Smart Nanotextiles

Wearable and Technical Applications

Edited By

Nazire Deniz Yilmaz

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Preface

The landscape of the last several decades, especially the last one, has been dotted with natural disasters, such as earthquakes, tsunamis, tornados, droughts, floods, and other extreme weather events often attributed to global warming; in addition to international disputes and a pandemic unprecedented in a century. This has taught us two things—the importance of self-sufficiency and the fact that Earth's resources are not limitless.

In order to survive in hard times, countries, cities, neighborhoods, families and individuals need to develop increased levels of self-sufficiency in terms of energy, communication and protection, among other things. This can be realized without exhausting Earth's resources by using smart technologies to produce nanomaterials that allow obtaining great performance from very small amounts.

It is possible to scavenge energy present in a medium or body and transform it into a useful form of energy, mainly electrical energy, via smart nanotextiles. Smart nanotextiles also allow remote health monitoring and disease diagnosis via wearable nanobiosensors; and can detect toxic gases and infection in wounds, defend against approaching substances and bullets, and protect against radiation, fire and other hazards. Moreover, it is possible to achieve tunable filtering performance for clean water production and air climatization via smart nanofiltration. And smart houses empowered with nanotextiles not only offer energy savings, but also allow energy scavenging, protect the elderly from falls, enable early detection of building failures and so on.

Not only are smart nanotextiles useful in difficult times, but also for making everyday life experiences more satisfying in areas such as recreation and sports, well-being, and fashion. And they are not only capable of affecting our lives today, but also of shaping life in the future. For example, smart nanotechnology holds the possibility of contributing to starting life on different planets.

As can be seen from the above, it is impossible to write about all the application fields of smart nanotextiles in only a page. During the process of reviewing the literature, deciding on content, and editing manuscripts from the outstanding contributors, I was constantly amazed by the possibilities smart nanotextiles offer. I hope the reader also enjoys and gets inspired by the wonders of the smart nanotextiles world.

This book was completed in a time frame exceeding two and a half years interrupted by my change of affiliation, move to a different city, and a global pandemic, I would like to thank the contributors for their dedication and hard work. Thanks also to Martin Scrivener, president of Scrivener Publishing, to whom I am very indebted for his patience and support. I recently read *Romeo and Juliet,* the famous play by William Shakespeare, and would like to conclude with a line spoken by the Prince in Scene 3, Act V of the play:

"And let mischance be slave to patience."

Dr. Nazire Deniz Yilmaz
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May 2022

Section 1

INTRODUCTION

1

Smart Nanotextiles Applications: A General Overview

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Abtract

Smart nanotextiles form a novel group of materials that are utilized/can be utilized in an array of application areas, such as biomedicine (health monitoring, controlled drug release; wound care, and regenerative medicine), communication, sports, fashion, energy harvesting, protection, filtration, civil and geotechnical engineering, transportation, and so on, including wearable and technical fields. Whereas textiles provide a convenient platform for smart functionality, nanotechnology assures that the favorable characteristics of the textile structure are not impaired by the smart functioning components. Furthermore, based on superior characteristics of nanostructured components in comparison to macro materials and micromaterials, nanomaterials provide augmented smart functionality. Despite the fact that immense research efforts have been devoted to smart nanotextiles, most of them have not been yet transcend commercialization stage due to challenges comprising high cost, difficulty in large-scale production, low reliability, potential detrimental effects of nanomaterials for human health and the environment. If these issues can be addressed soundly, smart nanotextiles, as a member of smart nanomaterials, can be considered as the material of the future possessing the capability to improve people's living standards immensely.

***Keywords*:** Smart nanotextiles, intelligent textiles, e-textiles, smart textiles, electronic textiles, applications, nanotechnology, wearable

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1.1 Introduction

Textiles have been utilized by humankind for millenia for clothing due to their outstanding properties, including breathability, flexibility, durability and washability [1]. In recent years, textiles have started to be utilized as a platform for personal electronics, such as sensors, displays, batteries; in addition to their conventional uses. Textiles carry great promise for smart functionalities to serve as smart textiles. Development of nanotechnology has allowed better integration of smart functionality components in textiles for better comfort and aesthetic performance. Thus, smart nanotextiles merge the possibilities of textiles and the potential of nanotechnology to provide improved quality service in different areas including wearable and technical applications [2, 3].

