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MEDICAL, SENSORIAL AND PROTECTIVE TEXTILES DEVELOPMENT IN THE CONTEXT OF THE EUROPEAN ECONOMY AND DIGITALIZATION

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ABSTRACT

DigiTEX project aims to support innovative approaches and digital learning technologies to accelerate innovation, teaching and learning in the field of medical, protective, sensorial and smart 3D textiles design, testing and manufacturing of the innovative advanced products for healthcare (protective equipment, wearable monitoring devices) in the context of the digital economy.

This book provides a global view of wearable devices integrated into textile, from a researcher and end-user perspective. The aim is to provide the verdict on all aspects concerning the integration and efficiency of such wearable device-based textile for healthcare and protection. The wearable systems design and reliability are presented from the perspective of end-user acceptance and usability. In addition, are presented the role of artificial intelligence algorithms used to provide digital twins for healthcare and protection. The eco-design for wearable technologies is presented in a strong relationship with wearable comfort aspects, and reuse or recycle the components in the context of circular economy necessity. Wearable devices based textiles for protective and healthcare equipment would be an excellent resource for early-stage or senior researchers, designers and academics who are interested in developing wearable technologies integrated into textiles.

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Chapter 1. HISTORY

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1.1 Introduction. Smart fabrics research represents a new model for developing innovative and creative solutions for the integration of electronics into atypical surroundings and it will lead to new scientific breakthroughs. The ability to combine textile and electronics fabrication technologies to functionalize large-area surfaces at rapid rates is a fundamental motivation for smart textiles research. In this chapter, we overview the history of smart textile development and introduce the main trends in this field. Finally, we provide our outlook for the field and a prediction for the future.

1.2 History of smart textile development

This historical overview of smart textiles will provide the reader with a better understanding of the evolution. Textile innovation 27,000 years ago could be disputed as humanity's first material invention [1]. The knitting frame, invented by William Lee in 1589 [2], the flying shuttle, invented by John Kay in 1733, and the spinning jenny, invented by James Hargreaves about 1765 [3], were all major inventions that transformed society and laid the groundwork for the first industrial revolution. The usage of illuminated headbands in the ballet La Farandole in 1883 was one of the first examples of smart textiles [4]. Electronic textiles are divided into three generations depending on the integration of electronics in textiles: putting electronics or circuitry on a garment (first generation), functional fabrics like sensors and switches (second generation), and functional yarns (third generation) [5]. Figure 1.1 depicts the evolution of E-textiles as a timeline.

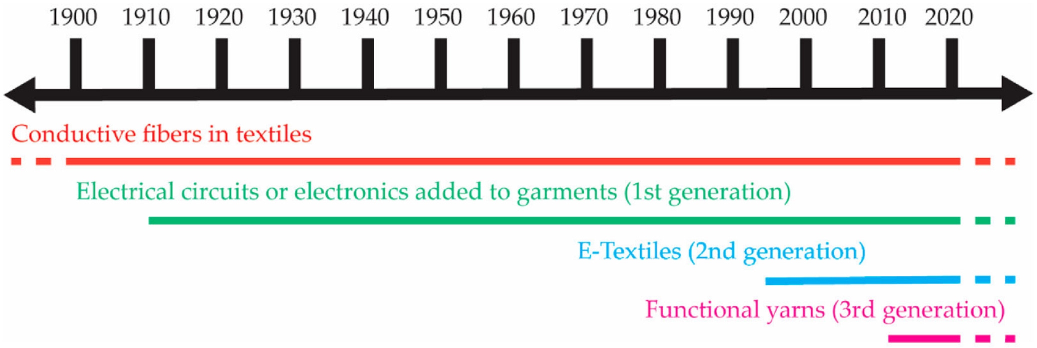

Figure 1.1 Evolution of electronic textiles over time [5]

Although medical applications of electricity in clothes such as corsets and belts have been studied since the 1850, the scientific world has only recently become interested in wearable electrical applications (particularly wearable computing) [6]. Edward Thorpe and Claude Shannon created the first wearable computer in 1955 [7]. Wearable computers are characterised by the lack of connection between the wearer's electronic equipment and their clothing. Wearable computing evolved into smart textiles in the early 1990, with electronic functionalities incorporated more intimately into cloth. The level of integration of ‘smart’ components with the textile structure will be illustrated stepwise in this section.

First step. Smart textile was stuck and devoted to the wearable computing concept by creating a fabric computing platform. One significant goal was to create easily reconfigurable interconnection technologies inside textiles. Fibres and yarns were employed, and the dimension of the function was limited. The single functionality such as electrical or optical conductivity was observed for integrated textile materials. To achieve the desired system performance, these interconnects were paired with regular standard off-the-shelf components. The Georgia Tech Wearable Motherboard (GTWM) was, for example, an early smart textile created from 1996 onward (Figure 1.2 (a)) [8].

Second step. In this stage, smart textile was produced by combining several novel textile fabrication technologies. Embroidery was used to create smart hybrid textiles. Fabric was usually an integral part of the textile device or circuit in these smart textiles. It was more than simply a carrier for textile yarns and circuits. Smart textile design was still handled from the perspective of traditional electronic system design, but the textile itself began to perform more and more functions. Traditional textile fabrication processes (such as weaving or embroidery) were also combined with traditional electronic circuit fabrication methods such as printed circuit board design [9]. Quilted and embroidered keypads, as well as the firefly outfit developed (Figure 1.2 (b)) by the MIT Media Lab in 1997 and 1998 are early examples in this stage.

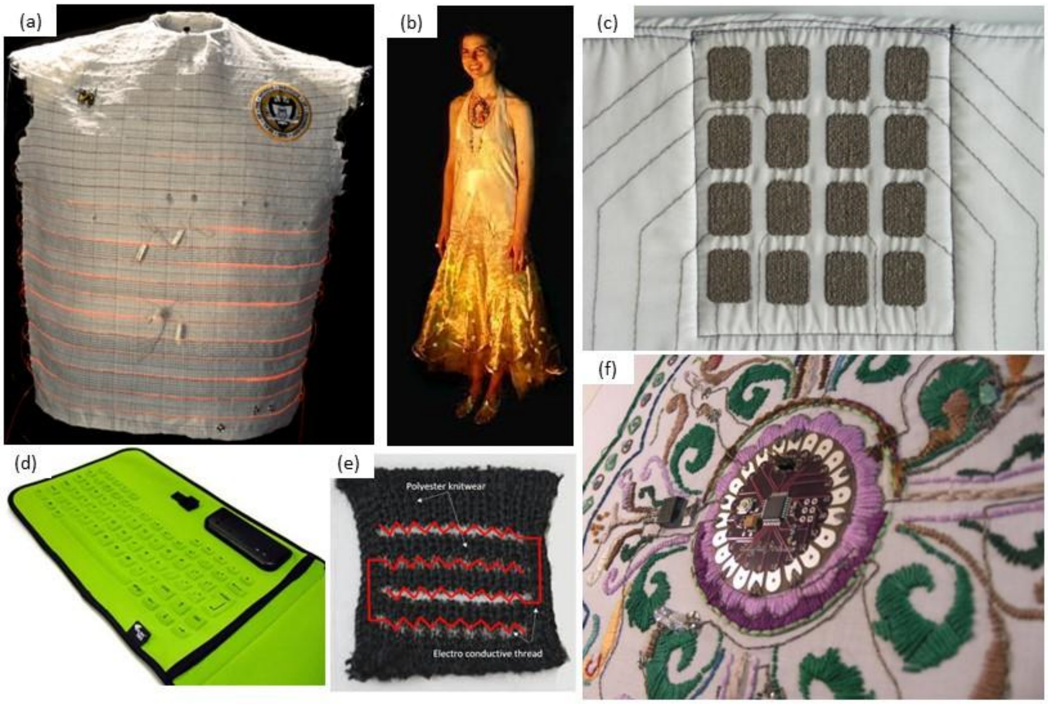

Figure 1.2 Various smart textiles; (a) GTWM. Reproduced with permission [8]. Copyright © 2002, ACM. (b) Firefly dress. Reproduced with permission [10]. Copyright© 2000, International Business Machines Corporation. (c) Textile Pressure Sensor with 16 sensing elements embroidered with conductive yarn. Reproduced with permission [11]. Copyright© 2006, IEEE proceedings. (d) Eleksen fabric keyboard for rim blackberry [12]. licensed under Creative Commons BY-NCSA 2.0. (e) Textronic hominidy sensor [13]. (f) a Lillypad Arduino microcontroller chip integrated into a textile [14]. licensed under Creative Commons BY-NC-SA 2.0

Table 1. Timeline and progress of smart textiles [16, 17]

1600	Gold threads were weaved into garments for a shining accent during the Elizabethan era.
1990s	MIT students started researching smart apparel for military use.
1996	The conductive fabric superstore launches for EMF blocking purposes.
1998	Sabine Seymour launches Moondial.
2000–2009	E-textile Lounge launches as a resource for e-textile craft.
2000	i) E-broidery design and fabrication of textile based computing. ii) Plug and wear launches, selling conductive materials for knitting and sewing.
2003	Georgia Tech Motherboard shirt appears in press.
2007	Leah Buechley develops the Lilypad, a microcontroller made specifically for textiles.
2009	Forster Rohner launches the Climate Dress using their innovative embroidered techniques.
2011	MICA Fiber department begins to explore conductive thread and electronics, creating the Midi Puppet Glove.
2012	Drexel launches their Haute Tech Lab exploring smart fabrics and additive manufacturing for textiles.
2013	Machina Launches the Midi Controller Jacket on Kickstarter.
2014	Dupont presents their stretchable, conductive ink at printed electronics and bebop sensors launches wearable tech and textile circuits.
2015	Polotech Shirt developed; Google's Project Jacquard directs tech eyes to e-textiles at Google I/O and ZSK embroidery reveals conductive thread and sequin LEDs.
2016	$302 million DoD and M.I.T collaboration and the U.S Commerce Department's first ever smart-fabrics gathering.
2017	Harnessing the power of enzymatic oxygen activation (OXYTRAIN); Smart Clothing Gamification to promote Energy-related Behaviours among Adolescents (SmartLife).
2018	Design and integration of graphene fibre based antennas for smart textiles (GFSMART).

Third step. In the early 2000, the first attempts to develop more complex fibre-level electronics appeared. Fibertronics is another name for this field of study. The goal of these studies was to develop devices and logic circuits "below the device level," that is, to achieve higher-order electronic operations at the fibre level and produce more sophisticated smart textiles from individual fibres. These studies are typically more focused on technological development, and systems are constructed from the fibre upward. Flexible stripes with basic thin film transistor (TFT) circuits were used to introduce fibre-level smart textiles into woven textile inverter circuits [15]. Although there is a general trend in this industry to gradually integrate more and more component systems into textile fibres, most approaches combine these concepts. The most appropriate approach will be determined by the ultimate usage of smart textiles in commercial products, and future smart textiles may look radically different from those that exist today. Figure 1.2 shows various smart textile systems from the first to third steps, and Table 1 states the timeline and progress of smart textiles.

1.3 Conclusion and outlook

Despite the fact that smart textiles research has been going on for up to 30 years, there are few commercial solutions on the market. Smart fabrics have recently made significant progress, and this study topic enjoys widespread support from both the research and commercial sectors. To ensure that smart textiles successfully migrate from research facilities to industrial applications, a number of concerns must be addressed. The lack of standardisation, the lack of legislation for new products, the lack of coordination and collaboration among value chain participants, and the financial limits among firms to support development expenditures have all been mentioned as barriers. Safety, as well as ethical and social considerations, must be addressed. To enable the next wave of smart textile products, further basic research is required. Within a smart textile environment, we are still far from fully leveraging the capabilities available from the textiles sector. 3D textiles, in particular, provide previously untapped possibilities.

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Chapter 2. DEFINITIONS AND CLASSIFICATION

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2.1 Introduction. Fibres, yarns, and fabrics that have been designed and manufactured to contain technologies that give the user with greater functionality are known as smart textiles. In this chapter, we review the definitions and classifications of smart textiles based on different perspectives.

2.2 Definitions of smart textiles

Intelligent or smart materials are the source of the term 'smart textiles'. In 1989, Japan was the first country to define the term 'Smart Material'. Silk thread with shape memory was the first textile material to be labelled as a 'smart textile' in retrospect. Smart textiles, also known as intelligent textiles, electro or e-textiles, are intelligent materials that detect and respond to external stimuli. Simpler functional textiles are sometimes included in the definition of smart textiles [1, 2].

The first formal definition was found as 'smart textiles are composed of materials or structures that sense and react to environmental stimuli, such as those from mechanical, thermal, chemical, magnetic or other' [3].

According to the European committee for standardisation (CEN), the definition of a smart textile system is: 'Assembly of textiles and non-textiles integrated into a product that retains its textile properties and interacts with its environment' [4].

The CEN gives additional definition about integration levels:

Integration level 1	The electronic component can be removed without destroying the product. The components can be treated as separate units.
Integration level 2	The electronic component is attached to the textile and it is impossible to remove it without destroying the product. Components can no longer be treated separately but as a whole. In this case, textile could be considered as a
Integration level 3	One or more components are the textile type (or textile finishing). They are combined with integrated level 1 or 2 components. In most cases, the textile is the connection.
Integration level 4	All components of the smart textile system are of textile-type (or textile finishing). In this case, the textile is the component.

Figure 2.1 Definition of integration level 1-4

2.3 Classifications of smart textiles

There are no clearly established classifications of smart textiles. In this chapter, examples of used classifications are simply given and explained.

A first classification is possible from the definition of ‘smart textiles’ given by the European Committee for standardization [4].

This classification splits ‘Smart textiles’ and ‘Smart textiles systems’:

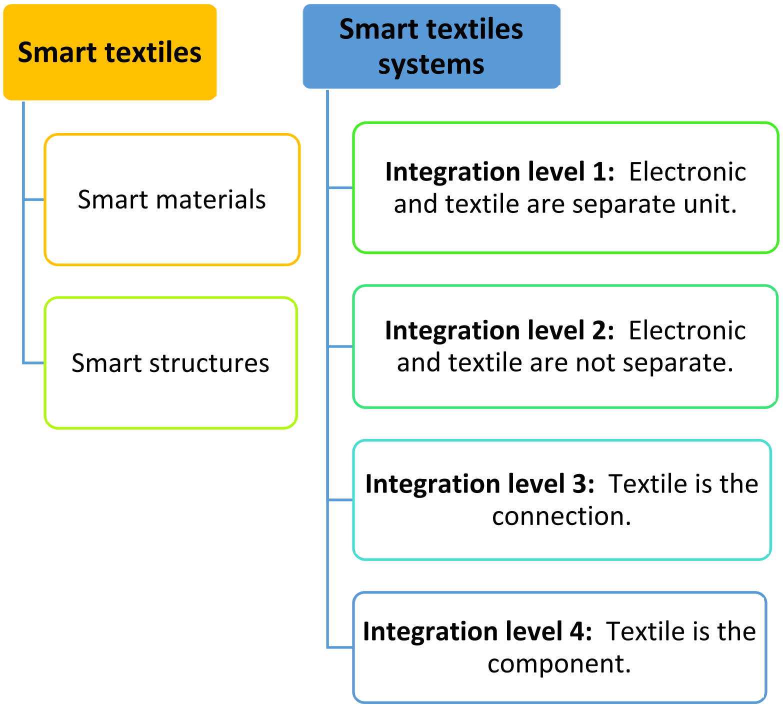

Figure 2.2 Classification based on CEN definition

The smart textiles can be divided into three subgroups [3, 5–8]:

- **Passive smart textiles.** The Passive smart textiles are only able to sense the environment or user. This is also called the first generations of smart textiles. These smart textiles are only considered as sensors. A good example is a textile embedded temperature probe. Wide range of capabilities, including antimicrobial, anti-odour, anti-static, bullet proof are the other examples.
- **Active smart textiles.** Active smart textiles are able to sense stimuli from the environment and act. This is also called second generations of smart textiles. They contain a sensing part and acting function. This response is considered as pre-determined. Active smart textiles are shape memory, chameleonic, water-resistant and

vapour permeable (hydrophilic/ nonporous), heat storage, thermos-regulated, vapour absorbing, and heat evolving fabric and electrically heated suits.

