can be customized for specific requirements, ensuring that textiles can function even under extreme environmental conditions.[81,82] Developing superhydrophobic fabrics is one of the most prominent uses of nanocoating, where textiles coated with nanoscale structures mimic the lotus leaf and result in water-repellent properties. This not only keeps wearers dry, but also reduces energy consumption by enabling faster drying times.[83]

Cellulose nanocrystals (CNCs) have emerged as a promising green finishing agent for the development of multifunctional textiles. Due to their exceptional physicochemical properties – such as high stiffness, large surface area, and excellent mechanical strength – CNCs enable the fabrication of textiles with enhanced functionalities, including antimicrobial activity, ultraviolet (UV) protection, hydrophilic surface modification, flame retardancy, and insect repellency. Beyond textile applications, CNCs are also incorporated into a variety of advanced products such as filtration membranes, face masks, and antimicrobial wound dressing films. Their biocompatibility, biodegradability, and low cytotoxicity further contribute to their appeal in scientific and technological domains, particularly in the fields of healthcare, environmental engineering, and sustainable materials science.[84]

Nanocoatings of photochromic and thermochromic polymers can add functionality in textiles to sense changes in temperature or light intensity.[85] Therefore, in addition to the aesthetic attributes employed in the fashion industry, these nano-coated textiles also have diverse applications, such as optical displays, temperature monitoring, humidity monitoring, pressure, strain, data transfer, and communication in complex textiles. Several industries, including fashion, sporting goods, and medical gadgets, employ these materials.[86,87]

NANO-REVOLUTION IN SMART TEXTILES

Nanotechnology has effectively integrated intelligence into the basic needs of human existence. The combination of nanotechnology with textiles has resulted in the emergence of a new chapter of advancement, specifically in the creation of intelligent textiles. Smart textiles are becoming more advanced and competent by including nano-sensors, actuators, energy-harvesting components, and communication technologies.[88,89] These intelligent fabrics provide improved functionality, comfort, and interactivity, making them extremely valuable in several industries, such as healthcare, sports, and fashion.

Nano-sensors, composed of tiny components like nanoparticles and nanowires, are embedded within textile fibres to monitor various physiological and environmental parameters, such as body temperature and heart rate.[90] These sensors can detect changes in body temperature, humidity, and even biomarkers, providing real-time data for health monitoring and diagnostic purposes.[91] The tiny size and high surface area of nanomaterials used in these sensors make them exceptionally sensitive and responsive. The data collected by nano-sensors can be processed and transmitted wirelessly to external devices, such as smartphones or medical monitors, enabling individuals to track their health and well-being seamlessly.[90,91] The different technologies employed in the development of smart textiles with different application areas are depicted in Figure 3.

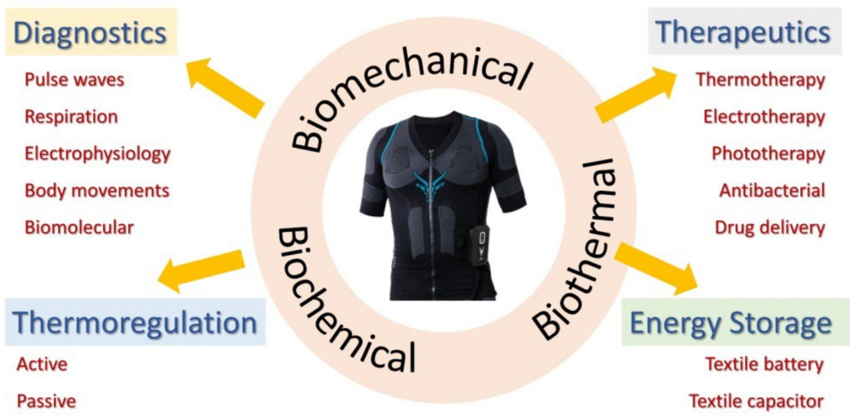

Figure 3: Different technologies employed for the development of smart textiles

Beyond health, nano-sensors can be employed in environmental monitoring, such as detecting air quality or harmful pollutants. When integrated into clothing, they offer wearers the ability to assess their surroundings in real time, providing information about air pollution, allergen levels, or UV radiation exposure.[92,93] Moreover, nano-sensors have the potential to enhance safety in industrial settings, as they can detect exposure to hazardous chemicals or excessive heat, sending alerts to workers or supervisors.[94,95]

Smart textiles have the ability to synergize sensing and actuation capabilities. Nanotechnology empowers textiles to possess actuation capabilities, making them dynamic and adaptive. Smart textiles incorporating shape-memory polymers can provide adaptive solutions in various application areas. Shape-memory polymers composed of nanoscale elements, such as shape-memory polyurethane, poly-hydroxyproline, polysilamine, poly (N-isopropyl acrylamide) hydrogels, polythiophene gel, *etc*., when subjected to specific triggers like temperature changes or mechanical stress, can change shape or stiffness.[95-98] Such textiles can automatically adjust their breathability, creating a cooling effect in response to temperature or humidity, enhancing wearer comfort in varying climates.[98,99] Additionally, nanoscale actuators can be used in therapeutic garments to generate vibrations or gentle pressure to provide relief for individuals with mobility issues or sensory sensitivities.[99] In sports apparel, they can dynamically adjust the fit and comfort of clothing in response to body movements and environmental conditions. This dynamic support optimizes the athlete's performance, reduces the risk of injury, and offers a level of personalization previously unimaginable in sportswear.[100,101] Similarly, these shape-memory textiles can be used in spacesuits, ensuring a snug fit under the vacuum of space or adapting during the extravehicular activities of astronauts.[97] Incorporating shape memory polymers into fabric offers a multitude of intriguing and enhanced characteristics, including aesthetic appeal, comfort, soft textile display, intelligent drug release, imaginative design, wound monitoring, intelligent wetting properties, and resilience against drastic changes in the environment.[102]