Hence, smart nanotextiles have become the topic of intense research efforts. Smart nanotextiles have found/may find use in different areas like medicine & healthcare, drug delivery, tissue engineering, sports, communication, fashion, energy harvesting, protection, filtration, civil & geotechnical engineering, and transportation fields among others. Accordingly, development of smart nanotextiles is the result of multidisciplinary research efforts including textile technology, materials science, electrical engineering, computer engineering, chemistry, electronics, nanotechnology, and others [3, 4].

Smart textiles mean fibrous structures that are able to sense and react to external stimuli, such as the changes in the mechanical, electrical, optical, chemical, etc., properties of the environment. Furthermore, smart textiles allow generation of communication; power harvesting, storage and transmission; provide interconnection so that a network of information processing devices is established to carry out smart functions [3, 5].

The miniaturization of smart textile components allows seamless incorporation of smart functionalities. This has led to increased penetration of smart textiles in the market [6] due to enhanced mechanical flexibility, user-friendliness, aesthetics, comfort, noninvasiveness [7]. Advancement in nanotechnology accelerates miniaturization and carries this concept into a further extent [8]. Whereas textiles provide a convenient platform for smart functuality, nanotechnology assures that the favorable characteristics of the textile structure are not impaired by the smart functioning components.

The feature that renders the smart textiles revolutionary is their capability to carry out functions that conventional fabrics cannot do, such as communication, energy generation, and information processing [9].

Conventional wearables, such as smart-wristbands, watches, glasses, mostly include rigid components, which impair comfortable and effective use. This situation limits their use in daily life outside the lab. It is essential to get rid of these bulky rigid devices to achieve better wearability and improved usefulness [7]. Thanks to miniaturization, which is fueled by emergence of nanotechnology, it has been possible to seamlessly integrate smart devices in textiles [2].

More and more people demand to obtain real-time information related to their health status, physical performance, and data related to the environmental conditions, such as environmental pollution or presence of hazardous substances. Furthermore, the rise in the population of elderly people, increased burden on healthcare delivery system, as well as the search for detection of pathologies with reduced risk of contracting or transmitting diseases, like COVID-19 infection, has lent impetus to development of remote health monitoring by use of smart textiles [2].

Studies on smart textiles, supported by miniaturization fueled by nanotechnology, provides novel noninvasive conformal solutions without impairing the exceptional textile and aesthetic features in different areas, like everyday life, healthcare, and technical applications, where textiles serve outside the "wearable" region, such as filtration, transportation, and civil engineering applications [2, 3].

In order to build a smart textiles product, some components are needed. These are sensors, actuators, connection components, as well as data processing and power supply elements. Sensors sense physical, chemical, and biological differences in the medium; actuators react to stimuli via actions, like color and shape changing or light emitting. Connection components convey signals, like electricity, radio frequencies, and others. They include conducting elements, antennae, radio frequency identification (RFID), circuits and alike. Data processing units, which execute program directives, store data, whereas power supply provides energy that is necessary to carry out smart functionality [2, 10, 11].

These smart functioning components can be integrated into textiles by different means: (1) classical electronic devices can be attached to textiles, (2) miniature components can be embedded onto textiles, (3) textiles themselves can be produced as smart functioning devices. By use of microelectronic devices, the second approach can be taken. Emergence of nanotechnology allows realization of the third approach [2, 11]. With the accelerated miniaturization fueled by advanced nanoscience and nanotechnology, now it is possible to impart smart functionality on a single fiber alone. With cost-efficient textile production processes; one-dimensional, two-dimensional, and three-dimensional smart textiles can be obtained [1].

The emergence of smart nanotextiles is timely and groundbreaking as the possibilities they offer are inconceivable. Smart nanotextiles combine opportunities brought by miniaturization of electronics, well-established textile technology practices, and developments in nanotechnology, to name a few. Research in smart nanotextiles forms a nascent field which is influenced by and have the potential to influence different disciplines, including materials science, data analytics, and fashion [3, 12].

This chapter attempts to provide an introductory overview of smart nanotextiles in terms of their current and future applications. The application fields for which the use of smart nanotextiles are investigated include medicine and healthcare (health status monitoring [13], targeted drug release [14, 15], and wound dressing & regeneratative medicine [16]), communication [17], sports [18], fashion [19, 20], energy generation [21], protection & defense [22], filtration [23], civil & geotechnical engineering [24], and transportation [25] areas.