- **Very smart textiles.** The very smart textiles are able to sense, react and adapt their behaviour to the given circumstances. This classification is valid for intelligent textiles with and without electronics even if the "very smart textiles" category seems to be reserved for "e-textiles ". This is also called the third generation of smart textiles or ultra-smart textiles. A very smart or intelligent textile essentially consists of a unit, which works like the brain, with cognition, reasoning and activating capacities. The production of very smart textiles is now a reality after a successful incorporation of traditional textiles and clothing technology with other branches of science like material science, structural mechanics, sensor and actuator technology, advance processing technology, communication, artificial intelligence, biology etc.

The e-textiles can also be sub-classified as:

- **NoReact:** The NoReact family contains e-textiles with only one function, like sensing, acting, transmitting.
- **React:** The React family is smarter and contains e-textiles with at least two functions, such as sensing and acting.

Smart textile can be also classified based on the type of stimulus / response. But this classification is much less universal. Figure 2.3 presents lists of stimuli and responses of smart textiles.

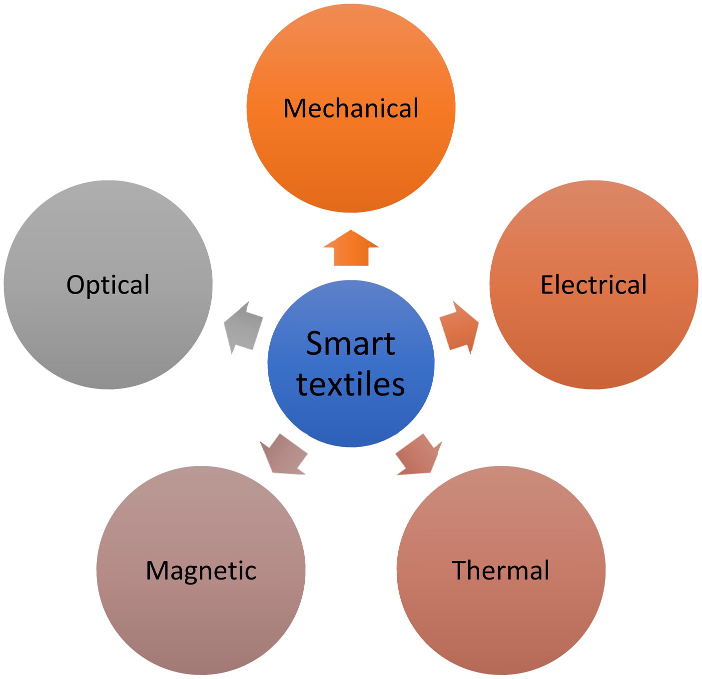

Figure 2.3 Classification of smart textile based on different stimulus / response

Here is another example of a classification that is a little more limiting. It consists of separating the communication and energy activities. 'Communication' should be interpreted broadly, and encompasses not only wave emission but also, for example, the diffusion of a visual message (through screen) and vibration. The creation and storage of electrical energy are included in the 'energy' function. Figure 2.4 indicates the classification of smart textile based on communication and energy supply.

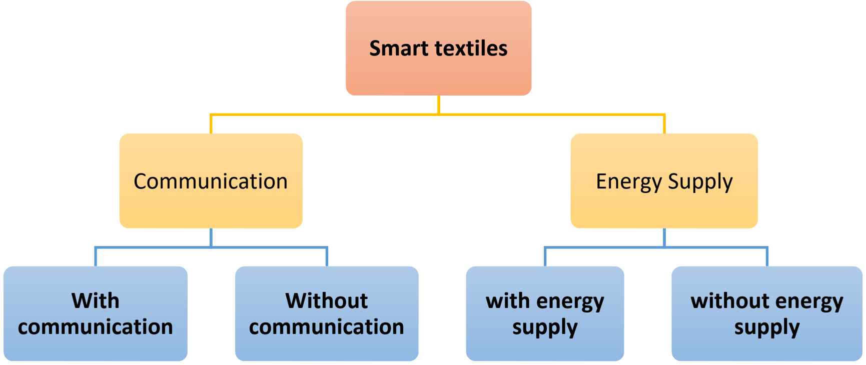

Figure 2.4 Classification of smart textile based on communication and energy supply

2.4 Conclusion

In the last three decades, the development of new kinds of textiles, smart and interactive textiles, has continued unabated. Smart textile materials and their applications are set to drastically boom as the demand for these textiles have been increasing with the emergence of new fibres, new fabrics, and innovative processing technologies. The demand of the smart textiles market is increasing with advanced functions and miniaturisation of electronic components. Therefore, there are no clearly established definitions and classifications of smart textiles. In this lesson, the used definitions and classifications have been simply given and explained.

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Chapter 3. ADVANCED MATERIALS FOR HEALTH CARE

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3.1 Introduction. Smart and interactive textiles have a high potential in biomedical research and are a relatively new subject of learning. Smart textile materials are an example in which the incorporation of smart devices may recognize, record and transmit basic data to the target authority. These devices can be used for observation and recording of heart activity, body temperature, breathing rate, etc. data, which later can be transferred through the Internet, mobile or any other accessible media to the emergency/health centre [1]. Clothing can predict muscular overload and stress meditations, which aid in the prevention of strain injuries, monitor babies' heart beats, and evaluate biochemical signals of fluid generated in daily activities or when involved in physical exercise [2]. The capability of smart fabrics to interact with the body provides a technique for determining the wearer's physiology and adjusting to the wearer's requirements. Smart clothing can provide a customised solution by increasing awareness of individual health status and encouraging people to take a more effective role in their individual health care. Smart clothing can help clinicians make more accurate diagnoses by preserving a digital record. Nowadays, to meet various health purposes, wearable medical devices can be wrapped in cloth [3]. Medical engineering incorporates the expertise of engineers, scientists, and physicians [4, 5].

3.2 Antimicrobial textiles

Antimicrobial textile materials are used to minimise hazardous microbiological accumulation. Various antimicrobial agents, such as metal ions, chitosan, tannins, triclosan, quaternary ammonium compounds, polyhexamethylene biguanides, n-halamines, and polypyrroles, are used not only to defeat microbial attacks but also to reduce odour and give mechanical strength to garments. The development of stimuli-responsive textiles with humidity and microbiological management facilitates the regulated application and long-term availability of antimicrobial chemicals coated on textile fabrics. Sensor-based fabric is one of the advances in intelligent antimicrobial textiles. Several antimicrobial chemicals are used to create smart antimicrobial fabrics.

Chitosan has a wide range of applications in the textile sector. Chitosan is active against specific types of microorganisms on its own [6]. The repulsion property to water of fluorocarbon or polysiloxane-treated chitosan reduces surface energy allows pollutants to adhere, and therefore helps to protect individuals from the microbiological atmosphere. The chitosan-covered textile protects those operating in the clinical and non-clinical sectors. At skin pH, the ionised form of chitosan interacts with the microbial cell wall, resulting in altered cell permeability and eventually microbial death [7].

Antimicrobial fabrics functionalized with metals are rapidly expanding globally. At low / nontoxic doses, the combination of metals, including Ag, Cu, Ni, Zn, Co, and Cd, improved the antibacterial action in human keratinocyte cells [8]. The melt-blown CuO_3Si functionalized nonwoven composite has extremely high antibacterial capabilities against *S. aureus* and *E. coli* bacteria. However, the addition of various polymers, for example $(C_3H_4O_2)_n$, (R)-3-hydroxy fatty acid, to copper silicate reduces the biological breakdown ability of the mixture by altering the melting/crystallisation processes [9]. Bimetallic Ag / Cu nanoparticles can enhance the antibacterial activity of cotton / polyurethane fabrics [10]. Due to effective antibacterial and detection properties, graphene is playing an active role in medical and electronic applications [11]. Graphene sensors can detect viruses, allergic symptoms, respiration rate, amount of glucose in the blood, interactions between small molecules and proteins, blood pressure and body temperature [12]. An electrochemical immune-sensor for the identification of the influenza virus was created utilising shellac-derived thermally reduced graphene oxide (rGO) flakes. These thermally rGO-based sensors have great stability and repeatability, due to the fact that they can be used to create a range of immune-sensors.

The common conductive polymers used for antibacterial activity are polypyrrole (PPy), polyaniline (PANI), polythiophene (PTh), polyacetylene (IUPAC), etc., and these are all conjugated polymers. Sustainable antimicrobial textiles can be developed by coating them with π-conjugated polymers. Positive charges of conducting polymers attach to negative charges of the bacterial membrane, preventing bacterial activity [13]. PTh shows robust antimicrobial activity against *B. cereus, E. aerogenes*, *E. aureus,* and *E. coli* bacteria; PANI has strong antimicrobial activity against pathogens because of amino units, low polymer chain, electrostatic interaction; IUPAC exhibits antimicrobial activity caused by three conjugated parts. Microcells are mainly damaged due to the electrostatic interface [14].

3.3 Drug-eluting textiles

When traditional treatment methods are not acceptable, a drug-loaded textile may be a viable option. Drugs are absorbed into the upper abdomen or intestinal system in ways of deglutition such as capsules and tablets. However, some medications may lose their effectiveness as they are destroyed in the acidic environment of the stomach or metabolised in the liver. Smart textiles can be coated with specific drug carriers and delivered to a specific stimulus. Various coating procedures can be followed to formulate drug-releasing textiles. These textiles can be degradable or non-degradable; it can be used for drug-eluting fibres, woven and nonwoven fabrics. Nonwovens are commonly used in medical applications because of their high flexibility, quick manufacturing cycles, and low cost of manufacture. Within the nonwoven, drug-containing threads are entangled and have been revealed to be highly suitable for controlled and sustained drug-release systems. The desired drug release behaviour can be modified according to the application requirements. Electrospinning is an effective and versatile technology for producing drug-eluting fibres, as it allows the incorporation of attractive and water-repulsive drugs, proteins or ultra fine metallic particles within the mass phase of fibres [14]. Pharmaceuticals and agents that have biological effects can be placed into the outer resorbable sheath and released at controlled rates depending on the polymer thickness, molecular weight, and shape.

A weft-knitted polydioxanone stent has been developed for 5-fluorouracil-loaded colon or rectum cancer medication [15]. Flat knitted cellulosic fabrics, coated with chitosan, sodium alginate, and calcium alginate, were found to be suitable as a bandage, which is suitable for wound healing [16]. To increase antibacterial and wound healing characteristics, chloramphenicol and tetracycline hydrochloride medications were added to the coated polymers. When the medication on the fabric surface wears off, the polymer coating on the surface creates a new barrier against germs, according to the study.

Woven systems are used in some medical applications to assemble fabrics that are encapsulated with drugs or functional substances. Antimicrobial wound dressings can be made with bioactive woven cotton gauze; for example, medical gauze was adorned with ultrafine Ag (silver) particles and medicated with acacia gum [17]. Caffeine nanoparticles were placed in micro-modal woven cotton and viscose textiles for transdermal antioxidant patches. When worn near the skin, the device can provide caffeine for some periods without the patient having to do anything else [18].

3.4 Health monitoring textiles

Wearable devices can now be integrated into clothing for a variety of reasons, including monitoring physiological indicators. Electromyography (EMG) is a technology that helps clinicians measure electrical muscle activity to monitor the conditions of nerves and muscles. Three electrodes placed directly on the skin are the most commonly used to record muscle activity. Textile electrodes integrated with shorts were used to create this three-electrode configuration of three electrodes [19]. The possibility to record electromyograms in a contactless manner was investigated in the EU-funded ConText project. To perform the measurements, two embroidered EMG electrodes were incorporated inside a shirt and a vest also using a conductive thread to send signals from the contactless sensor to the data recorder [20].

Electrocardiogram (ECG) is a skin-surface assessment of the electrical activity of the heart muscle. Ions flow through the heart muscle with each beat, forming charge gradients. Different ECG vectors result from differential measurements of the electrical potential on the body surface at different sites. Various textile technologies have been investigated in the past few years in order to create and develop textile electrodes that can be integrated into clothes and provide an ECG. Embroidery technology can be used to improve the interaction between electrodes and the skin, as the embroidered section is lifted from the surface of the cloth, allowing for better contact [21]. Fabric sheets can be used to record an ECG treated with piezoelectric polymer [22].

The electroencephalogram (EEG) is a tool for monitoring the electrical activity of the brain muscles. Using soft conductive textiles, an EEG textile-based device can be used to monitor the activity of the new-born brain [23]. Because new-born skin is extremely sensitive to pain, the researchers devised unique electrodes to allow long-term monitoring. The voltage changes between the scalp sites created by the brain structures are recorded by EEG electrodes which are typically tiny metal plates connected to the scalp. The electrodes are usually fastened onto a cap made of elastic fabric, as suggested by the international standard [24].

Smart textiles have the potential to play an important role in the prevention and treatment of diabetes. The blood glucose levels can be detected utilising Fiber Bragg Grating sensors [25]. In another study, it was found that smart socks, used by diabetic patients to monitor key health parameters, confirmed that their socks with a system for detecting temperature and foot pressure had a substantial association [22].

The average breathing rate is between 12 and 25. It is a belt that measures the breathing cycle and detects apnoea / hypopnea attacks [26]. Chest volume and respiration rate can be measured using a flexible sensor attached to the shirt [27]. In addition, smart shirts with textile sensors were developed to measure respiration times and phases, inhalation rate, and chest size [28]. Several other researchers have also fabricated textile-based devices to detect respiration rate, making this kind of health monitoring more prevalent in the world of smart textiles.

One of the most essential criteria for clinical assessment and health supervision is body temperature. Composites comprising conductive tools and temperature-responsive polymers can be used for fabrication of temperature sensors.

3.5 Conclusion

Most medical disorders are treated in phases that involve inhibition, acute care, rehabilitation, and ongoing support. Smart textiles have a responsibility in each of these stages of disease medication and prevention. Fabric sensors can be easily inserted into clothing and linked using conductive threads through embroidery, knitting or weaving processes. In the case of illness, smart clothing can help the medical society by offering a more complete image of the health of their patients and enabling remote monitoring to minimise clinical calls. A smart garment in rehabilitation can help the patient in taking an active role in his or her healing and prevent future relapses. Smart textiles may have therapeutic functions in the future, providing a variable and adjustable way of treatment. However, there are several difficulties that must be resolved before wearables can be widely adopted. To satisfy the demands of typical clothing, wearable technology should be soft, flexible, and washable. Washing is a crucial aspect in the life cycle of a product.

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Chapter 4. ADVANCED MATERIALS FOR PROTECTIVE EQUIPMENT

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4.1 Introduction

Workplaces are not always safe. Actually, some of the existing jobs nowadays have several risky tasks that employees must face. That is why safety became a priority in the industry in a transversal way, particularly in some sectors such as surface and underground mining, construction sites, power plants, factories, etc. [1].

For that, it is important to prevent workers from possible hazards that can end up generating several types of injuries such as thermal, biological, electrical, mechanical or chemical ones, which can act at the same time [2] in different parts of the human body (eye and face, head, foot and leg, hand and arm, body, and hearing [3]). The personal protective equipment (PPE) helps prevent those injuries by protecting the wearer.

