

Transforming Fabrics: Nanotechnology's Revolutionary Impact on the Textile Industry

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Abstract: The textile industry has undergone a remarkable transformation in recent years with the integration of nanotechnology. This article highlights the revolutionary impact of nanotechnology on fabrics, elucidating its diverse applications and transformative effects on textile properties and performance. Some aspects of synthesis, characterization and types of nanomaterials have been discussed. Some major applications of textiles embedded with nanomaterials have also been discussed. In addition to material-focused aspects, the review explores the economic landscape of nanotechnology in the textile industry, outlining the current market trends, challenges, and future prospects. The article concludes with a forward-looking perspective on the evolving role of nanotechnology in textiles, emphasizing the need for continued research and collaboration to harness its full potential. This review gives overview of applications of nanotechnology in textile for different sectors.

Keywords: Applications, Nanomaterials, Nanotechnology, Synthesis, Textile.

I. INTRODUCTION

Technological advancements have transformed the global landscape, with nano science, nano engineering, and nanotechnology emerging as highly promising scientific fields that significantly expand the potential applications. Richard Feynman introduced the concept of nanotechnology for the first time in 1959 during his speech titled "There's Plenty of Room at the Bottom," delivered at an American Physical Society conference at the California Institute of Technology [2]. These concepts remained relatively unnoticed until 1974, when Norio Taniguchi coined the term "nanotechnology" [3]. The term "nano" is derived from the Greek word 'Nanos,' meaning dwarf, serving as a prefix to denote "one billionth" of something, represented by 10^{-9} . Particles with a diameter of less

than 100 nm are classified as nanomaterials, and the scientific study of such materials is termed Nanoscience.

Nanotechnology encompasses the design, characterization, production, and applications of structures, devices, and systems by manipulating shape and size at the nanometer scale [4]. Nanomaterials, situated at the core of nanotechnology, have played a pivotal role in driving groundbreaking advancements across diverse domains, revolutionizing drug delivery, textiles, renewable energy, electronics, and environmental remediation. The key feature of nanomaterials lies in their size-dependent properties. As materials enter the nanoscale, quantum effects become more pronounced, resulting in altered electrical, optical, and mechanical behaviors. Furthermore, the substantial surface area-to-volume ratio of nanomaterials makes them highly reactive, enabling interactions with other materials and environments in unprecedented ways.

Nanomaterials possess the potential to revolutionize various industries, including the textile sector, and address critical global challenges. The integration of nanomaterials and nanotechnology in the textile industry has opened new possibilities for creating textiles with advanced properties, improved performance, and increased sustainability. These innovations continue to drive research and development in the field, shaping the future of textiles and expanding their applications across various industries.

One of the key advantages of integrating nanotechnology into textiles lies in its capacity to precisely tailor material properties. Nanomaterials, such as nanoparticles and nanofibers, can be seamlessly incorporated into textiles to bestow specific functionalities, including heightened strength, durability, flexibility, and innovative features such as self-cleaning or antimicrobial properties. This high level of customization empowers the development of textiles that can adeptly meet the diverse and evolving needs across various industries, encompassing healthcare, sports, fashion, and beyond.

The contemporary textile industry grapples with ceaseless consumer demands for novel applications of cutting-edge technology and an unending influx of increasingly inventive products. Traditional textile sectors have witnessed substantial enhancements in product attributes, including mechanical strength, durability, surface texture, and the tactile qualities of fabric, along with the capacity for diverse coloration and intricate printing patterns. Advancements extend to personal care features such as anti-perspirant and deodorant properties, as well as flame-retardancy, self-cleaning, and anti-microbial characteristics.

Nanotechnology integration facilitates the production of smart and multifunctional textiles with numerous groundbreaking applications in health, pharmaceuticals, fashion, sports, military, advanced protection, and transportation (Fig. 1) [5-7]. The manufacturing of microelectronic devices has reached a stage where they can be seamlessly integrated into textiles, leveraging the distinctive capabilities of nanomaterials to imbue fabrics and garments with high added-value functionality. This occurs while preserving other desirable properties such as comfort, flexibility, lightness, and aesthetic appeal [8]. Common textile materials like cotton, silk, or polyester serve as ideal substrates for incorporating smart, functional nanomaterials [9]. Diverse methodologies have been devised to infuse nanomaterials into textiles.