This chapter has been organized as follows. The remainder of the chapter starts with presenting general information on textiles and discussing the features rendering textiles ideal for smart functionality. The following section introduces a brief history of smart nanotextiles succeeded by sections referring to terminology and classification related to smart nanotextiles. The following sections, presenting general information on nanotechnology, nanomaterials, and nanocomposites, comes before the section related to materials selection elaborating on characteristics required by smart functionality applications and sensors, which possess utmost important part in smart functionality. The succeeding section provides insight to the current status of global smart textiles and nanotextiles market, followed by sections highlighting their different wearable and technical application fields. The last two sections discuss challenges and opportunities in relation with the future advancement of smart nanotextiles and conclude the chapter. It is obviously impossible to present all relevant work in a book, let alone a chapter. Thus, findings of some most recent research studies have been shared in order to provide a glimpse of the current trends in this emerging field. One goal of this chapter is to allow exchange of developments related to smart nanotextiles across different application areas and to stimulate generation of novel ideas so that novel smart nanotextiles can be developed, and new uses can be found in application fields they are underutilized.

1.2 Textiles

Textiles have been utilized by humankind for millenia for protection, warming, and aesthetic functions due to the fact that they are breathable, flexible, enduring, and washable. These properties endow them ease of use, comfort, and functionality as clothing materials. On the other hand, their use has not been confined to clothes [1, 26, 27], as they are also used in home applications, such as home textiles [28], automotives as automotive textiles [29]; and some of other applications can be given as geotextiles [30], industrial textiles [31], agrotextiles [32], acoustic textiles [33], and many more.

Textile structures present important properties to act as ideal substrates for smart functions. They are soft and show deformation with low external load or even by force of gravity as they are drapeable. Their Young's modulus values generally lie between several MPas to KPas. Due to the surface roughness, their specific surface areas are high in the order of 10^2 to 10^3 m^2/kg. Their porosity values are close to 99%. The porosity is determined by packing density and fiber orientation. They are durable against wear and washing. They are able to be twisted, bent, pressed, stretched, and sheared in three dimensions. They are drapeable; thus, readily follow the contours of human body and provide close contact [1, 12, 27]. Their high porosity and great surface area allow them to trap air and render them heat insulator, as well as provide air and water vapor transport, and bestow breathability in consequence. Breathability is a major advantage of textiles against nonbreathable wearables plastics. Textiles show unique fatigue resistance and damage tolerance. Textiles do not allow crack propagation and catastrophic failure as commonly witnessed in solid films [1].

Another upside of textiles is that the textile production processes are well established and economic [1]. Furthermore, due to their ductility and flexibility, it is easy to manipulate them to serve for an array of different uses with different requirements [2].

Textiles are generally formed in a hierarchical order (fiber – yarn – fabric – clothing). This hierarchical order also brings some advantages for imparting smart functionality. The smart functionalities can be deployed as built-in or embedded into the textile structures. Textiles offer a platform to smart wearable devices, that is large-area and in close contact with the human body [1].

Textile structures are made of fibers, which are polymeric materials. By changing manufacturing parameters, it is possible to fine-tune characteristics of polymers, such as modulus of elasticity. While high Young's moduli refer to rigid materials, it is generally required that fibers to possess moderate modulus values so that they exhibit flexibility, drapeability, and bendability. Other than changing the fine structure of polymers; by producing them in porous geometry, it is possible to decrease modulus of elasticity and to increase breathability by enhancing permeability of gas and moisture to achieve comfort performance [7].

For millenia, textiles have been in the middle of technological advancements of human societies. Now, smart nanotextiles carry the concept of textiles to a further step to serve medical, protection, sports, fashion, communication, energy needs among others [11, 34].

1.2.1 Brief History of Smart Nanotextiles

The first textiles were assumed to be invented around 27 millennia ago. Since then, textiles have been a means of protection from the environment and a way of expressing oneself in the community as a sign of wealth or belonging to a social class. Major developments in textile technology can be given as invention of the knitting frame in late 16th century, of the flying shuttle and the spinning jenny in the 18th century. These inventions mark not only the progress in textile technology but also the establishment of the first industrial revolution [11].

Now a groundbreaking revolution is taking place in progress of textiles: development of smart textiles. Emergence of smart textiles occurred by combining electronic components with textile structures [11]. Even though the roots of integrated textiles can be traced back to centuries ago, when fine metals, including gold and silver, are embedded in fabrics for artistic effects, the first examples of smart textiles can be found in the end of 19th century when illuminated and motorized costumes were produced by incorporation of electrical components in fabrics [10]. The illuminated headbands in the La Farandole ballet can be considered among the first smart textiles [11].