To sum up, PPE can and should be improved, for its goals to be achieved in a more effective and efficient way by the development and integration of sensor technologies in the workers' clothing. This upgrade would provide a monitorization of workers' health, exposure to harmful elements, their proximity to danger zones, among others [4].

Smart PPE can be organised into four different categories depending on the technology applied to them. On one side, the presence of electronics or not, and, on the other side, according to their data collection characteristics (see Figure 4.1).

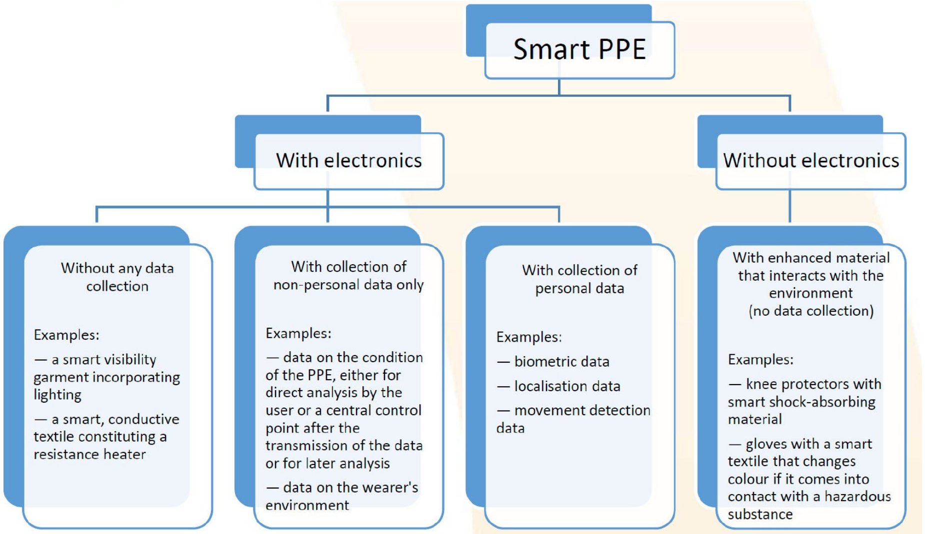

Figure 4.1 Classification of smart PPE, according to composition and data collection capabilities

Some examples of PPE with integrated electronics or smart materials [5] are the following:

First, *Smart knee protectors*. They can be soft and flexible, and facilitate normal movements such as walking and, at the same time, guarantee the smart material's properties of shock-absorbing in the moment of an eventual shock.

Then, the s*mart, conductive textiles that constitute a resistance heater.* Smart textiles can integrate electrical conductivity. With the provision of a constant electrical supply and the integration of sensors, these smart textile products can generate and keep a constant temperature around the heater.

Furthermore, *smart lighting garments* can emit light through the integration of optical fibres in the garment material. Optical fibres integrated into textiles and connected to a controllable light source can be used as part of smart garments. They even can determine the kind of illumination by the integration of a sensor.

Also*, smart gloves capable of identifying hazardous substances* are also an innovative product for PPE designed thanks to smart textiles advances. They turn into a different colour according to the contact to potential hazardous substances.

And finally, some *smart PPE* can also *collect data about its own use.* If equipped with sensors, it can collect several types of data on use duration or quantities… and communicate it to a central database.

As said, those are only a few examples of the wide range of possibilities that smart textiles can offer.

4.2 PPE applications

Applications of intelligent textiles in PPE are multiple and diverse. And every time the investigation in this field increases, their potential expands [6].

Nowadays, we can find three categories, three paths of product development. They are, basically, about practical needs of the users, about global systems and about reactions to external stimuli and environmental conditions.

For example, some specific ways found to deepen into PPE development through smart textiles [7] and their several fields of investigation (physiological condition, temperature and humidity sensors, power and data transmitters, and end-of-life indicators, smart materials…) could be the following ones: membranes with responsive permeability, including to water vapour, can be produced using shape memory polymers, polymer gels, superabsorbent polymers, grafted polymer brushes, and polymeric ionic liquids. These barrier membranes may even be made self-decontaminating with N-halamines, quaternary ammonium groups, bioengineered enzymes, metals and metal oxides, nanomaterials, and light-activated compounds. Thermal comfort can also be improved with phase change materials that can provide additional heat or coolness as the need arises. Also, thickening fluids that solidify and become shock absorbers when impacted at high speed.

4.3 Further horizons on PPE

Not all potential risks are visible or perceptible to human senses. Protection against gas, dust, sound and/or smoke is essential. The connectivity is a key field that gives a wide range of new utilities for PPE obtained through specific materials such as smart textiles. Once they are interconnected with the Internet of Things, smartphones, and any smart device, they can provide applications like the following in order to increase the protection of the person who is wearing the PPE in several conditions [1]. For example:

Connected PPE can detect invisible risks such as high temperatures. A temperature sensor can follow-up the external environment and alert the user in time about hazardous environments and alert supervisors if workers are in unsafe conditions.

Also, the geo-localization, integrated into a connected PPE, can monitor, and determine in real time the location of the user and give them information about which is the safer itinerary, where to continue or whether it is safer to get back from the area. Then the possibility to generate and transfer real-time data analytics, would enable to alert immediately the user when entering or being in contact with a hazardous environment or some other external aspect that has the possibility to damage the user integrity.

Also related with the communication systems, the PPE can facilitate fast and effective integrated channels of communication under loud or low-visual conditions.

And finally, but not less important, the monitoring of the users' health constants such as their heart beating rates become basic for guaranteeing the person who is wearing the PPE's safety.

4.4 Summary

The projection of the advanced materials and smart textiles as dynamizers for PPE is clear, long, and worthy to keep in. Most of the applications are currently under pilot testing, need to be improved or are just being prototyped. But some of the already applied ones are just showing impressive performances and a high potential.

Still, some risks and legislation need to be overcome and standards for these new products should be set.

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Chapter 5. ADVANCED MATERIALS FOR THERMAL PROTECTION

Michail Delagrammatikas, Creative Thinking Development, Ntrafi Rafinas, Greece

5.1 Introduction

Textiles for thermal protection may be used against exposure to extreme high or low temperatures, for mitigation of health hazards by long term exposure to temperatures outside the human thermos-physiological temperature limits or for avoiding discomfort, usually under intense physical activity. The main mechanisms for thermal protection textiles are thermal insulation and regulation of heat transfer. Advanced and smart materials may incorporate temperature sensors as well as 3D structures and properties changing textiles responding to different conditions. Extreme temperature protecting wearables are mostly based on insulating properties, aiming to maintain body heat, produced by metabolic activity, from escaping to the environment or avoid environmental heat from reaching the body.

The human body generates heat through metabolic activity and needs to maintain a quasi-constant temperature of 36.6±5 °C. Depending on the ambient conditions, humans need to retain or to discharge body heat. The comfort zone for humans lies at temperatures between 22 °C to 27 °C and relative humidity (RH) between 40% and 60% [1]. Evolution has deprived the human body of the fool body fur, which acts as a heat transfer regulator for most mammals. This function is more or less substituted by the use of garments for entrapping body heat and sweating for discharging excess heat.

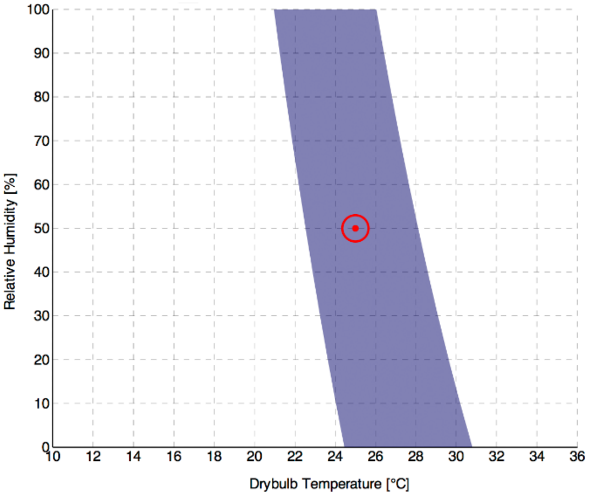

Figure 5.1 Comfort zone of the human body. Centre for the Built Environment, University of California Berkeley, CC BY-SA 3.0, via Wikimedia Commons

Heat transfer may occur mainly through three mechanisms: thermal conduction, thermal convection and thermal radiation. Thermal conduction occurs between solid bodies or entrapped fluids that remain still. The rate of heat that can be transferred by conduction is highly dependent on the nature of the materials. Metals have a very high thermal conductivity, while most materials used for fabrics have a low thermal conductivity. Entrapped air exhibits very low thermal conductivity; thus most insulating materials use air trapped in bubbles or between fibres as the main mechanism for prohibiting heat transfer. Water exhibits high thermal conductivity; thus, a wet cloth will not protect from low temperatures. Thermal convection occurs when heat is transferred by the flow of a fluid. Heat transfer by convention may be very effective, as one may know from experience when it is hit by a cold breeze or when entering a building that uses central heating. Thermal radiation occurs when the temperature difference between the radiating body and the environment is high. The heat from the sun reaches the earth by radiation, same is the mechanism for the heat we feel when facing a fire or a red-hot metal. A different way for heat transfer to occur is phase transition and the key role in temperature regulation of the human body plays water evaporation. When water, either fresh water or sweat, evaporates, molecules pass from liquid to gas state and this lowers the temperature of the remaining water that is still in contact with the body, thus acting as a cooling mechanism.

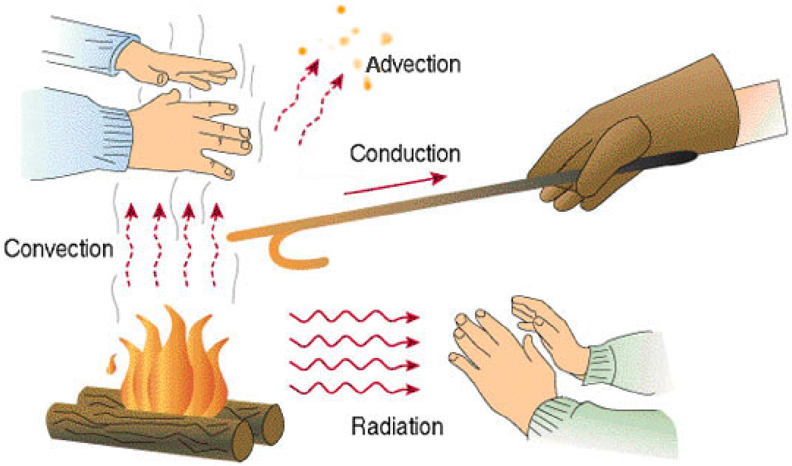

Figure 5.2 Heat transfer mechanisms. Kmecfiunit, cmglee, CC BY-SA 4.0, via Wikimedia Commons

The heat equilibrium of the human body depends on the balance between the heat that is generated by metabolism and the heat that is exchanged with the environment. Heat in most cases is not transferred by a single mechanism but by a combination of mechanisms which run in series or in parallel. Design of textiles and warbles for thermal protection requires understanding of both heat transfer mechanisms and the heat regulating mechanism of the human body, as to achieve the desired properties, in relation to the environmental conditions that the wearables will be used for.

In addition to regulating heat flows, advanced textiles may also incorporate heat generating or cooling components which actively interact with the heat transfer equilibrium in order to achieve the desired temperature for the human body. These technologies will be discussed in the next chapter.

Another important category of thermal protecting textile material are not wearables, such as insulation panels and upholstery.

5.2 Advanced textiles for thermal insulation and body heat regulation

Textiles for thermal insulation aim to minimise heat transfer from the human body to a cold ambient environment or decrease heat transfer from a hot environment towards the body, while allowing heat transfer from the body to the environment.

In the first case the main mechanisms of protection against cold consist in using low thermal conductivity materials (usually making use of air entrapped between fibres), preventing water from wetting the textile and prohibiting airflows from reaching inner layers, where these could induce water evaporation from near the body or replace warm entrapped. In the latter case, for protection against heat, insulating properties are also desired, but -especially in case of body heat regulation- quick water evaporation from near the body is sought.

These results may be achieved by using materials and fabrication techniques, both in yarn production and in textile making, to create novel products. Recent bibliography is rich in scientific publications that propose solutions using different approaches. N. Khadse et al. [2] exploit the difference in thermal expansion coefficient between two materials, Hytrel® and Crastin®, to produce a bi-component fibre which curves in low temperatures entrapping air. The fibre was produced by co-extrusion/melt-spinning and was originally assessed for producing non-woven paddings. Y. Chen et al. [3] developed a wearable membrane, based on recycled PET polymer, for regulating sweat transfer and enhancing thermal insulation. To this end they used vacuum filtration and magnetron sputtering to create a multi-layer membrane incorporating carbon nanotubes/manganese oxide nanowires (CNTs-MnO_2 nanowires) for sweat transfer regulation and silver nanoparticles (Ag) for increased antibacterial properties. Y. Xu et al. [4], inspired by polar animals' hair and feathers, used wet spinning in ethanol/water/ammonia mixture to develop biomimetic fibre with internal hidden nano-porous (HNPF) using alginic acid/quaternary chitosan as precursors. This way they achieved to produce a fibre with very low thermal conduction coefficient and biomimetic solar energy harvesting properties for woven textiles for cold resistance. L. Wang et al. [5], inspired by the same animal hair, produced hollow porous thermoplastic polyurethane (TPU)/polyacrylonitrile (PAN) composited fibres by wet spinning in water.

5.3 Advanced textiles for fire protection

Fire protection is a distinct case in thermal protection equipment due to the specific characteristics of fire which can deliver a very large amount of thermal energy, produce very high temperatures and induce rapid oxidising reactions, when an object is "set on fire". Thus, fire protecting textiles should retain certain properties such as, excellent thermal insulation, resilience to thermal shock and rapid heat transfer, stability in high temperatures i.e material should not melt, loose functionalities or ignite when they come in contact with flames, burning objects (e.g. flammable liquids) or when the temperature rises by hot fluid flows or as a result of thermal radiation. Also, fire protecting textile should not sustain fire and in case they are ignited, fire should be extinguished on its own.

Traditionally fire protecting fabrics were fabricated by woven asbestos fibres and when the carcinogenic nature of asbestos was understood were replaced by other inorganic fibres such as fibreglass and rockwool, which are also toxic.

J. Sulivan et al. [5] makes use of the anisotropy of thermal conduction of carbon nanotubes to model a textile that would be flame resistant and highly insulating towards heat coming from a perpendicular direction, but at the same, but proper alignment of the carbon nanotubes, directing the heat coming from the fire away from the body and towards the environment, reducing the temperature of the protective textile. G.M. Gonzalez et al. [6] created semi structured nonwoven para-Aramid fibre sheets, which exhibit both mechanical and thermal protection properties, due to the use of continuous ultra-thin para-aramid fibre achieving low compactness similar to an aerogel. This novel material can be used for protective equipment against explosive environments. The need for combining thermal protection and electromagnetic shielding properties in one fabric, lead M. Li et al. [7] to produce conductive composite aramid nanofibers for creating ultralight, flexible yet robust aerogel textiles. This was achieved by adding carbon nanotubes and mixing by mechanical stirring and ultrasonication of the precursor mix for wet spinning and freeze drying. A microporous yarn composed of nanofiber aerogel was thus produced.

Sensorial textiles often exhibit poor stretchability, limiting their potential applications. S. Zou et al. [8] created a flame resistant stretchable hierarchical yarn for temperature monitoring and strain sensor applications. The yarn consists of three parts: a flexible spandex core covered by two layers of aramid fibres. The inner layer is a conductive layer of complex aramid/carbon nanotubes fibre, and the outer layer is plain aramid. Both aramid fibre layers are produced wrapping the fibre around the core using friction rollers. The perpendicular direction of the aramid fibre layers, with respect to the spandex core, allows the yarn to be elastic, while the air entrapped between the fibres diminish heat transfer and provide insulation.