The integration of conductive nanoparticles, nanowires, and graphene coatings enables the conductive pathways into fabrics to create textile-based communication systems. This advancement allows smart textiles to interface with other devices in the Internet of Things (IoT) ecosystem, while maintaining their flexibility and comfort.[103,104] Nanoscale conductors are capable of transmitting electrical signals, enabling the creation of wearable antennas, sensors, and communication modules. These nanomaterials are lightweight, durable, and resistant to environmental factors, making them ideal for textiles that need to withstand the rigors of daily wear.[105] Clothing embedded with a nanoscale communication system can turn garments into wearable tech interfaces. A smart shirt with a touch-sensitive area on the sleeve can provide gesture control. These utilize the conductive properties of nanomaterials to detect touch or gestures on the textile surface. Simply by swiping or tapping on this area, the wearer can control music playback, adjust the thermostat, or even send a message.[106,107] Textiles embedded with nanoscale conductors can enable wireless communication for individuals with hearing impairments, enhancing their quality of life by enabling real-time text-to-speech and speech-to-text translations.[107,108] In healthcare, these smart textiles can transmit vital health data to remote monitoring systems, keeping patients safe by updating medical professionals.[109] This level of communication brings a new dimension to the way we interact with technology, making it more seamless, intuitive, and integrated into our wardrobe.

Cellulose nanomaterials exhibit significant potential in the development of smart materials and adaptive systems. These nanostructures are increasingly being utilized to fabricate materials capable of dynamically responding to external stimuli for a wide spectrum of applications, including in responsive coatings, smart textiles, biosensors, and energy-efficient systems.[12]

In the domain of surface coatings, CNF-based smart films have demonstrated the ability to react to environmental changes, such as fluctuations in humidity or temperature. These properties make them ideal for self-cleaning surfaces, anti-fogging applications, and adaptive glazing systems for windshields and architectural glass. Similarly, CNF-integrated textiles exhibit responsive behavior to environmental conditions, enhancing user comfort, breathability, and thermal regulation.[12,110]

In biosensing technologies, these serve as excellent platforms for immobilizing biological recognition elements due to their biocompatibility, hydrophilicity, and tunable surface chemistry. These features facilitate the detection of biomarkers, pathogens, and environmental pollutants, offering practical applications in healthcare diagnostics and environmental monitoring. CNFs have also been explored in the fabrication of shape-memory materials and soft actuators, where their mechanical reinforcement and flexibility significantly improve device performance. Such systems are particularly relevant in wearable electronics, soft robotics, and bioactuators. CNF-based actuators, in particular, offer lightweight, biocompatible, and sustainable alternatives to traditional synthetic materials in robotic and biomedical applications.[111,112]

Moreover, CNFs contribute to energy-efficient technologies. For instance, thermochromic window systems embedded with CNFs modulate light transmittance in response to ambient temperature, thereby reducing the energy demand for indoor climate control.[113] CNF-reinforced electrochromic displays and photovoltaic devices further exemplify the role of CNFs in advancing sustainable electronic technologies.[114]

In the construction sector, CNFs have emerged as sustainable alternatives to conventional building materials. Laminated wallboard panels incorporating CNFs as a bio-based binder, along with functional additives, such as flame retardants, exhibit enhanced mechanical properties, fire resistance, and biodegradability. These composites present a non-toxic, dust-free alternative to gypsum board, aligning with green building practices and circular economy goals.[115]

Recent advancements in biomedical engineering have also highlighted the versatility of CNFs in regenerative medicine. CNFs are being employed in the development of self-healing hydrogels – injectable, biodegradable biomaterials with intrinsic self-repairing capabilities. These hydrogels exhibit tunable mechanical properties and have shown significant promise for wound healing and tissue engineering applications, where controlled degradation, biocompatibility, and mechanical resilience are critical.[116] With the evolution of nanotechnology, CNFs are poised to play a pivotal role in next-generation adaptive systems, spanning environmental sensing, energy-efficient infrastructure, and advanced biomedical platforms.