Invention of MOSFET (metal–oxide–semiconductor field-effect transistors) in 1960 by Atalla [35] and Kahng [36], as well as conductive polymer in 1977 by Heeger [37] are key steps in smart textiles trajectory. Miniaturization and progress in nanoscience and nanotechnology fuel further advances in smart textiles [3, 11]. Furthermore, invention of nanogenerators by Wang and his research team (piezoelectric nanogenerator in 2006 [38], triboelectric [39], and pyroelectric nanogenerators [40] in 2012) bestowed smart nanotextiles energy autonomy; thus, they can function based on energy harvesting nanogenerators without needing outside power supplies.

In addition to the advancements in microelectronics, materials science, and nanotechnology; emergence of IoT and artificial intelligence, including machine learning boosts rapid development of smart textiles, that are capable of catering functional and aesthetical needs improving life quality of the general community [10, 41]. We are now living in a world with a more connected ecosystem compared to that in the past thanks to IoTs, smartphones, smart watches, as well as edge services and cloud services [10].

Lancos *et al.* [10] investigate the historic timeline for smart textiles in four stages. The first stage is between 1980 and 1997. In this period, the exploratory concept of wearable computers emerged, where textiles act as a substrate for computing components. A research group in MIT, including Steve Mann, Thad Starner, and Sandy Pentland, conducted the first studies on wearable computers in the 1990s.

The second stage covers the period between 1998 and 2001. This stage is marked by the joint efforts of the fashion and textiles industry for preparation of smart textiles via different collaborations like Levi's Ready-to-Wear clothing, a collaborative Project by Philips electronics and Levi Strauss. In comparison to the first stage, the products of the second stage was more conforming as clothing, they were not in the quality to cater for the needs of the general community [10].

The third stage took place between 2002 and 2005. In this period, important amount of efforts have been devoted to miniaturization of electrical components and improving the techniques [10].

The fourth stage starts from 2006 to the present date. In this stage, miniaturization and smart material technology are showing rapid advancement [10]. Furthermore, apart from research institutes and the industry; governments and international bodies have started to contribute to these efforts, including the projects WearSustain [42], Weafing [43], SmartX [44], and others funded by Research & Development (R&D) framework programs (FP) of the European Union including FP6, FP6, FP7, and Horizon2020 (H2020). In the fourth stage, the wearables entered in the market phase and the focus has shifted from wearables to smart textiles where the functional technology becomes invisible and merged in the clothing. Here, the trend moved away from the initial wearable computer and added devices where the smart functionality is embedded in the textiles [10].

Lancos *et al.* [10] expect the fifth stage where smart textiles will be improved with enhanced intelligence, more connection with cloud services and important developments in smart materials and nanotechnology.

1.2.2 Terminology

Smart textiles, which can also be referred to as "smart fabrics," are defined as textiles, which have the capability to sense and react to external environment by a predesigned mechanism of control or in a behavior that is cognitive driven [10]. On the other hand, wearables can defined as "hybrid, network-enabled devices that can be worn on or in the body, which are integrated with the user's everyday life and movements" [7]. The term "wearables" describes the electronics and computers that are integrated into apparels or accessories which can be worn on human body. Nevertheless, there is also "wearable" smart technology not incorporating electronic devices or computing components. In general, "wearable smart technology" can be considered as "smart textiles and apparels" [45]. Smart textiles differ from wearables in the sense that smart functional components are seamlessly integrated to textiles [18]. The scope of "smart textiles" do not completely coincide with wearables, but some wearables contain smart textiles. There are also smart textiles which are not "wearable," which we conventionally know from hometextiles [28], automotive textiles [29], industrial textiles [31], and others. It is important to note that textiles are described as "soft" materials that are flexible and drapeable [45]. Smart textiles are high-technology interactive textiles that serve in different areas where textiles are used, including clothing or nonclothing applications [2].

"Electronic textiles" or "e-textiles" are commonly confused with "smart textiles." In essence, smart textiles are textiles that can sense/react to/adapt to stimuli, as mentioned; while "electronic textiles" include electronic components to carry out smart functions. Thus, electronic textiles form a subclass of smart textiles, whereas there are smart textiles where intelligent functionality is not a result of electronic component activity [45]. Thus, "electronic textiles" or "e-textiles" refer to a narrower class of intelligent textiles [3]. E-textiles have also been named as textronic textiles [2].

A definition of smart nanotextiles could not be found by the author of this chapter. Smart nanotextiles can be defined as textiles which incorporate nanostructured components, such as nanofibers, nanoparticles, and so on, and have the capability to sense and react to external stimuli by a designed control mechanism and/or in a cognitive-driven manner.