A different approach was followed by L. Wang et al. [9] who created a smart fabric system by weaving a shape memory filament in para-aramid fabric. The shape memory filament (nickel/titanium alloy) can be “trained” to convert from a linear to a sinusoidal (wavy) form at a given temperature. The shape memory fabric can be introduced in a 2D multi-layer smart fabric system. When the shape transformation temperature is reached, the filament will bend and curve, creating a 3D structure with large areas of air and act effectively as a heat transfer barrier.

5.4 Summary

Cutting edge technology is used for designing novel fibres, yarns and textiles that can be used for thermal protection and comfort. Eco-design, use of recycled and recyclable materials, as well as substitution of toxic and carcinogenic materials is another key issue in research and production of innovative products. Examples from recent bibliography presented in this chapter provide an insight of the trends in materials use, production technologies and design. Both 2D and 3D design may be used for creating advanced wearables tailored for specific environments providing protection and comfort.

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Chapter 6. ADVANCED MATERIALS FOR ENERGY

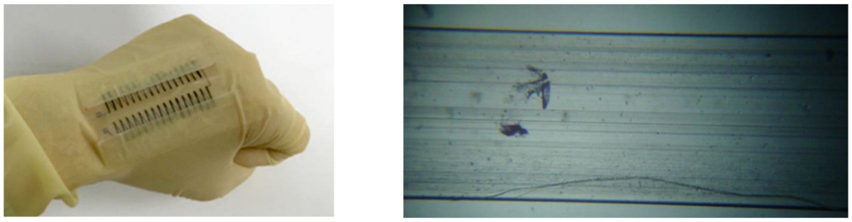
Michail Delagrammatikas, Creative Thinking Development, Ntrafi Rafinas, Greece

6.1 Introduction

Smart textiles often use small amounts of electricity needed for active sensors' operation or actuators' operation. The electrical energy source may come from batteries attached to the wearable, but energy may also be harvested from the environment and stored in flexible energy storage devices (batteries and supercapacitors) incorporated in textiles. Thus, there are two main subjects in wearable energy management: energy harvesting and energy storage.

Small amounts of energy may be derived by the ambient and become available for storage and use. This process is often called energy harvesting. Ambient energy sources for wearables may be solar radiation, electromagnetic fields, kinetic energy through the motion of a person wearing the smart textile or potential energy generated by pressure as well as many others. Usually all of these energy sources are used to generate electricity. While electrical energy production at industrial scale is possible only using few scalable technologies, small scale electricity production may take advantage of many more energy conversion phenomena and technologies. Some energy sources that can be used for small-scale energy harvesting and the associated technologies are listed below:

- Solar energy harvested by flexible photovoltaics (PV). Solar energy may also be used for harvesting thermal energy.
- Potential energy harvested by piezoelectric fibres and piezoelectric generators (PEGs) that take advantage of textile bending and stretching, pressure applied during use or vibrations.
- Thermoelectric generators (TEGs) generate electricity by exploiting temperature gradients which may derive from body heat, radiating sources ect.
- Kinetic energy may be harvested by magnets to induce electricity or by triboelectric nanogenerators (TENGs).
- Electromagnetic fields may also interact with special antennas and induce electricity.

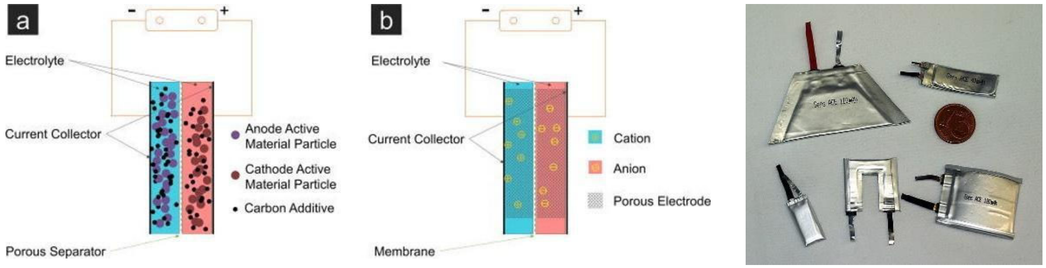


a

b

Figure 6.1 a – PEDOT:PSS thermoelectric generator embedded in a glove for the generation of electricity by human body heat. Eun Jin Bae et al., CC BY 4.0, via Wikimedia Commons; b – PVDF Piezoelectric ribbon yarn (2.5x). Ptosky, CC BY-SA 4.0, via Wikimedia Commons

Once harvested and converted to electricity, energy should either be used by devices like sensors and actuators or stored for future use. For the purpose of smart textiles and wearables this is achievable by electrical storage devices such as batteries and supercapacitors. Batteries and certain types of supercapacitors are charged by converting electrical to chemical energy, which become again available as electrical energy through electrochemical reactions. Electrochemical reactions are chemical transformations which involve the exchange of ions between two materials, the anode and the cathode, through a conductive medium named electrolyte. When the two poles, the anode and the cathode are connected through an electron conductive material (e.g. a metal wire, carbon nanotubes fibres, a conductive yarn) then, as a result of the electrochemical reaction, the conductive material is run by electrical current. When the electron conductive circuit is cut the electrochemical reaction stops and energy remains stored. Other types of supercapacitors store energy in the form of electrostatic potential energy or take advantage of both electrostatic and electrochemical mechanisms. A comprehensive review of battery and supercapacitor technologies can be found in [1].



a

b

c

Figure 6.2 a-b – Schematic illustration of (a) a Li-ion battery and (b) a supercapacitor. Zhaoxiang Qi, Gary M. Koenig Jr [1], CC-BY 4.0; c – Several Gens ACE LiPo-Batterypacks in different sizes, designs and capacity, considered to power wearable computing devices, manufactured by GREPOW Battery Co., Ltd. Thomas Springer, CC0, via Wikimedia Commons

In some cases, energy is not stored or used in the form of electricity but in the form of chemical energy and thermal energy. Exothermic or endothermic chemical reactions are used for heating or cooling, respectively, without involving electrochemical reactions as in electrical energy storage devices. The next two sessions aim to present an exemplary case from recent bibliography on the advances of material for energy harvesting textiles and energy storage in wearables.

6.2 Energy harvesting textiles

Different technologies have been used for adding photovoltaics on wearables. The simplest solution is to add detachable common photovoltaic panels (and batteries) on textiles and use the energy for generating heat or for producing light. While such applications can be a solution when larger amounts of energy are needed, they pose certain disadvantages as these add weight to the textile, are rigid and uncomfortable, can easily be damaged and cannot be washed as normal clothes. Recent research focuses on flexible photovoltaic which are either adhered on the textiles or even development of fibres with PV properties. Three different examples from recent bibliography are presented. T.M Bandara, J.M. Hansadi and F. Bella [2] have recently published a review article on textile dye-sensitised solar cells (DSSCs) for wearable electronics. DSSC usually comprise a transparent anode made of Indium/Fluorine Tin Oxide Glass (ITO/FTO), porous medium containing the charge transfer dye and a conductive cathode for collecting electrons [3] which can include carbon nanotubes. DSSC textiles are lightweight, flexible, comfortable and scalable for industrial production. Textile DSSCs can be manufactured either as yarns or developed on textiles. E.N. Güler et al. make use of a different type of flexible PV, organic photovoltaics (OPV) [4]. OPV provides a highly flexible and very efficient (as generated power per mass ratio) energy harvesting solution for textiles having as a drawback they tend to oxidise under environmental exposure (solar UV radiation, exposure to sweat are two common oxidising environments). This work focuses on depositing the different layers comprising the OPV system directly onto a barrier film, avoiding sandwich encapsulation which is mostly used for protecting the OPV from oxidation. I. Borazan, A.C. Bedeloglu and A. Demir, proposes a solution based on a stainless steel mesh fabric [5], using techniques which are common to the textile industry, such as dip-coating. This product can be used for wearables but also as textile on structures having complex geometry.

Innovative solutions using PEG, TEG and TENG technologies for energy harvesting are also proposed by state-of-the-art research. L. Veeramuthu et al. [6] developed an electrospun reinforced conductive fibre (ERCF) based nano piezoelectric generator which is inexpensive and non-toxic. Energy harvesting is made possible due to achieving high order of alignment for the nanofibers during production which allows electrons to be collected by the anode and the cathode of the generator. U. Zubair [7] proposes powering of active sensors by harvesting energy from a piezoelectric nanocomposite coating consisting of zinc oxide nanoparticles dispersed in poly-vinylidene fluoride (PVDF) binder applied on textiles. R. Bagherzadeh et al. [8] summarise advances in PENG and TENG nanogenerators for use in smart and sensorial wearables.

6.3 Energy storage in textiles

3D printing techniques have been used by K. Jain et al. [9] to modify cellulose fibres using poly(3,4-ethylene dioxythiophene) poly(styrene sulphonate) (PEDOT:PPS) ink. The authors demonstrated that these easy to fabricate 3D prints demonstrate supercapacitor properties. Y. Liang et al. [10] developed flexible supercapacitors by embedding a zeolitic imidazolate framework on polymer yarns modified by carbon nanotubes developed by chemical vapour deposition (CVD) and knitted. Lithography was used by Y. Rao et al. [11] to create by means of laser-scribing graphene based micro-supercapacitors on Kevlar textile. This method allows for the development of complex electronic devices on textiles. The technological advance in the field of energy storage for wearable microelectronics is summarised in a recent review article by X. Xiao et al. [12]. This review also highlights state-of-the-art, existing limitations in the technology and future trends. A. H Khadem et al. [13] focus on their review on applications of graphene for developing textiles for supercapacitor applications, as 2D carbon technology may boost the efficiency of flexible energy storage devices.

A different way to store energy is by taking advantage of direct conversion of chemical energy to thermal energy (and vice versa) through exothermic and endothermic chemical reactions or phase changing phenomena. Cooling mats is a widespread application that takes advantage of endothermic reactions related to water released from hydrated salts, occurring at hot ambient temperatures. Use of phase changing material in yarns or textiles for heating and cooling applications in the textile industry is discussed as a distinct field of application in K.A.R. Ismail et al. review article [14]

6.4 Summary

Advances in materials technology related to various mechanisms of energy harvesting and energy storage, allow for the development of smart and sensorial textiles that embed energy consuming devices. Attaching power sources to wearable by means of detachable equipment which are merely adhered to an otherwise conventional textile is rapidly giving away to development of flexible, durable and effective energy harvesting and energy storage devices which are intrinsically embedded in or onto the textiles or even to yarns that can be knitted or woven.

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Chapter 7. ADVANCED MATERIALS FOR ELECTROMAGNETIC ATTENUATION

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7.1 Introduction

This module is meant to describe the manufacturing and use of textile fabrics for electromagnetic (EM) shielding. A first important property of these fabrics is the electric conductivity [1]. However, recent studies are associated with the EM shielding and other properties too, such as: breathability, anti-microbial character, mechanical resistance, wash-ability [2-6].

As main application, fabrics with electro-conductivity may shield the EM radiation according to the principle of the Faraday-cage, by inducing Eddy currents with an opposite direction to the incident EM field and thus with an attenuation effect [7]. The protection against EM radiation is important nowadays, due to the various sources of EM pollution: GSM, WiFi, Power transmission lines, broadcasting etc. Such radiation may cause severe health problems to humans, according to several studies [8-9] and also interference with other electronic equipment, which should be avoided according to the protection principles of electromagnetic compatibility [7]. The textile fabrics have several advantages when compared to classic metallic shields, as shown in Figure 7.1.

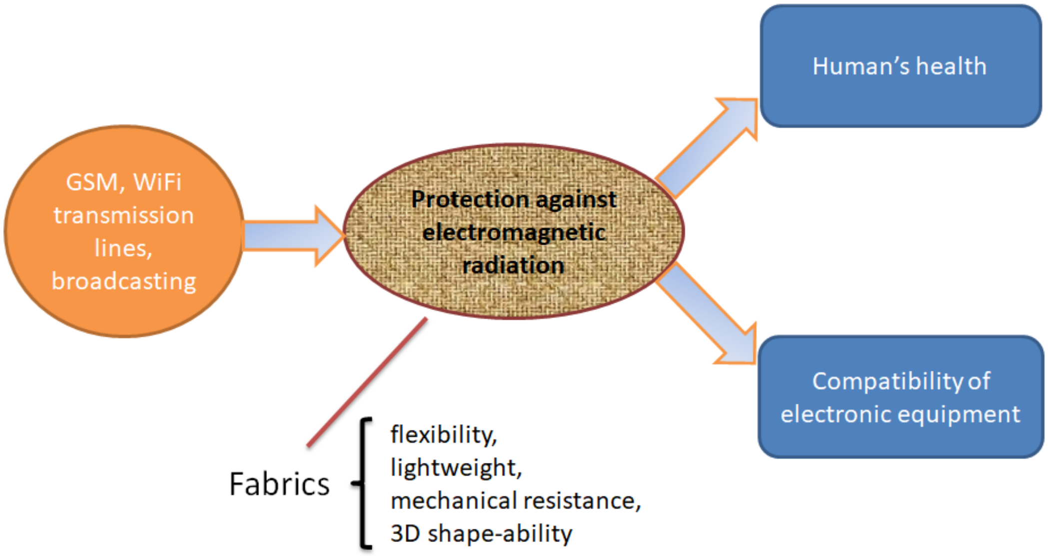

Figure 7.1 Application of fabrics for EMI shielding - rationale

The main intrinsic properties of textile fabrics are preserved in the process of conferring electric conductive properties: flexibility, lightweight, mechanical resistance and 3D shape-ability [10].

7.2 Electric conductive fabrics manufacturing for EMI shielding

Two main technologies may be distinguished in the manufacturing of electro-conductive fabrics, as shown in Figure 7.2.

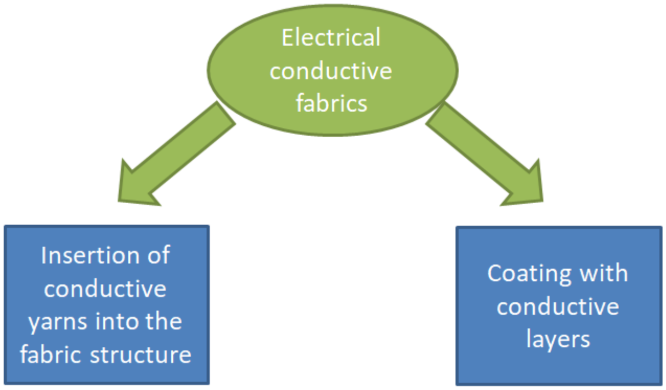

Figure 7.2 Main technologies to impart conductive properties to fabrics

The two main methods include:

- Insertion of electrically conductive yarns into the fabric structure (woven, knitted, nonwoven fabric) – Figures 7.3 and 7.4 present the weaving loom and the warp beam for preparing woven fabrics with metallic yarns;

Figure 7.3 SOMET weaving loom for inserting metallic yarns SC Majutex SRL

Figure 7.4 Warp beam for inserting metallic yarns in the warp structure

- Coating with electrically conductive layers (PECVD, magnetron, spraying etc.) – Figures 7.5 and 7.6 present plasma equipment for coating the fabrics with thin metallic layers.

Figure 7.5 Low pressure plasma equipment of INCDTP

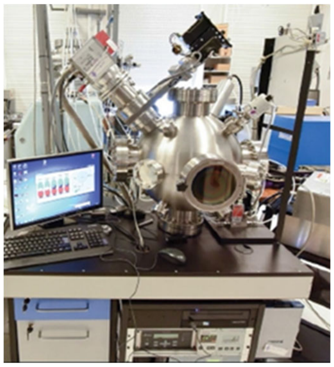

Figure 7.6 Magnetron sputtering plasma equipment of INFLPR

Firstly, we have to produce the EM shielding fabrics, next we have to measure their main functionality according to the application: the shielding effectiveness.