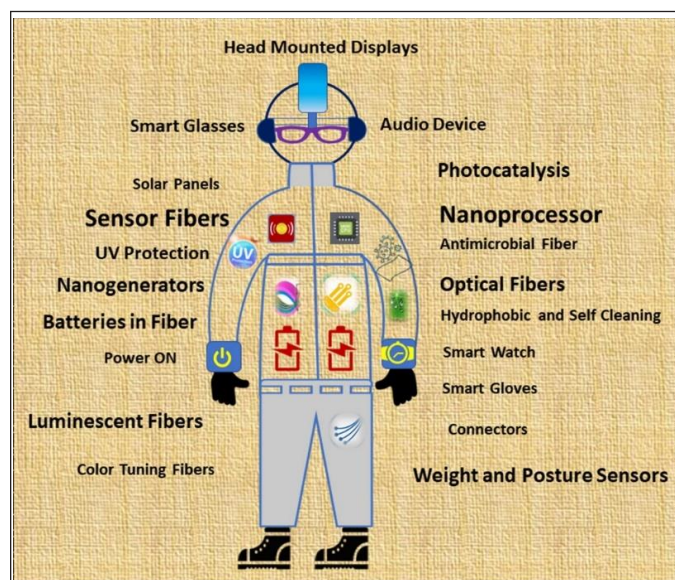


Fig. 1: Futuristic Clothing Made from Nanomaterial [5]

As the textile industry embraces nanotechnology, both researchers and manufacturers are actively exploring innovative ways to augment the functionality of fabrics. The transition from conventional textiles to nanotechnology-infused materials

signifies a paradigm shift, promising a future where clothing serves not merely as a passive covering but as a dynamic and intelligent interface connecting individuals with their environment.

This exploration into the realm of nanotechnology in textiles seeks to unveil the multifaceted applications, challenges, and potential societal impacts of this groundbreaking convergence. As we delve deeper into the intricacies of nanotechnology in textiles, we will uncover how the synergy between these two fields is reshaping our comprehension of materials and presenting unprecedented possibilities for the textiles of tomorrow.

Several review articles and books have been published on the application of nanotechnology in textile industry but the literature is scattered [10-15]. Therefore, this review article briefly discusses the types, synthesis, and characterization of nanomaterials, with a more comprehensive exploration of nanotechnology applications in the textile industry.

II. SYNTHESIS OF NANOMATERIALS

Basically, there are two methods Top down and bottom-up approaches for the synthesis of NMs, In Bottom-up approach, green method is becoming more important (Fig. 2) [16]. However, in today's time much emphasis on the synthesis of NMs is given on green route particularly via plant extract and bacteria.

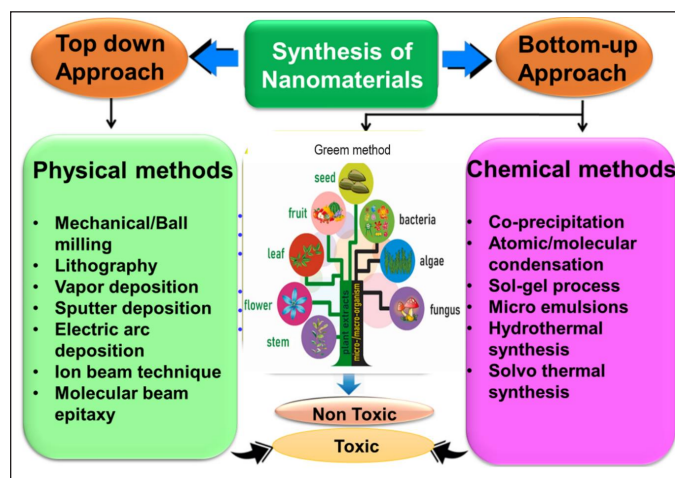


Fig. 2: Synthesis of Nanomaterials

III. CHARACTERIZATION OF NANOMATERIALS

There are number of techniques given in Fig. 3, used for the characterization of nanomaterials.