1.2.3 Classification

Conventional textiles can be considered to be functional as they provide insulation, water absorption, sheltering from sun, etc., but they are not smart. The minimal form of smartness is the capability of sensing external stimulus. This is defined as "passive smart"ness. "Active smart"ness refers to the capability of sensing and then reacting to the stimuli. The third class of smart textiles is "very smart," so they can sense, react to, and adapt themselves based on external stimuli [45]. Now, it is possible to manufacture very smart textiles thanks to collaboration among various disciplines, like textiles, materials science, artificial intelligence, and electronics [10].

Another way of classifying smart textiles is based on the extent of integration/"embeddedness." The smart textiles have been classified into three groups according to the integration of smart functional elements in the textiles [45]. In the first generation of smart textiles, fabrics only serve as the substrate, where intelligent components are attached. And in the second generation of smart textiles, the smart components are more deeply embedded in the fabrics, based on developments in materials design, but still separable from the fabrics. And in the current third generation of smart textiles, the fabric itself has become the intelligent component itself, acting as the sensor, actuator, energy generator etc, thanks to development of conductive organic materials and advancements in nanotechnology [10]. In lack of embeddedness, such as in the first generation of smart textiles, rigid functional components, such as hard electronic circuits take place and ruin the essential duty of textiles to comply with the human body skin contours, so they impair drapability [46]. So, the more embedded/integrated the smart functional elements, the better the performance of the smart textiles. Some examples to the first-generation smart textiles can be given as clothing with attached "LilyPad Arduino" electronic components on, circuits printed on fabrics by dying conductive ink, and fabrics embroidered with conductive yarns [45]. Fabrics with conductive yarns knitted or woven within can be considered as the second-generation smart textiles, whereas third-generation smart textiles are possible with nanotechnology where smart functionality can be included in one single fiber [45]. Consequently, we see a shift from a gadget-based technology to a fully-integrated approach through the generation of smart textiles [10].

In a different classification, smart textiles have been categorized as the past-stage, the present-stage and the future-stage smart textiles. The past-stage smart textiles are based on nonreneweable, nonbiodegradable raw materials and nonreneweable energy in manufacturing, functioning, maintenance (washing cycles, etc.) and disposal phases of the product life [45].

Increasing concerns on the ecological sustainability forms a strong impetus to the present-stage smart textiles. These textiles are produced with renewable/biodegradable materials and perform their smart functions based on renewable energy sources and exhibit self-maintenance characteristics (self-cleaning, self-healing, energy harvesting); thus form minimal environmental impact during manufacturing, functioning, maintenance, and after-life phases [45]. Some examples to present-stage smart textiles can be given as Mincor TX TT, which is nanoparticles-based coating exhibiting self-cleaning effect of ultraphobic lotus leaves [47], and smart textiles comprising nanogenerators harvesting energy present in the vicinity [48, 49].

The future-stage smart textiles were envisaged by Wu and Li [45] as the ones which can improve their smart functions and self-sufficiency by learning through artificial intelligence. They can predict when and where to react before the external change happens or know where their weak points are and send self-healing agents where they are needed [45].

1.3 Nanotechnology and Nanomaterials

Advances in nanotechnology have brought smart textiles to the next level resulting in enhanced physical and chemical properties. Moreover, the nanoscale leads to lighter weight, smaller size, and lower power requirement; thus, bestows smart systems improved portability [2].

Emergence of novel nanomaterials have opened new horizons for flexible smart textiles in comparison to rigid electronic components. The last decade has witnessed important developments in the nanoscience, novel assembly and patterning techniques, new equipment geometries and also unprecedented concepts. These progresses have led to fast advancement of smart textiles with nanocomponents, i.e., smart nanotextiles [50].

Nanotechnology enables the smart textiles to achieve required form factors. Form factor is a term which defines the combination of the size, shape, and relevant physical properties of a device. Thanks to wearables technology, electronical functions have been offered to the general community in inconceivable form factors, such as smart watches, goggles, etc. Smart nanotextiles expand the improvements in form factors to be small, light, flexible, and nonobtrusive due to the unprecedented potential of nanotechnology [7]. Descending to nanosize is useful not only for achieving better form factors, but also for realizing improvements in sensing performance [13].

1.3.1 Nanomaterials

The nanomaterials used in smart textiles applications can be classified as metal-based nanomaterials including silver nanowires or quantum dots,