ENERGY HARVESTING: POWERING THE FUTURE OF WEARABLES

Nanotechnology is ushering in a sustainable and energy-efficient future for wearable technology. The integration of nanogenerators and nanomaterial-based solar cells, wearables can now harness energy from motion and sunlight, reducing their reliance on traditional batteries.[117] This not only enhances the user experience by extending battery life, but also contributes to environmental sustainability by reducing electronic waste. Nanogenerators, a breakthrough in nanotechnology, are at the forefront of energy harvesting for wearables. These devices work on the piezoelectric effect, where materials generate an electric charge in response to mechanical stress. These nanogenerators are designed to convert mechanical energy, such as vibrations or motion, into electrical energy.[118] In wearables, nanogenerators can be seamlessly integrated into textile structures, where they capture energy from the movements of the wearer, such as walking, running, or even the subtle motions of the body. This harvested energy can then be stored in a nanoscale battery or supercapacitor, powering the functions and reducing the need for frequent recharging.[119] Nanotechnology allows the design and manufacture of nanoscale structures with unique properties that are ideal for energy harvesting. For example, zinc oxide (ZnO) nanowires and lead zirconate titanate (PZT) nanomaterials have exhibited excellent piezoelectric properties. These materials can be incorporated into wearable fabrics or attached to flexible substrates, making them an integral part of smart clothing.[120,121]

Similarly, flexible and lightweight solar cells based on nanomaterials can be seamlessly integrated into textile clothing, allowing smart textiles to generate electricity from sunlight.[117,121] This energy can be used to support electronic functionalities, charge batteries, and power LEDs to reduce the reliance on external power sources and enhance the autonomy of smart textiles. Nanoscale materials, such as perovskite solar cells and quantum dots, have been developed to create highly efficient and adaptable photovoltaic systems that can be integrated into wearable fabrics, creating garments that not only protect the wearer from the elements but also capture energy from sunlight.[122,123] The flexibility of these solar cells allows for easy integration into various wearable designs, making them unobtrusive and functional. The development of flexible and washable energy-harvesting textiles enables the creation of smart clothing that can provide continuous power for embedded sensors and communication modules without compromising the comfort of the wearer.[124,125] The different concepts involved in energy harvesting textiles for the generation of power for wearable smart clothing are depicted in Figure 4.

The rapid evolution of energy storage technologies has intensified the demand for high-performance, sustainable materials, and cellulose nanofibers (CNFs) have emerged as a promising material for next-generation supercapacitors and batteries.[126,127] In supercapacitor technology, CNFs contribute significantly to the development of high-efficiency, flexible energy storage devices. These systems typically utilize electrostatic charge accumulation at the electrode–electrolyte interface and often combine electric double-layer and pseudocapacitive mechanisms to achieve improved energy and power densities. The incorporation of CNFs into supercapacitor electrodes has led to impressive enhancements in performance. For instance, CNF-based flexible supercapacitors have demonstrated specific capacitance values as high as 410 F g^{-1} at a current density of 0.8 A g^{-1} and have retained up to 93% of their initial capacitance after 5000 charge–discharge cycles, outperforming traditional counterparts, which commonly exhibit around 85.3% retention after just 2000 cycles.

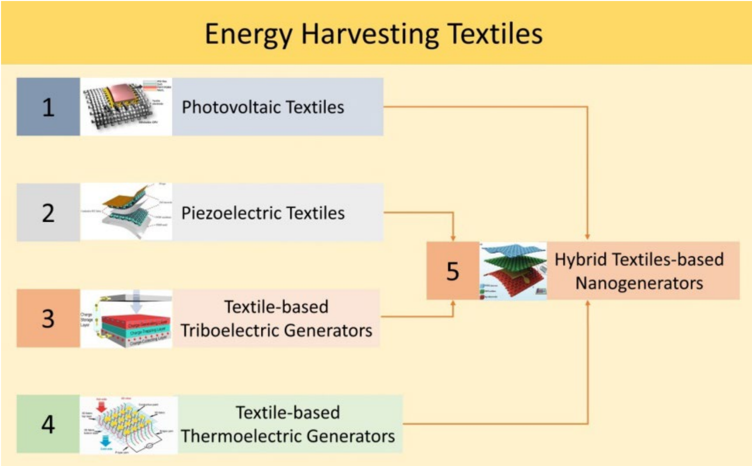

Figure 4: Different technologies involved in the energy harvesting textiles

When integrated with conductive nanomaterials, such as silver nanoparticles and graphene oxide, CNFs further augment charge storage capacity and electrochemical stability. Additionally, the utilization of recycled paper fibers in combination with CNFs for fabricating supercapacitor anodes offers an eco-friendly approach to device manufacturing, delivering high specific capacitance and excellent cycling durability.[127]

An inexpensive, biocompatible, and biodegradable smart cotton fabric was obtained with nanocellulose copper(I) iodide (CuI) thermoelectric semiconductor composite. The resultant fabric exhibits excellent thermoelectric efficiency for applications in body heat harvesting thermoelectric nanogenerator.[128]

Beyond supercapacitors, bacterial cellulose (BC) has shown substantial potential as an anode material for sodium-ion batteries. BC, synthesized via microbial fermentation, possesses an ultrafine nanofibrous network (10–50 nm diameter) characterized by high porosity, biodegradability, and a large electrochemically active surface area. Functional modification of BC with nitrogen-rich compounds, such as urea, polypyrrole, or polyaniline, enhances electrical conductivity and surface reactivity, two critical parameters for improving sodium-ion storage performance.[129]

Recent advances in cellulose-based 3D printing have enabled its application in a range of fields, including plastics, smart paper, biomedical devices, electronics, and sensors.[130,131] The application of carboxymethyl cellulose-lithium (CMC-Li) as a binder in lithium iron phosphate ($LiFePO_4$, or LFPO) electrodes improves electrochemical performance and enhances cycling stability of energy storing devices.[132] Furthermore, 3D printing of nanocellulose has facilitated the design of high-performance lithium metal batteries by enabling precise electrode structuring, improved ion transport pathways, and integration of complex architectures.