7.3 Methods to measure EM shielding effectiveness of textile shields

Electromagnetic shielding effectiveness (*EMSE*) is defined by the ratio between the power of the incident signal and the transmitted signal and is expressed in Decibel [dB]. *EMSE* is defined as:

$$EMSE = 10\ log_{10}\left(\frac{power\ of\ incident\ signal}{power\ of\ transmitted\ signal}\right)\ [\text{dB}] \tag{1}$$

One of the most convenient methods to measure *EMSE* is via the Transverse-Electro-Magnetic cell, or the TEM cell. The principle of the test is to measure the electric signal with and without sample and to compute the ratio according to relation (1). The TEM cell has according to standard ASTM-ES07 the following construction – Figure 7.7 [11]. A power generator creates the electric signal and an amplifier strengthens the signal which is introduced in one connection of the TEM cell. The textile sample has a shielding effect on the signal, which is measured by a network analyser or oscilloscope at the other connection of the TEM cell. The textile sample for testing has a washer-shaped format, in order to fit the inner and outer diameter of the TEM cell (d = 30 mm; D = 100 mm).

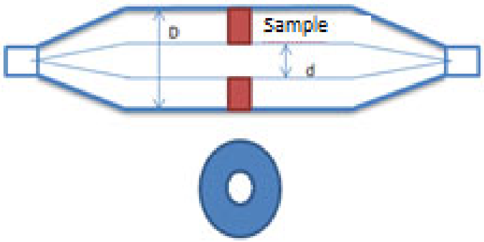

Figure 7.7 TEM cell according to standard ASTM-ES07

Two types of textile samples are presented in our educational module. First sample is a woven fabric with inserted silver yarns in warp and weft on a cotton substrate. The distance between silver yarns is 5 mm and the fabric has a specific mass of 118 g/m^2 (Figure 7.8). The same fabric was coated in magnetron plasma with a layer of 1200 nm of Copper on both sides (Figure 7.9). As mentioned in the previous paragraph, both samples were prepared in washer-shaped format for measurement via TEM cell.

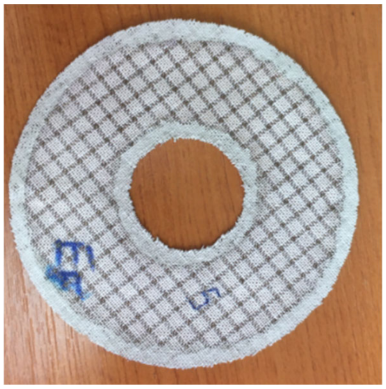

Figure 7.8 Sample F1 for TEM cell: woven fabric with inserted conductive yarns of silver

Figure 7.9 Sample F2 for TEM cell: woven fabric with inserted conductive yarns of silver and plasma coating with copper.

EMSE was measured in dB according to (1) on the frequency range 0.1-1000 MHz. Figure 7.10 presents the *EMSE* values on a logarithmic scale for the frequency in MHz. *EMSE* has values of 44-45 dB for the fabric with silver yarns and 50-53 dB for the fabric with silver yarns and copper coating, for the frequency range of 0.1-100 MHz. A slight decrease of *EMSE* values was measured for the frequency range of 100-1000 MHz, due to the electric thick material, where the sample thickness >> skin depth and the appearance of higher transmission modes in the coaxial TEM cell. These higher transmission modes superpose over the main transmission mode and can affect the measurement result [12].

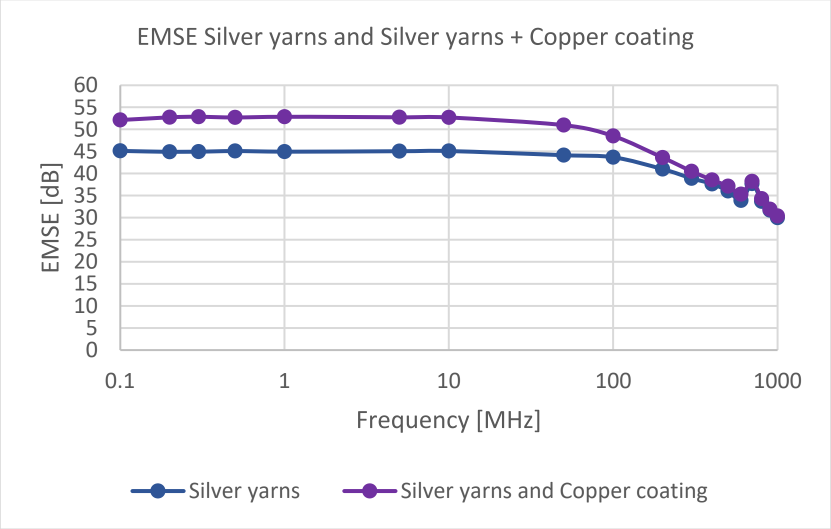

Figure 7.10 EMSE results of both fabric samples

7.4 Conclusions

Textile fabrics reached in the last 20 years additional applications to clothing products, named technical textiles. One of these applications is the shielding of the EM radiation, according to the principles of electromagnetic compatibility (EMC). Main property of shielding fabrics is the electro-conductivity, which enables the generation of Eddy currents with a shielding effect on the principle of the Faraday cage. The modern technologies of spinning and coating have permitted the manufacturing of metallic yarns and the coating with metallic layers. These new technologies resulted in manufacturing textile fabrics with inserted metallic yarns into the structure (woven, knitted and nonwoven fabrics) or in coating of the fabrics with metallic layers (PECVD, magnetron, spraying). After manufacturing of the electro-conductive fabrics, a next consideration is related to the measurement of their main functionality, the EM shielding effectiveness (*EMSE*). One of the simplest testing methods is via the transversal electric-magnetic (TEM) cell according to the standard ASTM ES-07. *EMSE* results show an increase of 5-8 dB for the plasma coated fabric on the frequency range of 0.1-1000 MHz.

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Chapter 8. ADVANCED MATERIALS FOR STRAIN SENSORS

Farima Daniela, Iovan Dragomir Alina and Bodoga Alexandra, "Gheorghe Asachi" Technical University, Romania

8.1 Introduction

When a textile structure is capable of sensing stimuli, reacting and adapting to them, then this becomes an advanced textile. Advanced materials can modify or adapt their properties in response to external factors (e.g. electro conductive materials, materials capable of changing colour (Figure 8.1) [1], materials that can store the shape, materials than can return to the previous shape under the action of heat factors, materials made of fabrics with retardant or hydrophobic treatments).

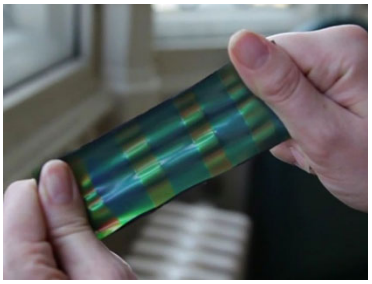

Figure 8.1 Colour changing smart materials [1]

A new generation of devices that combine strain sensing capacity with a one wearability and which have high stretchability capacity [2], are strain textile sensors.

8.2 Classification of sensors

In figure 8.2 [2] are presented many types of textile-based strain sensors.

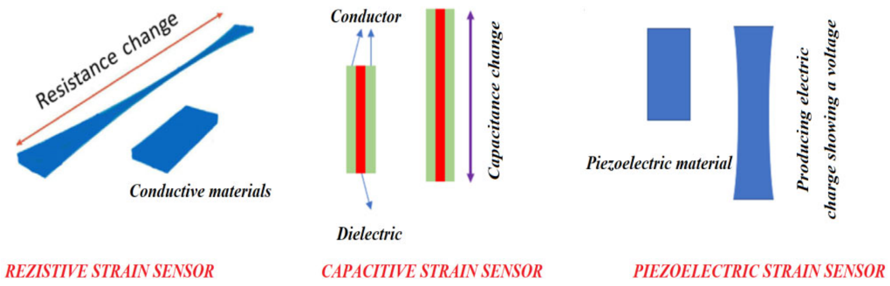

Figure 8.2 Classification of strain sensors

From figure 8.2 it can see observe that there are three categories of sensors:

- **Resistive strain sensors** (are composed of active materials and a flexible substrate [6]) which upon applied strain results in electrical resistance change in the sensor [3, 4, 5]. The electrical resistance of the sensor recovers as conductive materials re-establish the original states or structures, when the strain is released. The textile-based resistive strain sensors have a facile manufacturing process and accessible read-out signals [3]. The textiles-based resistive strain sensors are characterised through a layer of textile electrode from active materials which functions as a resistor when a voltage is applied, and the resistance alters according to the magnitude of the applied strain (Figure 8.3) [15].

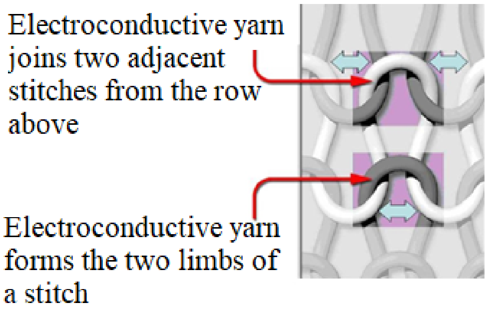

Figure 8.3 Structure of the resistive strain sensor

In figure 8.3 it observes the arrows which mark the regions where electrical contact is made as the base structure relaxes after stretching.

- **Capacitive sensors** (Figure 8.4) are composed of two opposite electrodes from active materials and which are separated by one dielectric layer of insulating materials in between [7,8,9,10,14].

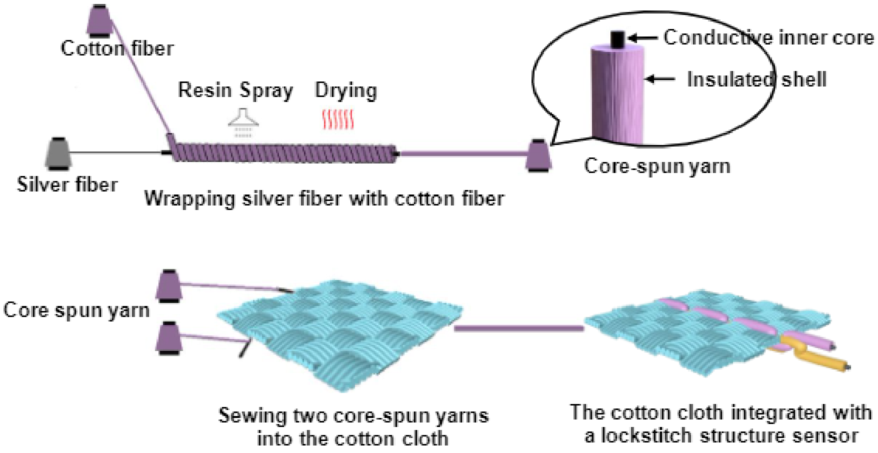

Figure 8.4 A capacitive sensor

- **Piezoelectric strain sensor** is a piezoelectric material which transforms deformation into electrical energy [11, 12]. In these sensors, when an external stimulus (pressure, tensile forces, compressive forces, and torsion) is applied voltage difference is generated (Figure 8.5).

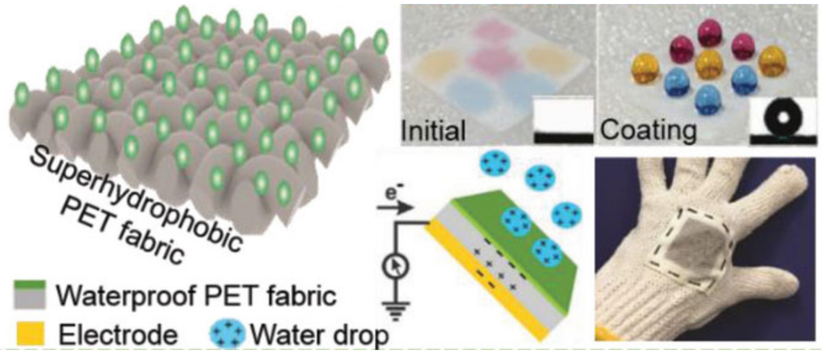

Figure 8.5 Piezoelectric strain sensor

Conductive textile materials are used for obtaining smart textile (sensors, heating textiles, electrostatic discharge clothing, communication).

The conductive textiles can be obtained through three methods:

1. Using inherently conductive polymers.
2. Adding carbon or metals in different forms such as wires, fibres or particles.
3. Coating with conductive substances [13].

8.3 Classification of conductive textiles

a. Anti-static textiles which can the build-up electric charge on the surface of objects.

b. Electromagnetic shielding textiles (EMs) which can restrict the diffusion of electromagnetic fields into a space (woven, knitting and nonwoven) (Figure 8.6) [16]**.**

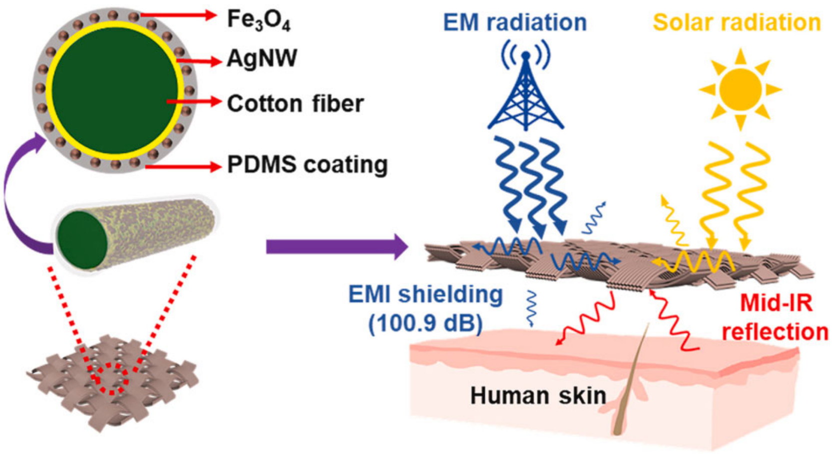

Figure 8.6 Electromagnetic shielding textiles

The yarns from figure 8.6 are electrically conductive for electromagnetic effect.

c. E-textiles, electrically conductive fibres and yarns, have features such as including reasonable electrical conductivity, flexibility, electrostatic discharge, and electromagnetic interference protection.

The main component for wearable smart textiles is conductive textile fibres used in sensors, electromagnetic interference shielding, electrostatic discharge, and data transfer in clothing [13].

d. Functional coatings can be material interfaces or surfaces and are a possibility for modifying textiles with conductive properties [16].

8.4 Conclusion

The strain sensors are resistive, capacitive and piezoelectric. The strain sensors react by reducing or increasing the electrical resistance when the stimuli (strain, pressure, tensile forces, compressive forces, and torsion) are applied.

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Chapter 9. ADVANCED MATERIALS FOR PRESSURE SENSORS

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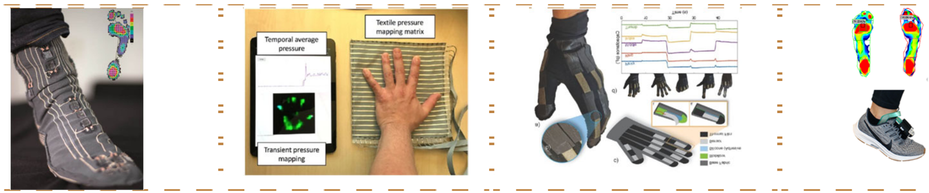
9.1 Introduction

Textile pressure sensor development is challenging for researchers trying to generate scientific advances in biomedical monitoring (motion, pulse, gate and respiration) or robotics (artificial electronic skins for robots). The versatile embroidering of textile materials, technologies with polymers, advanced micro/nanostructured composites and digitalization (software and microelectronics) generate innovative wearable products. This chapter presents the main aspects of the materials used and technologies for developing resistive and capacitive sensors.