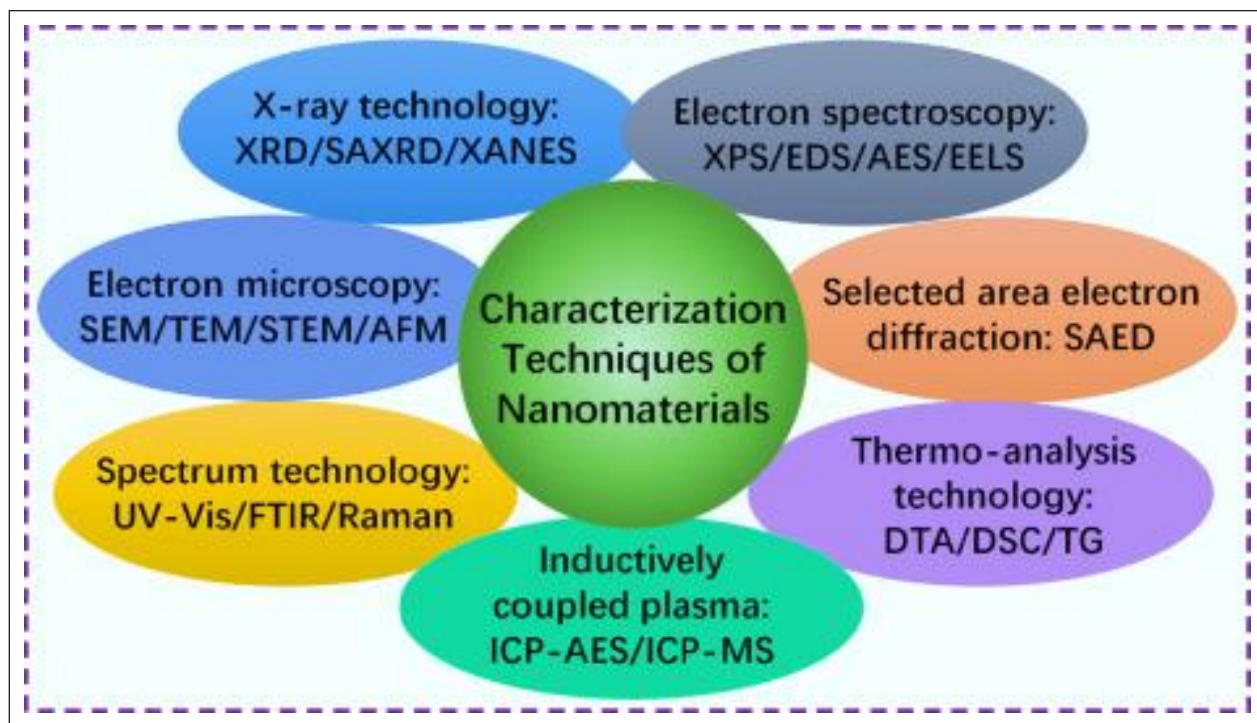


Fig. 3: Techniques for the Characterization of Nanomaterials

IV. TYPES OF NANOMATERIALS

Carbon nanomaterials given in Fig. 4 [17] and represented by Fig. 5 [18].