Thus, the versatility and effectiveness of CNFs and cellulose derivatives address the key challenges in energy storage, particularly in enhancing performance, sustainability, and structural integrity across various battery and supercapacitor technologies.

ADVANCING SUSTAINABILITY THROUGH NANOTECHNOLOGY

Nanotechnology is also ushering in a new era of sustainability by addressing some of the most persistent environmental challenges in the textile industry. Nanotechnology endorses sustainability by reducing water usage in dyeing processes, enhancing textile durability and recyclability, and enabling sustainable textile finishes.[133,134]

Resource efficiency

Nanotechnology can make textile manufacturing more resource-efficient. One of the most significant sustainability challenges in textile manufacturing is dyeing, which traditionally consumes vast quantities of water and chemicals.

Nanotechnology has introduced nanoscale dye particles (pigments and dyes) that adhere more effectively to fibres, requiring fewer chemicals and reducing water usage by up to 90%. Moreover, the precision of nanomaterials allows the production of vibrant and long-lasting colours that resist fading, reducing the chances of re-dyeing and extending the lifespan of textiles. Nanotechnology-driven dyeing processes are not only sustainable, but also cost-effective.[135]

A significant enhancement in dyeability on polyester fabrics was noted with the coating of cellulose nanowhiskers on rayon fiber, achieving a high color strength (K/S value) of 23.84 when dyed with direct dyes. This enhancement was attributed to a two-path nanocellulose coating strategy, which not only improved the dye uptake, but also imparted superior resistance to soaping.[13,136] Additional benefits of the nanocellulose treatment included increased fabric absorbency and air permeability, indicating the functional improvements achieved without compromising comfort.

Addressing environmental challenges in conventional dyeing processes, a nanofibrillated cellulose (NFC) based dyeing approach is proposed to reduce water and chemical usage. In a study, post-treatment with polycarboxylic acid on cotton fabrics results in the esterification and crosslinking of NFC fibers on the textile surface during dyeing. This treatment enhanced dye fixation by approximately 30% and reduced dye wash-off by up to 60%, thereby improving wash fastness. Importantly, the modifications preserved the inherent softness and breathability of the fabric. The process was successfully applied across a wide range of reactive dyes covering the entire visible spectrum, underscoring the method's versatility.[137]

In another study, a conductive textile was developed by coating cotton fabrics with a nanocellulose–polypyrrole composite. This innovative material demonstrated improved mechanical strength and electrical conductivity. These conductive textiles have potential applications in antistatic clothing, smart filtering systems, architectural ceiling materials, and hygienic fabrics designed to repel dust and microbes.[138]

In a patent, a wood-derived nanocellulose gel was suggested as dye carrier for advanced sustainable textile dyeing. In this approach, the application of pre-dyed nanocellulose gels directly onto fabric surfaces eliminates the water-intensive dyeing processes. Nanocellulose served as both binder and carrier for dye molecules, leveraging its high surface area and abundant surface functional groups to ensure strong dye–fiber interactions. This technique offers a promising waterless alternative for future textile coloration technologies.[139]

In addition to that, the study also revealed that the coating of nanocellulose exhibited stronger adhesion to cotton, and nylon surfaces compared to PET, which was attributed to enhanced hydrogen bonding, cross-linking potential, increased contact area, and greater surface porosity.

Further, the nanocellulose has applications in the development of antimicrobial medical textiles.[140] Conjugating a bioactive compound (Allicin) known for its antimicrobial properties onto nanocellulose, to fabricate cellulose-based fabrics, excellent antibacterial activity was obtained against *Staphylococcus aureus*. Both covalent and non-covalent attachment strategies impart antibacterial properties with the flexibility of nanocellulose functionalization for bioactive textile applications.[141]

Textile waste reduction

Sustainability is intrinsically linked to product durability. Nanotechnology is being leveraged to enhance the longevity of textiles through the development of durable nano-coatings that protect textiles from wear and tear.[142] These coatings are applied at the nanoscale, forming a protective barrier, without compromising the breathability and comfort properties of textiles. Nanoscale materials like carbon nanotubes and graphene can reinforce textiles, making them more robust and tear-resistant.[143,144] This innovation is particularly relevant in the development of workwear, outdoor gear, and military textiles, where durability is paramount. Furthermore, self-healing textiles, made possible by nanotechnology, are designed to repair minor damage automatically. Nanoparticles are embedded within the textile structure to respond when exposed to environmental simulations, such as heat or moisture, which triggers a repair process, extending their lifespan and reducing the textile waste.[145]

Cellulose nanofibers (CNFs) are emerging as highly effective materials for environmental remediation, particularly in the domains of water purification and pollution mitigation. CNFs exhibit excellent adsorption capabilities for a wide range of pollutants, including heavy metals, organic compounds, and microbial contaminants. Their biodegradability and renewability further enhance their suitability for eco-friendly applications.