Pressure sensors are used to sense the pressure and convert it into an electric signal where the value of the signal depends on the level and variation of the pressure applied. A pressure sensor consists of pressure-sensitive elements (piezoresistive, capacitive and electrically resistive) to evaluate the pressure applied and some components to convert this information into an electrical signal. The pressure represents the applied force by a liquid or gas on a surface (sensitive elements). The pressure sensors detect motion, gate, pulse, respiration rate or electronic skin (Figure 9.1). The most used sensitive elements are piezoresistive or capacitive materials.

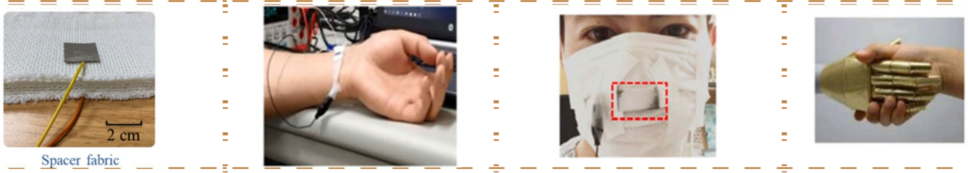


a. Washable textile pressure sensors integrated into socks for gait mapping [1]

b. Hand pressure mapping using textile pressure sensor [2]

c. Glove-based pressure sensors for control by different gestures [2]

d. Smart sole for foot pressure mapping [3]



e. Capacitive pressure sensor for motion detection [4]

f. Pulse monitoring [5]

g. Respiration monitoring [5]

h. Electronic skin [5]

Figure 9.1 Pressure sensors applications

9.2 Materials used for pressure sensors

The raw material used for pressure sensor manufacturing consists of non-conductive polymers (NCP), chemicals (CNTs, graphene, SWCNTs, MWCNTs), conductive polymers (CP=NCP+CNTs), intrinsically conductive polymers (PEDOT: PSS, PANI).

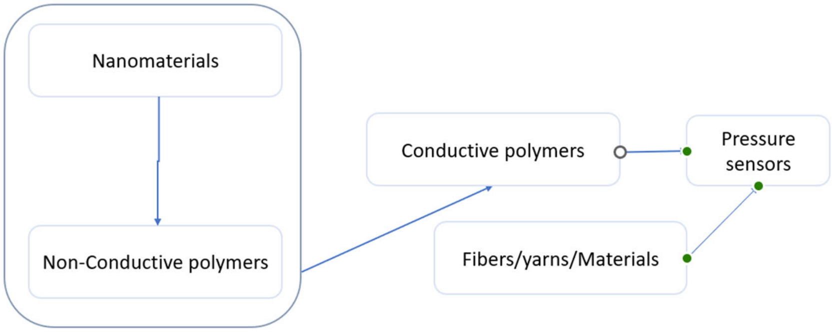


Figure 9.2 Materials for pressure sensors

- *Conductive polymers*

Poly(3,4-ethylene dioxythiophene)-poly(styrene sulfonate) PEDOT: PSS is a conductive polymer that can be deposited on textile substrates to form composites with electrochemical properties for applications like printed electronics. Polyaniline (PANI) is an inherently conductive polymer and semiconductor with sensors and printed circuit board manufacturing applications.

- *Non-Conductive Polymers -Elastomers*

Polyvinylidene difluoride (PVDF) is a thermoplastic fluoropolymer used in 3D printing and manufacturing sensors (tactile sensor arrays), batteries and supercapacitors. Usually, the polymer silicone is used for electrical insulation by integration in the polymeric matrix of the graphene nanotubes or CNT (carbon nanotubes) to become conductive silicone ideal to use in pressure sensors.

- *Nanomaterials*

Carbon nanotubes (CNTs) present excellent electrical properties for piezoresistive pressure sensors. In general, the piezoresistive pressure sensors are fabricated using a variety of elements such as gold wires, ZnO nanowires, silver nanowires, graphene, gold/silver nanoparticles and carbon nanotubes integrated into silicones.

9.3 Pressure sensors classification and manufacturing

A. Capacitive pressure sensors

Capacitive pressure sensors (Figure 9.3, 9.4) are made of conductive materials as plates separated by dielectrics (synthetic foams, fabric spacers, or soft non-conductive polymers). These sensors can be manufactured using different technologies such as weaving, sewing, 3D knitting (Figure 9.3), embroidering with conductive filaments/yarns, followed by 3D printing (Figure 9.4), which is deposited by sputtering, or screen printing with conductive inks/paste based on conductive polymers.

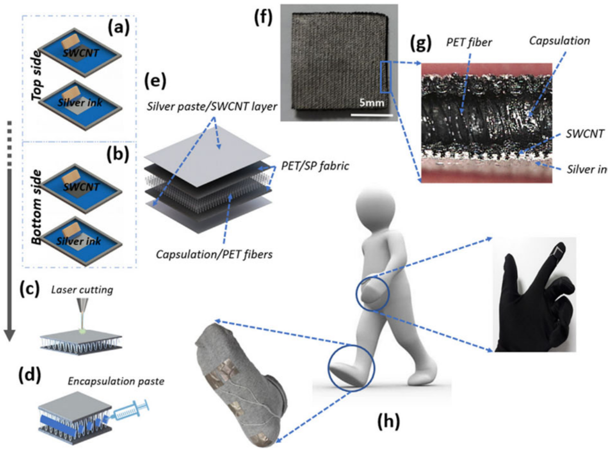


Figure 9.3 Manufacturing process of capacitive pressure sensor consisting of spacer fabric and SWCNT/silver printing [6]

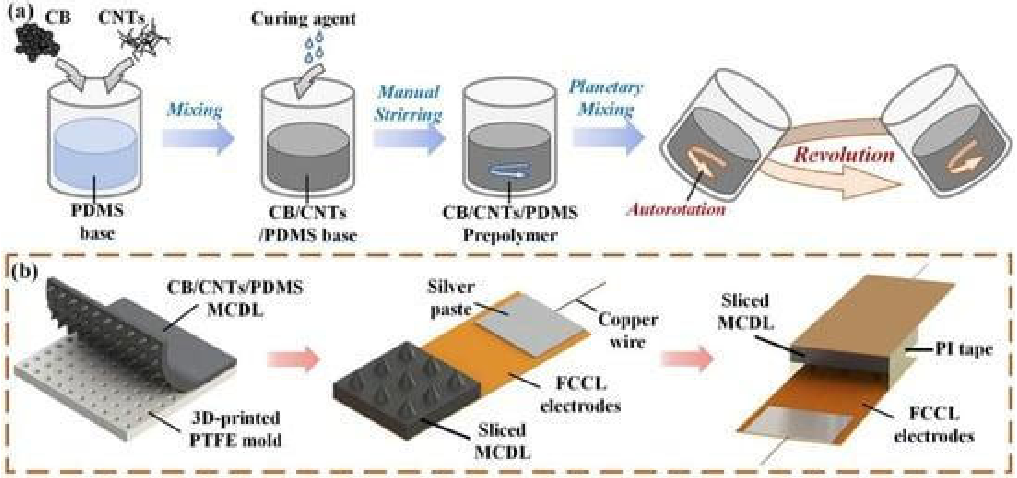


Figure 9.4 Flexible capacitive sensors fabrication [6] pressure sensors based on CB/CNT/PDMS [7]

Using conductive polymers (e.g., PEDOT: PSS (Figure 9.5), PANI (Figure 9.6)) can be developed as touch sensors for applications such as keyboards, pressure sensors integrated into beds, sofas or medical insoles [8] or motion detection, 3D tactile sensors for robotics movement detection [8]. The pressure sensor is made by weaving the yarns coated with the conductive polymer PEDOT: PSS and perfluoro dielectric polymeric film (Cytop) [8].

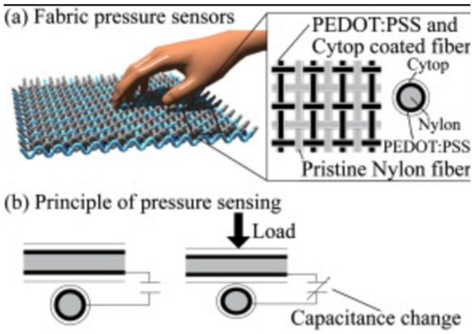


Figure 9.5 Fabric pressure sensor array [8]

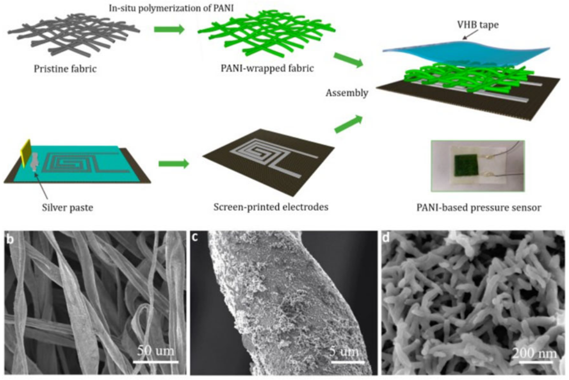


Figure 9.6 Flexible capacitive sensors fabrication based on PANI nanofibers and silver electrodes [9]

B. Resistive pressure sensors

The resistive pressure sensors can be made using electrically resistive/conductive materials such as yarns/filaments knitted, glued, weaved or embroidered in various structures by different manufacturing techniques (weaving, embroidering, knitting, sewing). The working principle is based on increasing the electric resistance when the fabric (woven, knit) is stretched or compressed. The sensors can generate voltage variation by stretching (Figure 9.7 a) or compressing (Figure 9.7 b).

a

b

Figure 9.7 Resistive pressure sensors: a – knitted pressure sensor-based piezoresistive yarns [10]; b – embroidered resistive pressure sensor [11]

9. 4 Conclusion

The pressure sensors used for sensing the pressure consist of sensitive elements of conductive polymers, elastomers and nanomaterials. Pressure sensors are classified as capacitive and resistive. The capacitive sensors can be manufactured using 3D printing, sewing, 3D printing, coating (magnetron sputtering, screen printing) and weaving. The resistive sensors can be fabricated by textile technologies (weaving, knitting and embroidering) and modify their electrical resistance when stretched or compressed. They can be fabricated by weaving, knitting and embroidering.

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Chapter 10. ADVANCED MATERIALS FOR ACTUATORS

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10.1 Introduction

Textile actuator (textuator) design represents a challenge for researchers trying to improve the solution by integrating lightweight, flexible and comfortable materials for wearable actuators (VR glove, artificial muscles, exoskeletons, electrostimulation devices, fashion items) or robotics (artificial electronic skins for robots). Developing soft/flexible actuators involves using classical technologies (knitting, sewing, weaving, embroidering) and advanced ones (plasma, sputtering, 3D printing). In addition, by integrating electroactive or electroconductive polymers, micro/nanostructures and digitalization (software, electronic components) can be fabricated as innovative wearable products-based actuators. This chapter presents the main aspects concerning the actuator type, materials used and technologies for flexible actuator development.

The actual researches in the field of flexible/soft actuators show an increased interest in solving current challenges by integrating flexible materials having actuating roles in wearable systems.

The actuators act mechanically, chemically, magnetically, electrically, and thermally upon the action of a stimulus (e. g., thermal, electrical, mechanical, optical, or magnetic). In order to develop actuators, several smart materials such as piezoelectric, electrostrictive, magnetostrictive, rheological, shape memory (thermally sensitive), pH-sensitive and electrochromic materials are used [1].

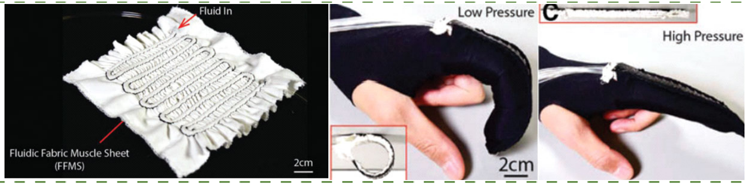
Actuators convert the input stimuli (electrical, mechanical, thermal, optical or chemical energy, magnetic field) to an action. Depending on energy conversion from input stimuli to output action, several actuators are presented in Table 1.1.

Mainly, the actuators integrate piezoelectric [2, 3], electrostrictive [4], electrochromic [5], magnetostrictive [6, 7], shape-memory [8] materials having thermal conductivity, low surface resistance, pH sensitive, rheological and magnetic properties. Actuators react to the input stimuli (electrical, mechanical, optical, chemical or thermal energy) and generate an action or a conversion of a type of energy to another one (Table 1.1). For example, it is known that artificial muscles (Figure 10.1) carry out based on electroactive polymers [9, 10]. To develop textile actuators are used classical technologies (knitting, weaving, sewing) combined with advanced technologies such as RF plasma, sputtering, 3D printing, and microwave.

Figure 10.1 Artificial muscle-based electroactive polymers [11]

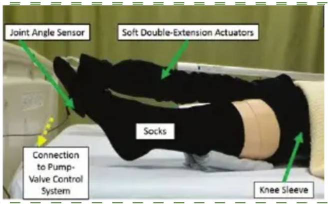
10.2 Actuators types and manufacturing

The actuators can be soft or hard, depending on the material's flexibility. Soft actuators are flexible, stretchable materials with variable and reversible properties. Soft actuators (Figure 10.2) are used for wearable devices, fluidic fabric muscle sheets (FFMS -Figure 10.2 a), artificial muscles (pneumatic artificial muscles (PAMs) made by braiding or knitting technologies – Figure 10.2 b), knitted exo-socks for rehabilitation (Figure 10.2 c), glove for rehabilitation (Figure 10.2 d), haptic glove for VR (Figure 10.2 e), dielectric elastomer actuator (DEA -Figure 10.2 f) and soft grips. On the other hand, hard actuators made of rigid materials with invariant properties are unsuitable for portable devices because they are uncomfortable.

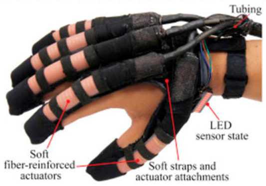


a. Textile Actuator - fluidic fabric muscle sheets (FFMS) [12]

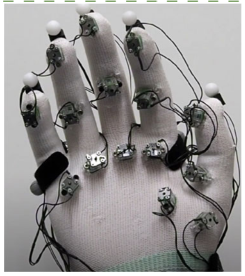
b. Power assistive orthosis for elbow-based PAMs [13]



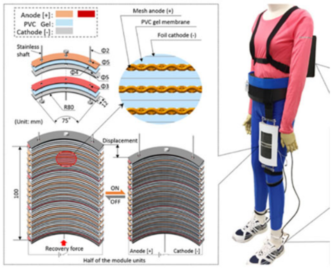
c.Exosocks for rehabilitation [14]



d. Robotic hand-assisted device [15]



e. EM actuator for haptic glove [16]



f. Dielectric elastomer actuator (DEA) for hip joint rehabilitation [17]

Figure 10.2 Textuators (soft actuators) applications

Figure 10.3 presents the action principle for textuators made by weaving or knitting.

