

Smart Fabric Textiles Using Nanomaterials: A Contemporary Overview

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Abstract

Recent years have witnessed the pivotal role of nanotechnology in shaping the landscape of smart fabric design. Nanomaterials have emerged as integral components, introducing sustainable attributes such as antimicrobial, ultraviolet resistant, electrically conductive, optical, hydrophobic, and flame-retardant properties into textiles and garments. The integration of nanomaterial-based smart devices into textiles has further expanded functionalities, encompassing energy harvesting and storage, sensing, drug release, and optics. Beyond the fashion industry, these advancements hold promise for applications in defense, healthcare, and on-body energy harnessing. This review aims to provide a comprehensive overview of the current trends in utilizing nanotechnology within modern textile industries, serving as both an informative resource and a catalyst for future research endeavors. Focusing on on-body electronics, the review delves into the potential of nanomaterials in achieving total energy reliance through innovative textile applications. Key scientific concepts explored include methods for nanomaterial functionalization and integration into textiles, with a keen emphasis on cost-effectiveness, comfort, wearability, energy conversion efficiency, and eco-sustainability. Recent developments are in nanogenerators, super capacitors, and photo electronic devices integrated into fabrics, with a specific focus on their efficiency and wearability. The discussion extends to possible remediation measures. Finally, the paper outlines the future outlook, envisioning further progress in the integration of smart nano-devices onto textile fabrics.

Keywords: Nanomaterial's, Smart Textiles, Nanotechnology

1. Introduction

The progression of textiles mirrors the evolution of humanity, from early leaf-based clothing to the advent of natural fibers like silk and cotton, and subsequently, the introduction of synthetic materials that have greatly enhanced our quality of life. The increased demand for high-quality products has driven advancements in textile applications. Traditional natural and chemical fibers, such as cotton or polyamide, no longer suffice to meet users' diverse requirements. Modern textiles must possess special attributes like energy collection, color tuning, and health monitoring, as well as unique features including shape memory and heat storage. From their initial use as reinforcements in composites to sophisticated applications like conductive or antibacterial fibers, the emergence of smart textiles represents a new era. These textiles encompass passive (sensing external conditions), active (responding to external conditions), and ultra-smart categories (sensing, reacting, and adapting to conditions). Smart textiles, as intelligent systems, observe ambient conditions and process the wearer's state, with roots dating back to their introduction in Japan in the late 1980s. [1]

The surge in research and development is driven by the need for wearable textile-based systems, particularly for health monitoring, safety, and a healthy lifestyle. The integration of advanced technologies from diverse fields like cloth manufacturing, artificial intelligence, biotechnology, and information sciences has become feasible due to scientific advancements. Applications range from temperature-regulating apparel to fabrics releasing medication or moisturizer into the skin. [2] This extends beyond everyday clothing to fields such as medicine, environmental protection, military, and aerospace. The desire for intelligent materials that can dynamically change properties or offer interactive elements has never been more pronounced, showcasing the transformative potential of smart textiles across various sectors. Smart textiles hold vast potential across various aspects of human life, encompassing aesthetic applications, temperature regulation for comfort in extreme conditions, disease monitoring, and military defense. Depending on external stimuli, whether environmental or from mechanical, thermal, magnetic,

chemical, electrical sources, these textiles respond through three key components: sensors, actuators (for active smart textiles), and controlling units (for ultra-smart textiles). The integration of metallic materials, conductive polymers, or conductive inks into the textile structure aims to impart specific properties, such as electrical conductivity, either throughout the entire structure or in printed areas serving as switches for circuit activation. The 1990s marked the increasing recognition of smart materials' benefits, and recent studies showcase the diverse applications of smart textiles. The medical and healthcare sectors are increasingly exploring smart textiles, driven by population growth, extended lifetimes, advancements in medical procedures, patient recovery, and medical devices.

2. Fabrication Methods

Fabricating smart textiles with nanomaterials involves employing advanced techniques to integrate functional properties seamlessly. Among the various methods utilized, electro spinning stands out for its ability to create nanofibers, offering an ideal platform for incorporating nanomaterials and enhancing textile properties. Chemical Vapor Deposition (CVD) enables controlled deposition of nanomaterial thin films onto textile surfaces, providing functionalities like conductivity or sensing capabilities.[3] Dip coating immerses textiles in a nanomaterial-containing solution, ensuring uniform coating and surface functionalization.[4] In situ synthesis involves the direct integration of nanomaterials into the textile matrix through controlled reactions with embedded precursors.[5] Layer-by-Layer Assembly allows for precise control over coating thickness by sequentially depositing nanomaterial layers onto textiles. Printing techniques, such as inkjet or screen printing, apply nanomaterial-based inks onto textiles, facilitating the creation of patterns and functional elements.[6] Sol-Gel processes coat textiles with thin nanomaterial films, offering versatility for introducing functionalities like self-cleaning or UV protection.[7] Physical Vapor Deposition (PVD) methods, such as sputtering or evaporation, deposit Nano scale coatings onto textile surfaces to enhance properties like barrier functions.[8] Melt extrusion uniformly disperses nanomaterials within textile fibers during the polymer extrusion process. Laser ablation selectively introduces nanomaterials or creates patterns on textiles by modifying surface layers using laser beams. [9] These fabrication methods empower smart textiles with diverse functionalities, making them responsive to external stimuli and suitable for a wide range of applications.