Engineered CNF-based composites have been developed to selectively remove specific contaminants, offering targeted and efficient solutions for wastewater treatment. CNFs have been incorporated into various formats, including adsorbents, hydrogels, aerogels, and membrane systems, demonstrating significant versatility across different purification strategies.

CNFs can physically entrap and inactivate pathogenic microorganisms, making them suitable for use in antimicrobial filtration membranes. Functionalized CNFs exhibit high affinity for toxic metal ions, such as Pb^{2+}, Cd^{2+}, and As^{3+}, thereby addressing critical concerns in potable water safety. In addition to that, surface-modified CNFs, with hydrophobic and oleophilic characteristics, facilitate efficient separation of oil from aqueous phases, offering potential for oil spill cleanup and industrial wastewater treatment. Also, CNF-based systems can effectively capture suspended solids, leading to marked reductions in turbidity and improvements in overall water quality.[146]

The integration of CNFs into water treatment technologies not only enhances purification performance, but also contributes to environmental sustainability due to their degradability and non-toxic nature. As multifunctional, sustainable nanomaterials, CNFs are poised to play a pivotal role in advancing global environmental and energy resilience.

Recycling and circular economy

Textile recycling presents challenges due to the complexity of fabric compositions and the difficulty of separating blended fibres. Nanotechnology addresses this challenge by designing textiles with enhanced recyclability. Nanomaterials enable the creation of textiles with easy-to-separate components, making recycling more efficient.[147,148] Additionally, nanotechnology aids in the development of circular economy models for textiles. Nanoscale sensors can track the history and composition of textiles, facilitating their sorting and recycling at the end of life.[149] By embedding nano-sensors into textiles, manufacturers can ensure that old textiles are repurposed into new products more effectively, reducing the environmental impact of textile disposal.[150]

Sustainable textile finishes

Nanotechnology-driven finishes for textiles have revolutionized their performance and sustainability. For instance, superhydrophobic nano-coatings make textiles water-repellent, reducing the need for frequent washing and minimizing water and energy consumption. Nanotechnology also enables the development of UV-resistant finishes that protect textiles from degradation caused by sunlight exposure. These finishes extend the lifespan of outdoor textiles, such as awnings and outdoor furniture, reducing the frequency of replacements and resource consumption.[150-152]

Nanoparticles, such as titanium dioxide, can be incorporated into fabrics to create self-cleaning textiles. When exposed to sunlight, these nanoparticles can break down organic contaminants on the fabric's surface, reducing the need for energy-intensive washing. Moreover, nanotechnology-driven developments like phase-change materials can be integrated into textiles.[153,154] These materials store and release thermal energy as temperatures change, contributing to improved insulation and reduced heating or cooling energy consumption.[154-156] This is particularly relevant in applications such as home textiles and outdoor apparel.

Sustainable nanocomposites

In contrast to conventional composites derived from non-renewable fossil fuel resources and typically lacking biodegradability, nanocellulose-based composites present a sustainable alternative with enhanced functional properties. Cellulose nanofibers (CNFs) and cellulose nanocrystals (CNCs), owing to their nanoscale dimensions and high aspect ratios, significantly improve interfacial adhesion and stress transfer within polymer matrices. These improvements translate into superior mechanical, thermal, and barrier properties, expanding their utility across sectors, such as automotive, aerospace, packaging, and biomedical engineering.[12,14,157]

Among various biodegradable polymers, polylactic acid (PLA) has emerged as a leading candidate, and reinforcement of PLA with CNCs has demonstrated substantial enhancement in mechanical strength, thermal stability, and barrier performance.[158] CNCs act as effective nucleating agents, promoting crystallinity within the PLA matrix and thereby improving the overall mechanical performance of the composite.[159] PLA-CNC composites have been extensively investigated over the past decades for applications in packaging, textiles, orthopaedics, tissue engineering, drug delivery, and biomedical devices.[160] The broad applicability of CNF-reinforced nanocomposites can be summarized across several industries:

- Automotive industry: CNF composites reduce component weight without compromising mechanical integrity, thereby improving fuel efficiency and reducing emissions;[161]
- Packaging sector: nanocellulose-based films offer superior moisture and gas barrier properties, enabling extended shelf life and reduced food spoilage in eco-friendly packaging solutions;[162]
- Biomedical applications: the inherent biocompatibility and mechanical robustness of CNF-based composites make them well-suited for use in implants, prosthetics, scaffolds, and drug delivery systems. Functionalization with bioactive agents further enhances their suitability for tissue engineering and targeted therapeutics.[14,131]

Ultimately, the performance of CNF-based composites is critically linked to the nature of polymer–nanocellulose interactions. Through a combination of mechanical interlocking, hydrogen bonding, and engineered surface functionalities, CNFs enable the design of next-generation sustainable composites with high performance, mechanical resilience, and environmental compatibility. These developments underline the growing relevance of nanocellulose in the advancement of lightweight, bio-based, and multifunctional materials across technologically significant domains.