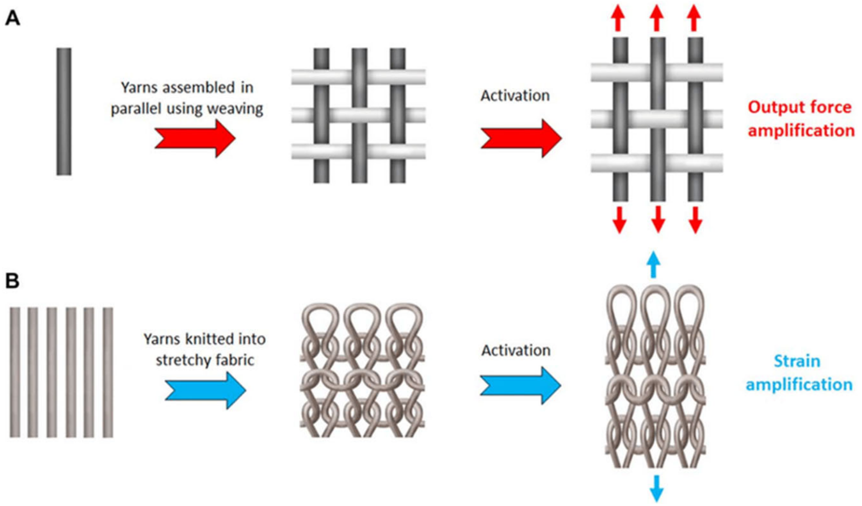


Figure 10.3 Textuators: A – weaving yarns amplified the force in parallel; B – the strain was amplified by knitting yarns in a weft knitting structure [18]

Figure 10.4 presents several advanced materials used for soft actuators.

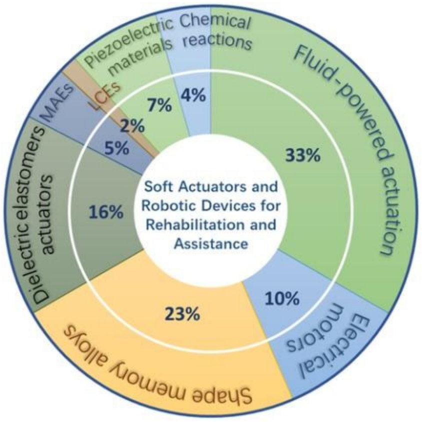


Figure 10.4 Soft actuators based on dielectric elastomers, SMA, MAE, LCE and piezoelectric materials [19]

Table 10.1 Actuators Type

Actuator Type	Input Stimul	Output Response	Action	Material Type	Example
Thermal	Thermal energy	Mechanical energy [19] (kinetic/motion)	Thermomechanical (contraction/ expansion)	Thermal energy	**Smart Thermally Actuating Textiles**
Thermoelectric	Thermal energy	Electrical	Thermoelectrical	Thermoelectric	**Turning heat into electricity**
Electromagnetic	Electrical energy	Mechanical	Electromechanical	Electromagnetic	**Electromagnetic Actuators for Rendering Haptics in VR**
Piezoelectric	Mechanical energy	Electrical	Piezoelectric	Piezoelectric	**Piezoelectric fiber for motion-sensitive textiles**
Optoelectronic	Optical energy	Electrical	Opto-electronic	Photoelectric	**Photovoltaic power from textiles**
Electro-photonic	Electrical energy	Optical	Electro-photonic	Electrophotonic	**LED into Textile for Smart Clothes**
Photothermal	Light energy	Thermal	Photothermal	Photothermal	**photothermal phase change textile**
Magnetorheological	Magnetic field	Magnetoelastic effect (deformation)	Mechanical (Elastically deformation)	Magnetoelastic	**Magnetoelastic fibers**
Electrochemical	Electrical energy	Chemical	Electrochemical	Electrochemical	**Twisted yarn actuator**
Photochemical	Light energy	Chemical	Photochemical	Photochemical	**Fiber-type FETs**

10.3 Conclusion

The actuators convert the input stimuli to output action (mechanical, chemical, magnetic, electrical, and thermal), mainly used for robotics (prosthetic arm, exoskeleton) and rehabilitation for artificial muscle. Soft actuators can be obtained based on textile technologies (weaving, knitting, braiding).

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Chapter 11. SENSORIAL MATERIALS DEFINITIONS, DEVELOPMENT, AND APPLICATIONS

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11.1 Introduction

Sensors are an essential part of current innovations. They are the core of the so-called 4rth Industrial revolution and the next generation of the Internet, or the Internet of Things as it is commonly known. When we refer to a sensor, we could describe it as a device, a module, a machine or even a subsystem, that can detect or measure one or more parameters of the surrounded environment. Sensors measure these parameters, (inputs) and provide (transmit) the results (values) in a way according to the structure of the measuring device that they are part of.

Sensors are being used in a large variety of applications, ranging from medical to environmental sciences. Recent developments in the design of sensors has diversified their applications and the materials where they can be incorporated. They become smaller, cheaper, and more efficient. They are also capable of operating in difficult environments and last longer. Materials in micro and nano-scale have provided for these improvements, as well as digital technologies. Techniques that are used for sensor fabrication are also something crucial to be considered. Novel methods such as printing electronic circuits, have been used with impressive results.

Sensors are carried in daily activities, often without explicitly being realised by the user. For example, smartphones have plenty of different sensors that are used in various tasks and applications like compass, accelerometer, proximity sensors, orientation sensors and light devices, to name a few. Sensors in medical science are vital for detecting, monitoring, treatment and curing of diseases. It is no exaggeration that current civilisation is immersed in sensor related technologies.

Wearable devices depend on sensors to report metrics such as distance covered, heart beat range and oxygen saturation in blood, among others. Temperature of the human body and the environment can also be measured through miniaturised sensors for the relevant application.

11.2 Wearable sensors for health monitoring

Wearable sensors can be fabricated by plenty of different transduction methods which include resistive, capacitance, piezoelectric and triboelectric. All these approaches report signals using electrons.

Wearable sensors could be divided into three main categories based on the measured biological signals, that is, electrophysiological, physical and chemical sensors [1]

11.3 Electrophysiological Sensors

In electrophysiological sensors it is crucial to design thin, conformal, and biocompatible epidermal electrodes to decrease skin-electrode contact impedance. The constant proximity of contact is the key to reduce skin–electrode contact impedance. Electrophysiological sensors detect the electrical potential difference between electrodes at specialised tissues like heart (electrocardiograph (ECG)), brain (electroencephalography (EEG)), and muscle (EMG).

These lead to a variety of final products which include Epidermal EEG, Sticky ECG, Epidermal ECG, Graphene EEG, and silk-based EMG. [2]

Physical Sensors

Physical sensors detect the physical signals of the human body. There are several physical signals related to human health, such as blood pressure, body temperature, and muscle or skin stretching. In the design of skin-conformal pressure sensors materials such as silver nanowires, gold nanowires, carbon nanotubes, graphene, conducting polymers, ionic liquids and liquid metals have been exploited.

The key parameters examined for these are sensitivity, hysteresis, and durability.

Physical sensors measure pressure, temperature, light, strain, and sound. Applications of such sensors can be found on tattoo temperature sensors, gesture detection, bending degree, limb movement and muscle training.

Chemical Sensors

In chemical sensors, materials such as potassium and sodium ions, chloride ions, lactic acid and glucose could be used in their manufacturing. Some of these sensors are blood glucose detectors, microfluidic sweat detectors, hydration sensors and textile multi-ion sensors that are used in diagnosing cystic fibrosis.

Sensor properties

Main objectives for a useful sensor are the provision of accurate results, durability, low-cost and to be harmless for people and the environment.

To provide the aforementioned characteristics a series of desired properties are necessary, namely stretchability, modularity, scalability, self-healing properties and transparency, among others. For all these to be achieved it is important the usage of nanostructured materials, gel-based ionic conductors, printed electronics, stretchable electrodes, and the usage of bioresorbable electronics.

Moreover, bioresorbable, biocompatibility, power consumption and permeability could be achieved through the detection of environmental exposure, the detection of health factors and the development of self-powered systems.

In addition, conductivity, sensitivity, detection range, reliability, selectivity, and water repellency are crucial for temperature sensors, strain and pressure sensors, electrophysiological sensors, optical and electrochemical sensors. [3]

Stretchability

A sensor that would be used in a wearable device or be attached to the human body must be stretchable. Ways to achieve stretchability include the downscaling of the dimension of the materials used as electrodes [4], usage of stretchable polymers, hydrogels, and ionic liquids [5].

Form Factor

In the aspect of form factor, the goal is to create flexible, wearable, thin, dry sensors that are transparent, lightweight, and comfortable [6].

Transparency

For sensor usage in the human body transparency is required. Transparent polymeric films and limiting the width of metal electrode lines are some of the ways to achieve it. Others include use of transparent elastic films of carbon nanotubes, silicon nanowires and metal nanowires [7, 8].

Biocompatibility

Low toxicity is vital for long-term usage of sensors on human skin. For that encapsulation or compositing with biocompatible materials could be used. Another way is using gel-free dry adhesives [9, 10].

11.4 Materials used in Sensors

Each sensor type includes specific materials that have been used, examined or are under research and examination for the potential to be used. The kind of materials highly depends on potential application.

For temperature sensors Cr and Au on silicone patches have been reported [11].

For electrophysiological sensors Au-Ag NWs, CNTs and AgNWs are used [12, 13].

Pressure and strain sensors consist of AgNW/polyamide nanofibers, ZnO sea-urchin shaped microparticles and stretchable and con-formable matrix networks on PVA or PDMS substrates [14, 15]

Electrochemical sensors use PEDOT: PSS on SEBS substrate and OECT-based cortisol.

Smart materials for sensors

Due to the outbreak of COVID-19 pandemic, developments in smart materials that are used for sensors were accelerated and showed significant growth.

Smart materials intersect at multiple disciplines spanning from materials science, chemistry, physics, engineering, and nanotechnology [16].

Most common materials of that type are nanomaterials, graphene, carbon nanoparticles, inorganic materials, organic nanoparticles, conductive and insulating polymers, and hybrid materials.

11.5 Conclusion

Sensors intercept human lives in countless diverse ways. It is essential to develop better sensors with higher capabilities to successfully integrate them in more aspects of our society. Health and sport monitoring sensors, sensors to monitor environmental metrics, the weather, the sea, animals are only some of the important fields that depend on these developments.

Research on the materials that have the potential to lead to more complex and sophisticated sensors is ongoing and happening all over the world in research labs and universities.

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Chapter 12. SENSORIAL COMFORT EVALUATION

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12.1 Introduction

Sensorial comfort plays a determinant role in the textile evaluation. This concept is usually used in terms to describe the fabric sensation regarding its contact with human skin with respect to the smoothness, silkiness or other qualitative qualities that add wearability to the textile. It can also be called *fabric hand* or *fabric feel* because of the direct allusions to the degree of sensitivity and comfortability of the body when it is in contact with the fibre [1]. It is relevant to mention that depending on the preferences of the person who is wearing the textile in question, the variables that would determine its quality, and comfortability will vary, as this kind of evaluation is completely subjective [2].

The mechanical contact of the textile with the skin is what causes the presence or lack of comfort sensation. It can be clinging to a sweat-wetted skin, scratchy or too stiff, which is commonly felt as an unpleasant sensation, or it can be soft and smooth, sensations attributed to comfortability and pleasantness. Furthermore, some textiles can even produce irritations when they contact the skin through mechanical contact. That one would be classified as uncomfortable textiles. [3] Smart textiles are highly likely to produce this kind of effect due to the conductive yarns they might have in their structure.

The friction and the rugosity of the fabric and how they perform on human skin are also key factors to evaluate the comfort of the fabric. This contact and/or friction, together with the rugosity or smoothness of the textile, are what generate the sensation that is evaluated afterwards. Generally, the smoothness is associated with the commodity and given a good evaluation [4].

12.2 Key factors of comfort evaluation

More specific fabric sensations can be considered in the evaluation of the comfortability of a fibre, fabric or textile, are the following [5]:

Firstly, we can talk about the most genetic tactile sensations: prickly, tickling, rough, smooth, craggy, scratchy, itchy, picky, sticky.

As already mentioned, the frictional force plays an important role in the physical evaluation of a fibre or textile: an irregular or rough surface from the fibre will always generate more friction than a smooth one [6]. So, the force required to move the fabric along the skin during the fabric-skin contact is opposed by the frictional force created by that contact. When the applied force exceeds the frictional force, movement of fabric against the skin occurs. Frictional characteristics of sliding surfaces are often described by the coefficient of friction which is defined as the ratio of the drag force (parallel to one surface) to the normal force pressing on the contacting surface [7, 8].

Secondly, the sensations that moisture presence or absence can generate into the fibre, such as if it is clammy, damp, wet, sticky, sultry, non-absorbent, clingy.

Some studies suggest that the presence of moisture increases the friction between the fabric and the skin so the human sensation to the textile under these conditions is more rough than in a dry environment. In other words, the more presence of humidity the more friction and non-comfortability perception. So, the reaction to humidity becomes an important key to the sensorial comfort evaluation [9].

The number of filaments in a yarn also changes the sensation when touching a fabric: the higher the number of filaments, the softer the fabric will be. This is why microfilaments are used in some specific applications that need to generate a pleasant feeling in contact with the skin. When speaking about smart textiles, the conductive yarns have different properties than the yarns of the fabric, and the concept of microfilament is not used. Also the rigidity of the conductive yarns can play an important role in the smoothness of the fabric.

Some of these properties are easy to modify in synthetic fabrics rather than in natural fibres (specially the vegetal ones).

Then, the fit or adjustment to the body and how it feels, like snug, loose, lightweight, heavy, soft, stiff.

And, finally, it is also an important variable: the thermal sensations: cold, chill, cool, warm, hot.

12.3 Innovation & comfort

A field that demands a high performance of the textiles and such an accurate comfort sensation is essential is the sports clothing market. In this area of application, athletes do not only need to feel comfortable in normal conditions but for specific activities means that repeated movements for long periods that test the friction of the cloth with the skin, how the cloth reacts to the humidity and sweat, its resistance and protection to adverse climatic conditions (both high and low temperature environments),… So, indeed, that is the reason why the sports world exemplifies properly the evaluation of textiles comfort. Furthermore, the combination between innovation, sports and comfort is currently in the spotlight [10]. In that sense, an interesting compilation of examples is represented below [10]:

Figure 12.1 Sensoria smart products (Sleeveless t-shirt, Sports bra, socks and running shoes)

Sensoria trademark has developed several lines of smart products related with sport clothing. The range includes clothes from trainers and socks to t-shirts. The particularity of these innovative products are able to track heartbeat ratio, speed, calories and distance, among others.

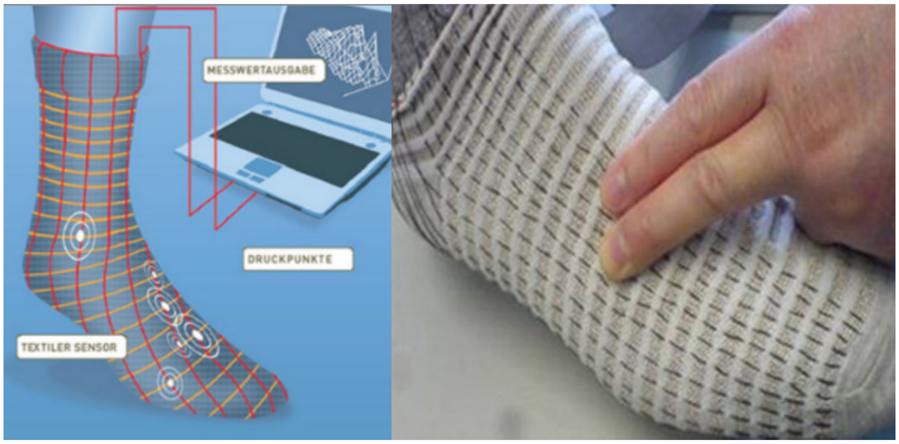

Figure 12.2 SmartSock from Alphafit to measure fit

SmartSock is a product with interesting properties and functions. It gives the possibility to evaluate how fit the foot is within the shoe.

Figure 12.3 Moov HR sweatband and swim cap

MOV HR is a sweatband that can track human constants such as the heart rate or provide more personalised inputs, as it can be connected and synchronised to earphones. Furthermore, it can be used under a swim cap.