Nanomaterials are broadly classified as Inorganic, Organic and

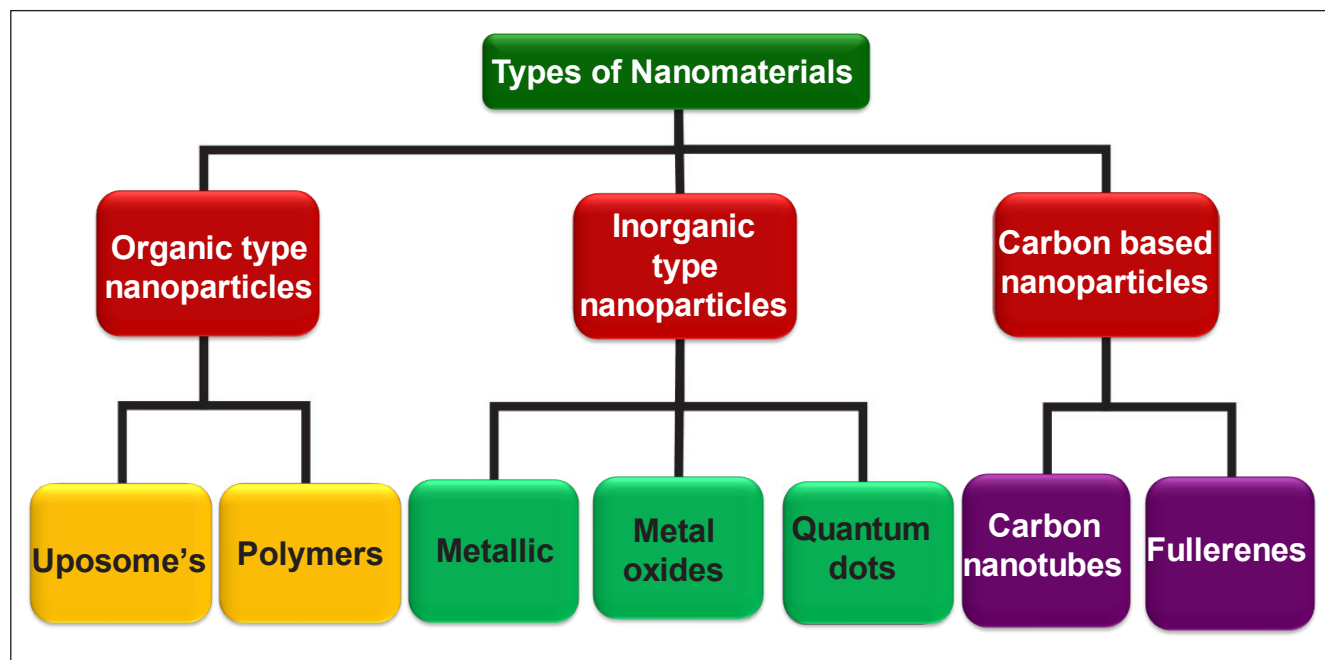


Fig. 4: Different Types of Nanomaterials [17]

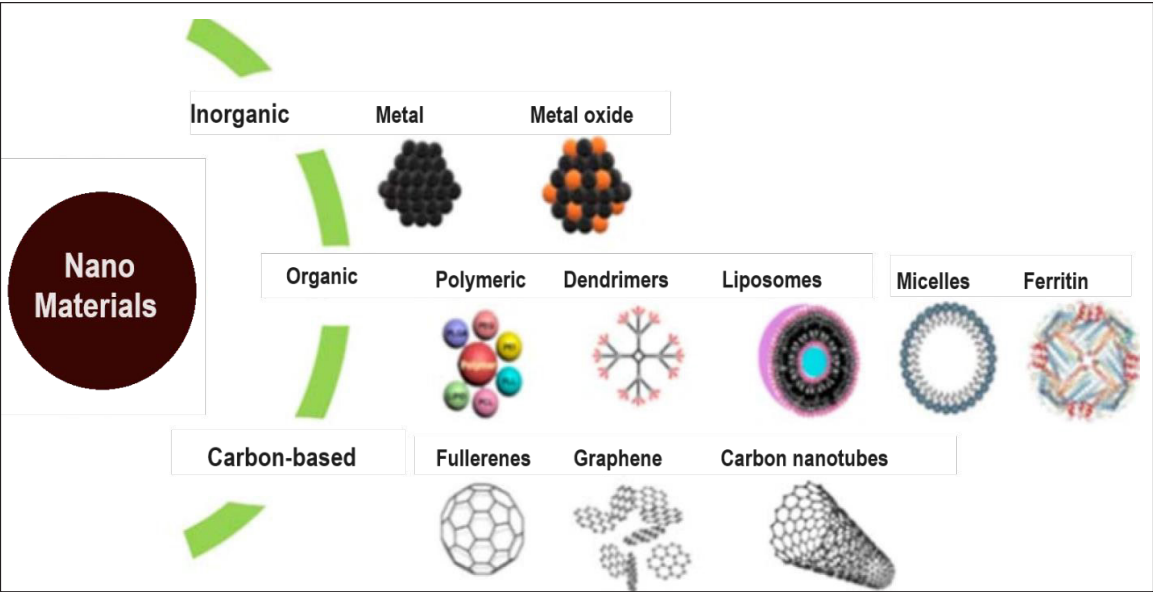


Fig. 5: Different Nanomaterials

V. APPLICATIONS OF NANOTECHNOLOGY IN TEXTILE

While earlier research suggested a wide-ranging timeline for the origin of clothing, spanning from 40,000 to 3 million years ago, a recent anthropological report specifies that approximately 170,000 years ago, the human species commenced the practice of adorning itself with animal hides [17]. Subsequently, with the development of the ability to transform cotton into threads and fibers, humans progressed to creating basic textiles. Over time,

this evolution has led to the production of more intricate and practical forms of clothing. In contemporary times, the fusion of textiles with nanotechnology, smart textiles, and electronics has ushered in noteworthy advancements in the textile industry. Smart textiles are characterized as textiles endowed with the capability to detect and react to environmental changes arising from chemical, mechanical, electrical, and thermal sources. In recent years textiles incorporating nanomaterials are being used in different areas (Fig. 6) [12].