CHALLENGES OF NANO-REVOLUTION IN TEXTILES

Nanotechnology in textiles offers numerous benefits, but it also raises various concerns and potential risks. The application of nanotechnology in textiles brings forth a set of challenges that must be addressed for the responsible and safe use of nanomaterials in this industry Figure 5. Key concerns include potential health and environmental impacts associated with the release of nanoparticles during the life cycle of nanotechnology-enabled textiles.[163-170] The specialized facilities and expertise required for manufacturing processes involving nanomaterials contribute to elevated production costs.[167] Achieving uniform dispersion and stability of nanomaterials within textile matrices poses a technical challenge. Furthermore, fostering increased transparency and effective communication about the use of nanomaterials in textiles is essential to address consumer apprehension and promote ethical practices.

Figure 5: Challenges associated with the nano-revolution in textiles

Health and environmental impact

One of the foremost challenges in nanotechnology-based textile finishing is the potential impact on human health. The toxicity and the emission of nanoparticles are the major factors for their impact on humans and the environment.[164] The toxicity of nanoparticles is contingent upon several factors, including composition, size, shape, surface area, morphology, functionality, and dose exposure. In contrast, the risk of nanoparticle emission remains for the entire product lifecycle.[165-167] In all the stages from production to usage and final disposal, the nanoparticles present a risk of inhalation. Airborne nanoparticles have the potential to cause adverse health effects when breathed into the respiratory system. Additionally, direct skin contact with nanotextiles may cause unknown diseases in humans due to the possibility that nanoparticles may be absorbed through the skin and then travel through the bloodstream to other tissues and vital organs.[168]

Studies have demonstrated that nanoparticles can easily enter to human body and are more toxic compared to conventional-size particles of the same chemicals. After entering the human body, these nanoparticles can cause severe health issues, with an increase in the risk of cardiopulmonary diseases,[169] and respiratory tract inflammation, which is detrimental to tissues.[170,171] The nanoparticle, because of its extremely small size, can enter the human body via the nostrils and freely circulate through it, accessing the internal organs. Many research studies have investigated that even chemically inert metals like gold, copper, and platinum in their nanoform can catalyse several reactions in the human body.[172] Analyses conducted both in living organisms (*in vivo*) and in laboratory settings (*in vitro*) have demonstrated that the toxicity of silver nanoparticles has adverse impacts on biological functions, including the degradation of DNA in mammalian cells,[173] detrimental impact on neuronal cells, white blood cells, as well as cells in the spleen, liver, and lungs.[173,174]

Nanomaterials containing zinc have been widely utilized in various commercial goods due to their UV protection, antibacterial properties, and healing capabilities. The effects of this substance on the human body have been acknowledged, yet it is less dangerous compared to other substances like silver and copper. Currently, the main concern is directed towards the repercussions of its overall toxicity resulting from excessive consumption.[175] Prolonged consumption of high levels of zinc can cause oxidative damage to the immune system, resulting in symptoms such as tiredness, weakness, shivering, elevated body temperature, inflammation, heightened activity, and cell demise. In addition, it can lead to urinary tract infections and elevate the likelihood of developing prostate cancer.[176-178] Furthermore, it can enhance the synthesis of proteins, such as creatinine, amylase, and urine protein, which can lead to the deterioration of the glomerular structure and the death of renal tubular epithelial cells.[179] Silica-based nanoparticles have garnered considerable interest in the fields of textiles, agriculture, and biomedicine.[175–177] The cytotoxicity of silica nanoparticles is influenced by the surface charge as well as varies according to the kind of cells. According to the findings, cancer epithelial cells have a strong resistance to silica nanoparticles, and the toxicity of these nanoparticles mostly affects white blood cells, specifically macrophages.[178-180]

Several studies have been carried out to examine the toxicity of titanium dioxide nanoparticles,[181-183] which may be inhaled as aerosols or diffused through the skin into the bloodstream. Inhaling nano titanium dioxide can lead to several physical problems, such as spleen damage, immunological dysfunction, oxidative stress, apoptosis, alterations in the metabolic process, and abnormal cell proliferation.[181] In addition to that, these nanoparticles cause respiratory tract inflammation, which is detrimental to tissues, and raises the risk of cardiopulmonary disorders.[182,183] One of the organs that nanoparticles target is the central nervous system, and the most susceptible region of this system is the hippocampus.[174,182] The nervous system is stimulated by nanoparticles to release cytokines and reactive oxygen species; these substances have the potential to harm the blood-brain barrier and cause nervous system dysfunction. Numerous animal studies have demonstrated that the reproductive system is negatively impacted by exposure to metal-based nanoparticles.[175-177] The primary indicators of nanoparticle reproductive toxicity in mammals include genital harm, sex hormone suppression, and effects on germ cells and progeny.[183-185]

Quantitative risk assessments for the use of nanoparticles in clinical settings are made more difficult by the fact that even nanoparticles with the same chemical composition may exhibit notable variances in their toxicological properties.[186,187] Therefore, a major technical problem is developing efficient and consistent development procedures to manage the health risks associated with these nanomaterials. The risk and the impact of nanoparticles on humans and the environment are depicted in Figure 6.