3. Types of Smart Textiles

Smart textiles, infused with nanomaterials, encompass a diverse array of types, each bringing distinct functionalities to the realm of wearable technology. Conductive textiles leverage nanomaterials like conductive nanoparticles or nanotubes, enabling the creation of fabrics with electrical conductivity for applications in interactive clothing and wearable electronics.[10] Thermo chromic textiles, utilizing nanomaterials that exhibit reversible color changes in response to temperature fluctuations, find applications in temperature-sensitive clothing and indicators.[11] Photovoltaic textiles integrate nanostructured semiconductors, harnessing solar energy for tasks such as charging electronic devices or powering embedded sensors.[12] Antibacterial and antimicrobial textiles incorporate nanomaterials, like silver nanoparticles, offering hygienic applications in medical garments and wound dressings.[13] Shape memory textiles utilize Nano scale shape memory polymers, allowing fabrics to change shape in response to external stimuli, such as temperature alterations.[14] Sensing and monitoring textiles employ nanomaterial-based sensors for tracking parameters like temperature or moisture, catering to health monitoring, sports performance, and environmental sensing.[15] Energy harvesting textiles, integrating piezoelectric or triboelectric nanogenerators, convert mechanical energy into electricity, ideal for powering electronic devices through movement.[16] Electro chromic textiles, with nanomaterials possessing electro chromic properties, change color in response to an electric field, finding applications in dynamic fashion and interactive displays.[17] These innovative smart textiles underscore the transformative potential of nanomaterials, enhancing fabrics with advanced functionalities across various sectors.

4. Current Applications of Smart Textiles

In contemporary times, smart textiles incorporating nanomaterials have found diverse and innovative applications across numerous industries, revolutionizing the way we interact with and experience textiles. One prominent application is in the realm of wearable technology, where conductive [18] nanomaterials are integrated into fabrics to create interactive clothing and accessories. These smart textiles enable features like touch-sensitive surfaces, making them ideal for applications in fitness trackers, smart watches, and other electronic wearable's. In the field of healthcare, nanomaterial-based sensors woven into textiles facilitate continuous monitoring of vital signs, offering a non-

intrusive and comfortable solution for patients. These smart textiles are employed in medical garments, bandages, and even in-home monitoring systems, contributing to personalized and proactive healthcare. Nanomaterials have also paved the way for advancements in protective clothing, with textiles that possess antibacterial and antimicrobial properties. [19] This is particularly significant in healthcare settings, where the need for infection control is paramount. Additionally, smart textiles with built-in sensors can detect environmental hazards or chemical exposures, providing enhanced safety in industrial and emergency response scenarios. In the fashion industry, nanomaterials are utilized to create textiles with dynamic properties, such as color-changing fabrics and garments with embedded LEDs. These smart textiles offer opportunities for designers to explore interactive and customizable fashion, contributing to the growing field of e-textiles. Moreover, the integration of nanomaterials in energy-harvesting textiles has implications for sustainability. Fabrics with piezoelectric or triboelectric nanogenerators can convert mechanical energy from movement into electricity, potentially powering small electronic devices and reducing the reliance on traditional energy sources. As technology continues to advance, the applications of smart textiles with nanomaterials are expected to expand further, influencing diverse sectors such as automotive, aerospace, and sports. The intersection of nanotechnology and textiles holds immense promise for creating intelligent, responsive, and multifunctional fabrics that enhance our daily lives in unprecedented ways. [20]

5. Way Ahead

Smart textile fabrics play a pivotal role not only in advancing, transforming, and upgrading the global textile industry but also in catalyzing the development of disruptive emerging sectors. Projections suggest a robust expansion of the global smart textiles market, with an anticipated compound annual growth rate (CAGR) of 25% from 2021 to 2031, reaching a value surpassing US\$23.82 billion by 2031. Ongoing research and development endeavors aimed at exploring advanced technologies in smart textiles serve as a primary driver for market growth. Despite being in the early stages of development, the potential for innovative smart textiles to enhance the overall utility and functionality of standard fabrics is immense. This market is poised to offer lucrative growth opportunities across various end-use industries, with certain smart textiles already being commercialized at a relatively affordable cost, as observed in smart watches

and wristbands featuring wireless sensor networks. [21] Recent developments enhancing performance in smart textiles encompass technologies like ultrasonic assembly and specialized fabrics used in outer space, space transportation systems, and innovative sportswear. The broad application spectrum extends to medical and healthcare industries for tasks such as heart rate monitoring, the automotive sector, and personal protective equipment. Advanced technology facilitating the miniaturization of electronic components expands the range of applications for these materials. In the pursuit of comfort and lightweight solutions for sports and fitness applications, an accelerated growth rate is anticipated in the coming years. The ability to monitor physiological parameters like blood pressure, diabetes, and temperature broadens the relevance of smart textiles in medical applications, with an expected higher [22] growth rate compared to conventional uses. Challenges include the compatibility issues between certain textiles and electronic systems, limiting their applications, and the slow adoption rate for specific smart textiles. Additionally, the absence of regulations and standards hinders the steady growth of some products.

Conclusion

Following extensive scientific endeavors and developmental phases, smart textiles have captured the attention of consumers and are positioned as the future of the textile industry. The rapid growth and advancements in textile technologies, coupled with breakthroughs in nanotechnology, biosensors, novel materials, and miniaturized electronics, have yielded a plethora of commercial products. Concurrently, numerous scientists are actively engaged in devising innovative solutions, generating new ideas, and creating tangible products in response to the growing demand for smart textiles across various aspects of life. The applications of these textiles, spanning from medical devices to entertainment and defense, continue to broaden substantially and witness daily expansions. Despite the significant progress, there is room for accelerated development, a prospect that could be further stimulated through increased investments in future research and development activities. Notably, in the realm of wearable devices, paramount importance is placed on ensuring comfort. Nevertheless, the incorporation of mechanical resistance and durability considerations is imperative in the final product. As the field evolves, there is a growing recognition of the need for a multidisciplinary approach to fashion more sophisticated materials, emphasizing the interdisciplinary collaboration necessary for advancing smart textiles to

meet the diverse needs of consumers.

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