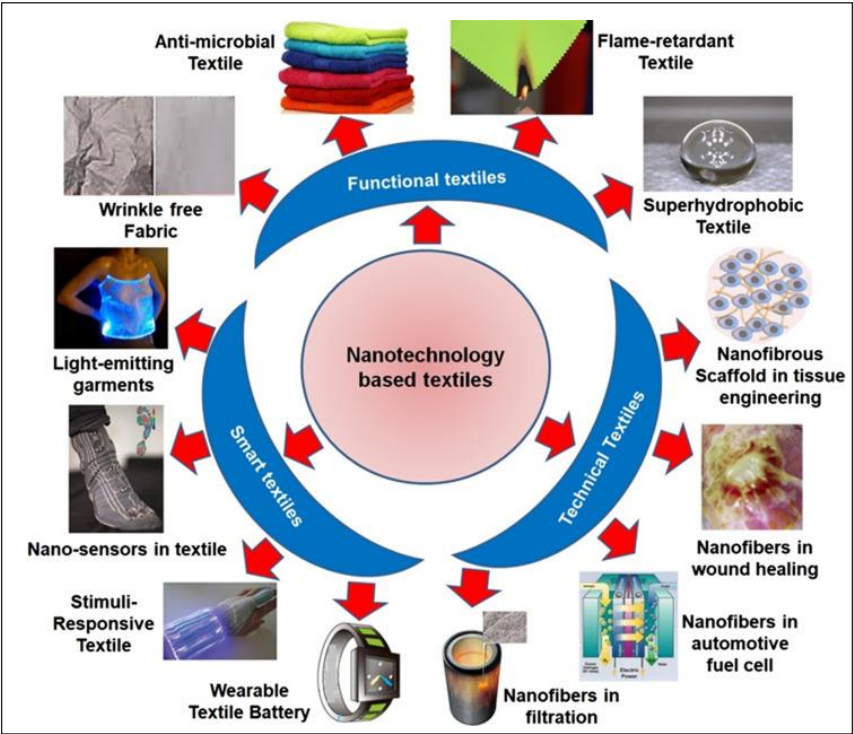


Fig. 6: Nanotechnology Based Textiles [12]

Details of some applications of nanotechnology in textile industry are given below:

A. Healthcare Sector

Nanotechnology-based textiles not only enhance fabric protection and durability but also confer remarkable antimicrobial properties to the material. Nanoparticles such as silver (Ag), zinc (Zn), and copper (Cu) inherently possess antimicrobial activity, acting against microbes through mechanisms distinct from traditional antibiotics and chemical antimicrobial agents. This addresses the pressing issue of antibiotic and drug resistance in pathogenic microbes. The nanoparticles applied to fabrics exhibit three primary antimicrobial mechanisms: contact killing, release killing via the discharge of reactive oxygen species (ROS) or ions, and anti-adhesion, preventing microbe adhesion to the fabric [19].

Sol-gel, layer-by-layer, and plasma polymerization are a few methods that can be used to integrate nanoparticles into textiles to produce nano-engineered fabrics. A change in the texture of the fabric indicates the presence of nanoparticle coating on textiles. Textiles are coloured differently by metal-based nanoparticles according to their sizes and shapes because of their surface plasmons [19, 20]. Because of their strong antibacterial and antimicrobial qualities, silver nanoparticles

are used extensively. Their broad breadth of biocidal qualities and ability to effectively combat a variety of resistant diseases make them suited for a wide range of biomedical applications, including nano gels and nano lotions. Silver nanoparticle-fortified goods are currently widely available in the market and used in water disinfection, hospitals, textiles, implant coatings, and burn and wound care. However, researchers suggest that direct skin contact with silver nanoparticles during wound and burn treatment may happen, which might be harmful if applied excessively and cause skin damage. Another kind of nanoparticles with broad-spectrum antibacterial activity is zinc oxide (ZnO) nanoparticles, the potency of which is dependent on the particle size and concentration.