Nanoparticles released during the life cycle of nanotextiles may have ecotoxic effects on ecosystems, potentially harming aquatic life and soil organisms.[188] The persistence and bioaccumulation of certain nanomaterials can have far-reaching consequences. The risk of nanoparticles to the environment is associated with their entire life cycle: starting from manufacturing to their incorporation into the products, then from the product utilization, and finally with their recycling and disposal (Fig. 7). Similarly, the impact of nanoparticles on the environment can be understood with comprehensive knowledge of their identification, their source of emission in the environment, and their toxicity.[189]

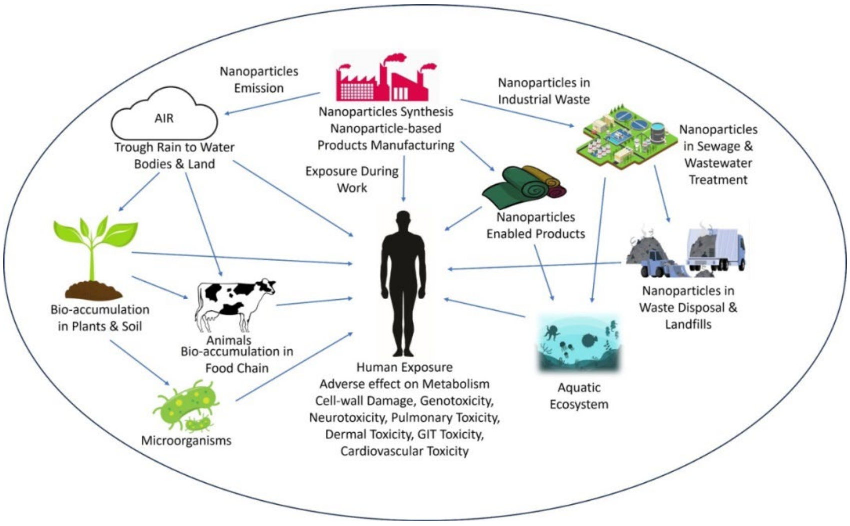

Figure 6: Impact of nanoparticle exposure on humans and the environment

The ability of nanoparticles to penetrate and infiltrate soil, water, and air is what essentially determines their natural potential toxicity, and the number of nanoparticles released into the environment directly affects this ability. So, once they reach the environment, the impact of nanoparticles is directly related to their ability to accumulate in organisms, therefore, the risks associated with the use of nanomaterials are determined by all those processes that control their release or emission into the environment.[190]

The highest risk of nanoparticle exposure for humans and the environment occurs during their use and disposal[189] (Fig. 7). Understanding a product's life cycle is crucial to assessing risks associated with nanoparticle emissions from nanotextiles and nano-finishing techniques. This involves evaluating the nanomaterials' properties, application methods, durability, storage, transportation, use, disposal. Analyzing the life cycle helps identify phases and environments where nanoparticles are released. However, due to uncertainties in characterizing nanotechnology, life cycle assessments (LCA) tailored to specific decisions are often more effective than attempting to map life cycle impacts explicitly.[188] While LCA is a comprehensive tool for assessing environmental and human health impacts, limited data hinder its application for nanoparticle development.

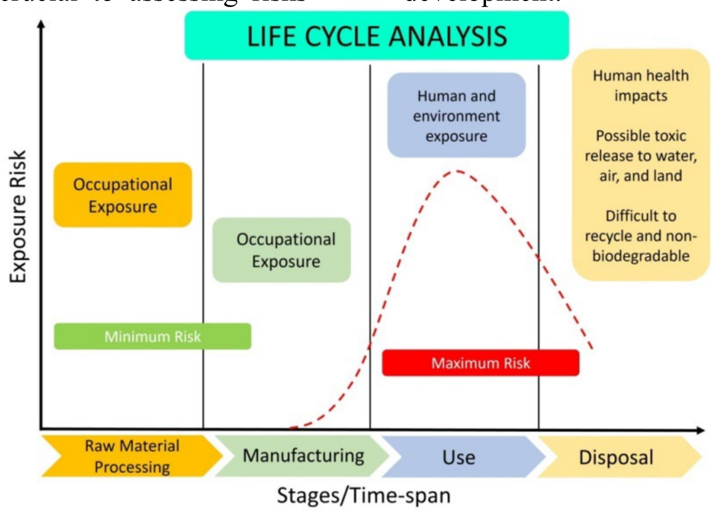

Figure 7: Life cycle analysis of nanomaterials with risk associated at different stages

Safety concerns in nanotechnology further complicate LCA impact assessments, often omitting normalization and weighting phases.[189,190] For effective risk assessment, integrating life cycle concepts into nanoparticle risk evaluation is essential to avoid an incomplete understanding of their environmental and health risks.

Regulatory and standardization issues

The textile industry lacks comprehensive regulations and standardized testing procedures for nanomaterials used in finishing processes. This regulatory gap may result in inconsistent quality control and safety procedures throughout manufacturers and geographical areas. The absence of definitive rules makes it challenging to regulate and ensure the safe use of nanotechnology in textiles.[191] After nano-products are synthesized and characterized, comprehensive research into the toxicity of specific nanomaterials and their exposure risks is essential to assess potential hazards.[192] Governments, research institutions, and manufacturers should collaborate for study programs to better understand the safety implications. Meanwhile, the manufacture, distribution, storage, and transportation of nano-products are not governed by such organizations.

Regulatory agencies should establish clear guidelines and standards for the use of nanomaterials in textiles, encompassing manufacturing, labelling, and disposal. These guidelines should consider the unique properties of nanomaterials. Most developed nations have joined international organizations, such as the OECD WPMN (Organization for Economic Co-operation and Development the Working Party on Manufactured Nanomaterials), REACH Annex (Registration, Evaluation, Authorization and Restriction of Chemicals Annex), ISO/TC 229 (International Organization for Standardization /Technical Committee 229), and others in response to the risk associated with nanomaterials.[193-195] The NIOSH (National Institute of Occupational Safety and Health) organization is primarily researching the exposure of nanoparticles to workers, their impact on their health and safety at work, and offering recommendations for lowering that exposure. Establishing clear regulatory guidelines for the development, production, and use of nanotextiles is essential, therefore, governments, industry stakeholders, and researchers need to collaborate to create and update regulations to ensure the responsible use of nanotechnology.

Ethical issues

The rapid development of nanotechnology in textiles may outpace regulatory frameworks, leading to potential gaps in oversight and accountability. Consumers may not be aware of the presence of nanotechnology in the textiles they purchase. There is often a lack of clear labeling to inform consumers about the use of nanomaterials in textile products. Ensuring consumers are informed about the presence of nanotechnology and any potential associated risks is essential for transparency and safety.[192-194] Manufacturers should also be transparent about the use of nanotechnology in their textile products, and consumers should be educated about potential health and environmental impacts. Textile manufacturing facilities should implement adequate worker safety measures, including the use of personal protective equipment and ventilation systems to minimize exposure to airborne nanoparticles. Thus, promoting ethical considerations in research and development, ensuring transparency in disclosing potential risks, and engaging in public dialogue can help to address these concerns. Encouraging a multidisciplinary approach involving scientists, ethicists, policymakers, and the public can contribute to responsible nanotechnology development.[195]

Scalability and costs

The challenge of scalability is a major obstacle in the application of nanotechnology in textiles. Although nanotechnology offers promising advantages to improve fabric properties and performance through functionalities, the transfer from laboratory-scale research and development to large-scale industrial production presents several significant challenges.[170,182,196] The cost of manufacturing nanomaterials is not only exorbitant, but the standard technologies used in their production are also hazardous, energy-intensive, and lack biocompatibility and environmental friendliness.[196] Furthermore, the production of nanoparticles necessitates the utilization of several substances, such as surfactants, capping agents, and stabilizers to regulate their dimensions, structure, and stability. These substances pose a risk to both land-dwelling and aquatic organisms. It is imperative to discover replacements for these additives, and other methods must be investigated for the production of nanomaterials.[197-198] The process of biosynthesis, also known as green synthesis, is a growing alternative to traditional methods of creating nanomaterials. It is regarded as a straightforward, cost-effective, safe, biocompatible, and environmentally friendly approach.[199–200] Various microorganisms or botanical extracts can be utilized for the process of synthesizing nanoparticles.[201] Additional research and development are necessary to achieve biocompatible and eco-friendly manufacturing, as well as to explore cost-effective strategies for utilizing nanoparticles with little time and energy usage. To successfully address this challenge, it is necessary to employ a blend of inventive thinking, financial resources, and collaborative efforts to fully capitalize on the advantages of nanotechnology in the textile sector and satisfy the need for extensive manufacturing capabilities. Ongoing research and development endeavors to enhance and simplify the process of synthesizing and producing nanomaterials.

CONCLUSION

Nanotechnology offers a promising strategy to revolutionize the industry, delivering improved functionality, customized intelligence, and sustainability, but the journey of the nano-revolution is not so simple. Cellulose nanomaterials offer a wide range of applications, such as enzyme immobilization, synthesis of antimicrobial and medical materials, green catalysis, biosensing, synthesis of drug carriers in therapeutic, diagnostic medicine, reinforced composites, *etc*. Nanocellulose-derived materials offer distinct advantages for a wide range of electrochemical energy storage applications, such as supercapacitors, lithium-ion batteries (LIBs), and Zn-ion batteries (ZIBs). Despite the successful development of nanocellulose-based advanced materials/devices for high-performance energy storage, there are still certain challenges that need to be addressed in the future, such as large-scale fabrication, surface/interface engineering, flexibility, new materials, and new applications. The challenges of toxicity, health, and environmental hazards associated with the use of nanomaterials emphasize the need for careful consideration and responsible practices. It is imperative that we establish stringent rules and standards systems to protect consumers and the environment, and that ethical concerns associated with nanotextiles must be carefully considered. A balance between technological progress and ethical responsibility is needed to ensure that nanotechnological progress meets societal norms and expectations. Advanced research, innovation, and the responsible use of nanotechnology hold the promise of ushering in a new era of safe, efficient, and environmentally sustainable clothing, and ultimately benefit individuals and the planet. The careful navigation of these challenges and the embrace of these opportunities can embark the textile industry on a transformative journey toward a more advanced, ethical, and sustainable future.

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