B. UV Protection

Certain inorganic substances absorb ultraviolet light. Typically, these materials are semiconductors like SiO_2 , TiO_2 , Al_2O_3 , and ZnO . Zinc oxide and titanium dioxide are the most widely used semiconductors. It was discovered that zinc oxide and titanium dioxide at nanoscale are more effective than their conventional counterparts at both absorbing and scattering UV radiation, making them superior UV protection materials. It is therefore unnecessary to take extra precautions when these oxides are impregnated into the fabrics because they inhibit UV rays.

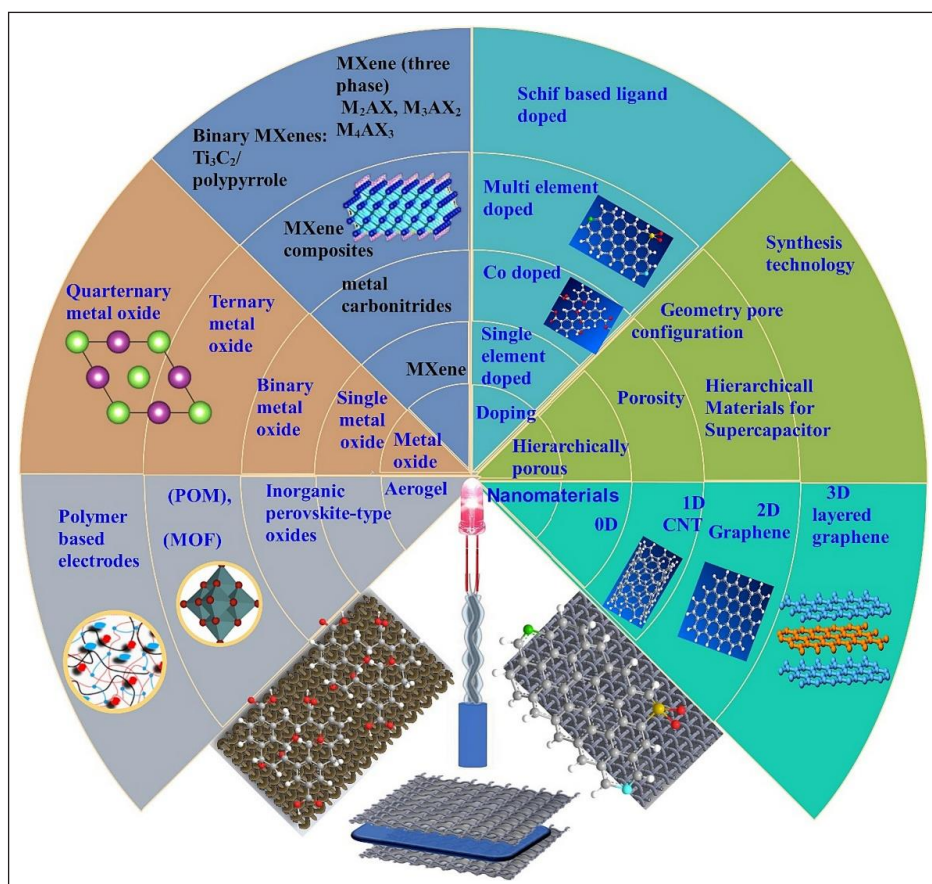


Fig. 7: Nanomaterials Used in Textile Based Supercapacitor

C. Supercapacitors

Fossil fuels supply about 80% of the world’s energy needs. But there is a significant impact on climate change, natural disasters, and environmental degradation from this. Consequently, clean energy sources are required. Since they are wearable, flexible, and stretchable, textile-based supercapacitors are now utilised in energy storage devices. Constructed from conductive materials (especially nanomaterials) placed on textile fabric, yarn, or filaments, textile-based supercapacitors (SCs), lower carbon footprints [20]. Because of its natural deformability, flexibility, and tensile strength, textile fabric or yarn is used as the foundation material for supercapacitors [21]. Fig. 7 [21] displays the various nanomaterials that are used in textile-based supercapacitors.

D. Self-Cleaning Nanotechnology Fabrics

The concept of self-cleaning fabrics is not new, and various methods have been developed to achieve this goal. One particularly promising approach involves the application of nanotechnology. Nanoparticles can be integrated into the fabric fibers or applied as a coating on the fabric’s surface to imbue it with self-cleaning properties. These nanoparticles consist of diverse materials like titanium dioxide, zinc oxide, and silver, each possessing antimicrobial and photocatalytic properties. When exposed to light, these nanoparticles generate reactive oxygen species (ROS) capable of breaking down organic compounds, such as dirt and bacteria, present on the fabric’s surface. This process, known as photocatalysis, can occur even under low-light conditions, such as indoors or on cloudy days. Furthermore, the nanoparticles showcase antimicrobial properties, aiding in the suppression of bacterial growth and odors on the fabric.

E. Hydrophobicity in Textiles

The authentic creator of intelligent functional materials is nature itself. It has frequently served as a muse for scientists seeking to replicate biological phenomena. By integrating carbon nanotubes (CNTs) into cotton fibers, a hydrophobic textile is produced [5]. Additionally, water-resistant fibers can be created by incorporating hydrocarbon-mounted nanowhiskers. These materials exhibit dimensions approximately one-third that of traditional cotton fibers. Embedding these nanowhiskers into textile fibers produces a peach fuzz-like effect, enabling the development of water-repellent coatings through nanoparticulate films on textiles. By employing precise processing techniques to refine fiber texture, superhydrophobicity can be achieved without compromising the comfort, softness, and durability of fabrics.

A primary nanocoating layer on fabric surfaces was fashioned using SiO₂ nanoparticles in conjunction with an epoxy-containing poly (glycidyl methacrylate) (PGMA). This layer was subsequently treated with diverse functional polymers containing amino, anhydrido, carboxy, and hydroxyl functional groups. The myriad applications centered around hydrophobicity encompass waterproofing, anti-fouling, controlled wettability, self-cleaning, water repellency, oil/water separation, anti-icing, and anti-corrosion.

F. E-Textiles

Intelligent designs and enhanced capabilities in electronic textiles (e-textiles) present promising solutions to various medical and fitness challenges. Currently, e-textiles find extensive applications in the realm of apparel. The value of e-textiles lies in their adaptability, making them a valuable resource not only in the medical and safety sectors but also across diverse industries. Fig. 8 depicts the wide range of cutting-edge application areas for e-textiles [14].

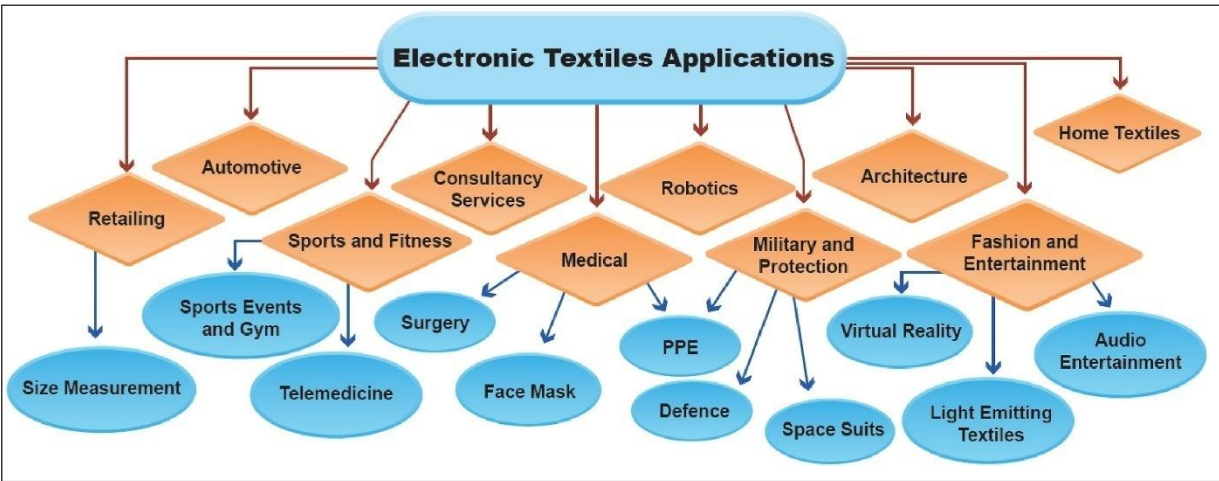


Fig. 8: Applications of E-Textiles

G. Wrinkle Resistance

Nano-silica enhances the wrinkle resistance of cotton and silk fabrics, respectively. Additionally, nano-titanium dioxide, in conjunction with carboxylic acid as a medium under UV irradiation, was utilized to catalyse the cross-linking reaction between the cellulose molecule and the acid. Moreover, when nano-silica was applied with maleic anhydride as a catalyst, the results demonstrated that this application successfully improved the wrinkle resistance of silk [22].

H. Flame-Retardant Applications

Synthetic fibres, like polyamide or polyester, exhibit high flammability. Consequently, ongoing research is being conducted to create flame-retardant products due to industry regulations mandating the use of products with minimal flammability. El-Hady *et al.* introduced an innovative flame-retardant method that involves the incorporation of ZnO nanoparticles for treating cellulosic fabrics, especially a blend of cotton and fabrics [22].

VI. IMPORTANCE AND COMMERCIAL SIGNIFICANCE OF NANOTECHNOLOGY IN TEXTILE INDUSTRY

Nanomaterials have significant future potential, as they find application in a diverse range of cutting-edge applications across various industries. Presently, companies are concentrating on manufacturing nano-textile products that exhibit traditional qualities and adhere to global standards for safety, health, and the environment. Given the burgeoning consumer interest in nano-textiles and the stringent environmental regulations in force, textile producers must uphold high ethical standards in the production of these goods. The integration of technology into textiles represents a longstanding trend, exemplified by endeavors to enhance clothing with sensing capabilities. Companies are actively involved in developing textile-based nano-sensors, unlocking a multitude of opportunities for nano-textiles. This encompasses the creation of clothing adaptable to changing weather conditions, monitoring wearers' vital signs, and establishing specialized healthcare systems. Nevertheless, a significant challenge in the development of nano-textiles is the high cost associated with the technology. While thermos- or temperature-regulated clothing is prevalent in the garment industry, its adoption by consumers is hindered by the elevated cost. Despite these challenges, nanotechnology offers a wide array of benefits, including the capacity to confer enhanced corrosion resistance, increased durability, reduced weight, and greater strength to textile items. Research focused on improving prospects and developing exceptional textile functionalities points towards a promising future for nanotechnology in the textile industry.

Nanotechnology holds substantial commercial significance within the textile industry, presenting innovative solutions to

enhance various aspects of textile products. The integration of nanotechnology into textiles has the potential to yield high-value products with enhanced functionality, comfort, and durability, aligning with the evolving demands of both consumers and industries. The economic impact of incorporating nanotechnology into textiles is diverse, encompassing improvements in product performance, enhanced energy efficiency, cost-effective manufacturing, and the development of innovative applications. As nanotechnology continues to advance, its influence on the textile industry is poised to expand, ushering in new economic opportunities and challenges. Nanotechnology enables the optimization of manufacturing processes by providing precise control over material properties and structures. This optimization can lead to more efficient resource utilization, reduced waste, and cost savings in production. Furthermore, advancements in nanomaterial synthesis techniques have the potential to result in economies of scale over time.

VII. CONCLUSION

The application of nanotechnology in textile industry, marks a revolutionary shift that promises to transform the way we perceive and interact with fabrics. The multifaceted applications of nanomaterials have enabled the creation of textiles with unprecedented properties, from enhanced durability and self-cleaning capabilities to intelligent sensing and therapeutic functionalities. The advent of nanotechnology in textiles not only addresses longstanding challenges in the industry but also opens up new avenues for innovation and sustainability. The development of smart fabrics with embedded sensors and responsive elements paves the way for a future where clothing becomes an integral part of our connected environment, fostering a seamless integration of technology into our daily lives. As we witness the continual evolution of nanotechnology in textiles, it is clear that the implications go beyond mere aesthetics and comfort. The potential economic and environmental benefits are substantial, with improvements in resource efficiency, waste reduction, and the creation of novel materials that challenge traditional manufacturing processes. In essence, the marriage of nanotechnology and textiles represents a groundbreaking era in the industry's history. As we continue to unravel the possibilities and address the challenges associated with this transformative technology, the textile landscape is poised for an exciting future where fabrics not only clothe us but also actively contribute to our health, well-being, and the sustainability of our planet.

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