Figure 12.4 Venture Heat Deluxe Heated Jacket Liner

Venture Heat Deluxe Heated Jacket Liner provides the person who wears it with a heating sensation that would soften the cold outside cold. It is particularly useful for motorbike riders.

All those items need a high level of comfort in order to perform correctly and do not disturb the athlete's activity.

12.4 Summary

At this point of the analysis, some affirmations are clear. On one side, the comfortability in textiles and clothing can be evaluated from multiple angles. And on the other side, we can infer the most considered variables, the better, as comfortability is, in a determinant percentage, a subjective quality. Still, for the general public, the tactile sensations related with softness and other conditions, linked to the humidity, are probably considered the most important variables that modules the comfort presence or absence.

And, finally, about the specific application of this comfortability in the new textiles generation, it is highlightable even the innovation endows the new products with new and multiple applications and improvements, the wearing sensation is never an aspect that should be forgotten.

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Chapter 13. PHOTONIC MATERIALS FOR SENSORIAL APPLICATIONS

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13.1 Introduction

Photonics is a field of study involving the use of radiation in the frequency spectrum of light by utilising the fundamental element of light, which is the photon. There is relevance between electronic applications and photonic applications: electronic applications use electrons and the photonic applications use the photon in a similar way. Photonics have specific advantages compared to electronics, and this is the reason for using them.

A variety of photonic components are already available and used in common applications, like Lasers, optical fibres, cameras and screens in mobile phones, optical tweezers, lighting in vehicles and buildings, computer screens and TVs and many more.

By the term “photonic materials” we refer to materials that emit, detect, manipulate or control light. Photonic devices emit, transfer and detect light and they are constructed using components like laser diodes, light-emitting diodes, solar and photovoltaic cells, displays and optical amplifiers.

13.2 Use of photonic materials in sensors

One common family of materials that are used as sensing elements are self-assembled colloidal crystals. They are crystals in micro or even nano-scale that are laid on a substrate, in a very fine dispersion. Usually they are produced from a solution. The structure and nature of the component materials determine the photonic band gap and the structural colour of these and for this reason, they are useful as sensing elements in various applications. [1].

Photonic sensors possess certain advantages compared to conventional electronic sensors. These are high sensitivity, low hysteresis, immunity to electromagnetic interference [2]

13.2.1 Materials

The available technologies and the use of photonic sensors have developed in the last years. The main categories of these materials are presented in Figure 13.1.

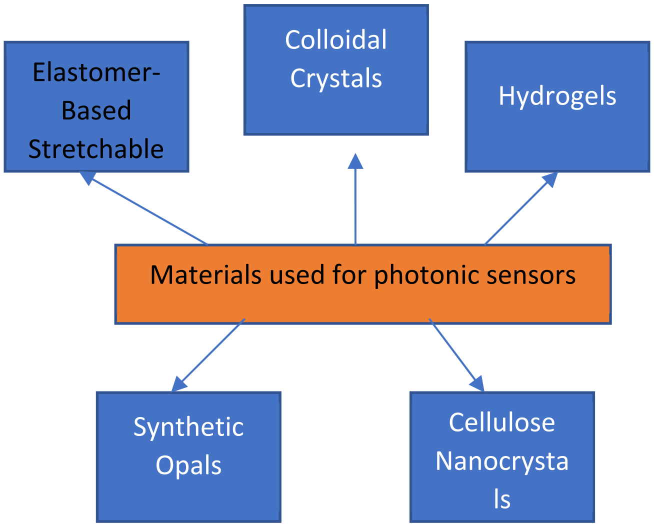

Figure 13.1 Materials used in photonic applications

13.2.2 Elastomer-Based Stretchable materials

A common component of smart textiles are functional stretchable materials and most often stretchable conducting elements. The substrate is usually an elastomeric that functions as either a matrix for conductive fillers and networks, or as a supporting material for conductive films, tracks, and functional devices [3]. The desired characteristic of elastomers is their flexible nature, meaning that they withstand strain forces and they can retain their original shape and form repetitively after the application of strain, for thousands of stretch/release cycles. Stretchable sensors provide functions like optical transparency, that facilitates optical applications in optoelectronics, photodetectors, light emitting devices, solar cells [4, 5].

Polydimethylsiloxane (PDMS) is the most widely used elastomeric material in relevant applications. It is a mineral- organic polymer containing Silicone and is a mature commercial product, since it is already in the market for a long time [6].

Moreover, elastomer materials have been used for the fabrication of electrical conductors. Most commonly used electrical conductors are constructed by (bulk) metal films, metallic nanowires, carbon-based nanomaterials, intrinsically conductive polymers, liquid metals, and ionic liquids.

Applications based on sensor elastomer-based materials have been fabricated, like strain gauges [7], pressure sensors [8], temperature sensors [9], gas sensors [10] and UV sensors [11].

13.2.3 Colloidal Crystals

Colloidal crystals are a sequence array structure composed of monodisperse, inorganic, or organic nanoparticles [12, 13]**.** All the interesting optical features associated with photonic crystals are due to the existence of energy bands [14].

Photonic crystals are classified according to their dimensions: one-dimensional (1D), two-dimensional (2D) and three-dimensional (3D) [15]. Colloidal crystals are classified in the category of the three dimensional photonic crystals.

Colloidal crystals have been reported to be integrated in time-temperature sensors [16].

A colloidal crystal based photonic sheet has been produced, by the application of mono-dispersed polystyrene (PS), on a polydimethylsiloxane (PDMS) substrate. According to the strain applied to the elastomer substrate and the deformation of it, the colour of the sheet is changing [17].

13.2.4.Hydrogels

Hydrogels are two phase materials, consisting of a liquid (that is usually water) and a porous and water permeable solid polymeric structure. Any change in their chemical synthesis (e.g. change in water concentration), produces a change in their mechanical properties (e.g. elasticity, shear strength etc.). Similar effect happens if they change their polymeric matrix structure. In this way, by tailoring their chemical properties and physical structure, they become sensitive to external stimuli and biocompatibility; they can be shaped in various structures and integrated into micro-systems [18].

Synthesis of Hydrogels is done in aqueous solutions by applying UV radiation [19], thermo-initiated radical polymerization [20], addition reaction [21], self-assembly of recognition motifs such as coiled-coils [22], peptides [23], hydrogen-bridges [24] or DNA [25].

Hydrogels can be used for sensors but can also act as sensors themselves. Another application of hydrogels is the possibility to be used as biosensors.

13.2.5 Synthetic Opals

Synthetic opals are man-made opals, meaning hydrated Silica SiO_2. They have the same chemical composition, internal structure, physical properties, and appearance as natural opals. They are also called lab-created opals, lab-grown opals, or cultured opals to indicate their man-made origin. Opals are crystals that can guide or trap light propagation, providing localization of light, which is a very desirable effect in photonic applications.

For example, a reference for synthetic opals composed of equal diameter a-SiO_2 spheres closely packed in 3D face-centred-cubic lattices with periods of about 200 nm, referred that they possess photonic stop bands throughout the visible spectrum (400–600 nm) [26].

13.2.6 Cellulose Nanocrystals

Cellulose in Nano form (nanoparticles- (NPs) are another promising new material in photonic applications. The properties of Cellulose NPs are quite different from the properties of cellulose in bulk form. Advanced sensing capabilities have been discovered for composite thin films made from cellulose Nanocrystals [27].

Applications of cellulose nanocrystals extend to a variety of sensor types such as pressure sensors, strain sensors, proximity sensors, gas and vapour sensors, biosensors, optical sensors, PH sensors, fluorescent sensors and electrochemical sensors [27].

Synthesis of cellulose Nanocrystals is usually done by the sulphuric acid hydrolysis method, a well-defined and established method. Already in use in some medical products, they definitely have a potential for wearable sensors [28].

13.3 Conclusion

Photonics applications have some advantages over electronics applications, mainly high sensitivity, low hysteresis and immunity to electromagnetic interference. Applications with optical fibres in smart textiles have been in place for quite some time, but they are restricted to the aesthetics part of the textile and do not provide any function. Use of photonics devices as light or chemical sensors in textiles, is based on micro- or nano-colloidal crystals that are deposited onto the textile substrate. These crystals are based on minerals like Silica e.g. mono-dispersed polystyrene on polydimethylsiloxane substrate or a-SiO2 micro crystals. A promising photonic material, with significant potential for wearable sensors is nano-crystals of cellulose.

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Chapter 14. DAMAGES ON E-TEXTILES

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14.1 Introduction

An active smart fabric that contains electronic elements in its composition, is called E-textile (smart textile). The electronic textiles are in fact wearable computing, or electronic devices, introduced into clothing designs. The smart fabrics can be used in interior design technologies. That supposes electronics components are introduced into fabrics or fibre [1]. Also, e-textile can be used in micro/nanofiber-based apparel, which have integrated electronics and which take off body- forms [3, 4].

E-textile are characterised through: elasticity, flexibility, and comfortability [2]. Depending on the field of use, e-textiles are also known as intelligent textiles, smart textiles, techno-textiles, wearable computers, wearable electronics [5, 6].

The multidisciplinary character of e-textiles, supposes:

-textiles (smart fabrics);

- digital electronics (wearable electronics);

-information technology (wearable computing) (Figure 14.1) [5].

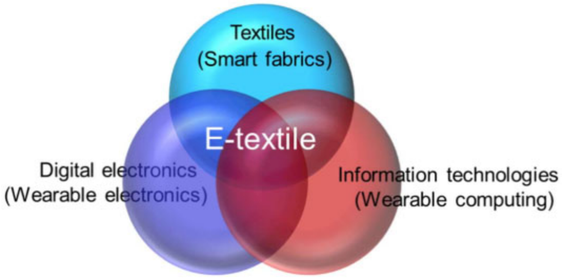

Figure 14.1 Multidisciplinary character of e-textiles.

14.2 Classification of e-Textiles

E -textiles can be classified in 3 categories [7]:

1. Passive e-textiles which are based on sensors which can sense the environment.
2. Active smart textile which reacts to stimuli from the environment, on base an actuator function and a sensing device. An example of active smart textile is in Figure 14.2 [8].

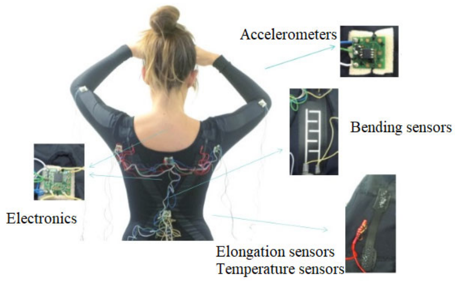

Figure 14.2 Active smart textile

3. Very smart textiles, which sense the environment stimuli, react and adapt their behaviour. The functions of e-textiles.
4. Very smart textiles: able to sense, react and adapt their behaviour to the given circumstances

The functions of e-textiles are presented in Figure 14.3.

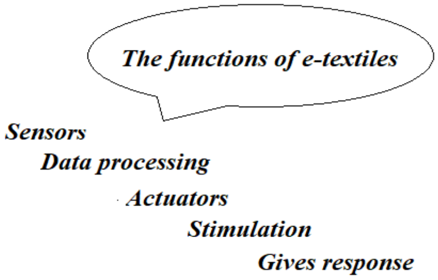

Figure 14.3 The functions of e-textiles

The sensors are necessary for capturing parameters from the environment. Active processing is for data processing and for responses by the resulting function of sensor (actuators). Stimulation is found from the environment.

Application of e textiles are for different activity fields and are presented in Figure 14.4 [7].

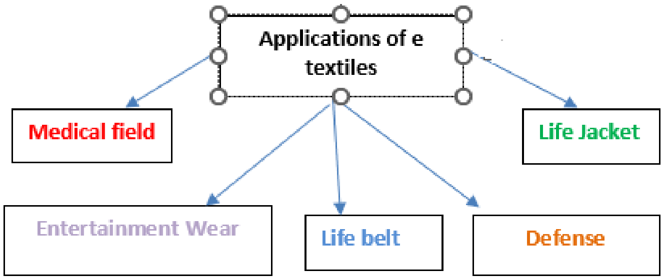

Figure 14.4 Applications of e textiles

Materials for e textiles

There are many types of materials (fibres, or in any other appropriate form, such as solder circuits, or as a printed layer) depending on electrical conductivity:

- metals;

- intrinsically conducting polymers;

conducting-particle/polymer (micro or nano) composites [7].

- environment, integrating an actuator function and a sensing device environment, integrating an actuator function and a sensing device.

Damages of e textiles

It is very important that e-textiles can be washed, but this is a big problem.

The factors which influence washing process (Sinners factors) are:

- the time;
- the temperature;
- the mechanical action;
- the chemistry/biology factors [8, 9].

The most common issues related to washing e-textiles are:

- Damages to conductive coatings and printed conductive structures (Figure 14.5) [10];
- Damages to metallization layers (Figure 14.6) [15];
- Damages to wires, conductive tracks and connections (Figure 14.7) [16];
- Damages to Protective Layers (Figure 14.8) [16];
- Textile Changes.

Figure 14.5 Damages to conductive coatings through washing

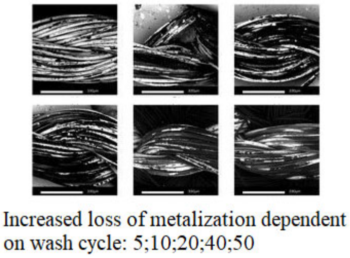

Figure 14.6 The metal quantity depend from cycles number

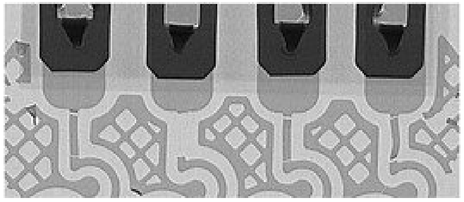

Figure 14.7 Cracks in cooper tracks at transition to contacting pads

Figure 14.8 Determination of protective layer along conductive tracks

After several washing cycles, the silver content increases, but the greatest silver loss is during the first few washing cycles [11] (Figure 14.6) [15]. The loss of metallization is dependent on the friction between the textile fabrics tested [12, 13]. Also, cyclic temperature changes during washing determine a mismatch of the thermal expansion coefficient in the involved materials, which leads to damages [14]. Breakages in the metal (at the transition from conductive area to contacting pads) can be observed when washing strips of flexible circuit board woven into textiles (Figure 14.7) [16].

Damages in the protective layers are dependent on the harshness of the washing program (the frictional forces acting on the samples will lead to thinning and eventual breaks of the PU layer) (Figure 14.8) [17].

Another damages during washing are:

- changes and damages to the textile substrate;
- wrinkling in test samples [18];
- pilling [17];
- entangling of fibres [19];
- the loss of fabric pre-treatment after washing [20];
- corrosion on some of washed conductive yarns;
- a darkening of the surface, indicating the oxidation of the silver coating [21].

14.3 Conclusions

Washing can lead to numerous issues in e-textiles. These failures can occur at specific points in the design or all over, depending on the type and composition of the e-textile. Weak points are contacts between different materials and components as well as transition areas within the same material. In conductive yarn or textiles without some form of protection, damages can occur throughout the structure. For now the damage types in e-textile research into single aspects of e-textile washability needs to be conducted.

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Chapter 15. WASHABILITY OF E-TEXTILES, STANDARDS AND NORMS

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15.1 Introduction

Washing electronic textiles (e-textiles) or textiles with conductive capacity is one of the challenges or weak points of this type of innovative product.

The main reason why electronic textiles are vulnerable to washing is because of their sensitivity to water. Contact with this element exposes them to the loss of their properties.

Nowadays, there are several procedures that evaluate and validate that an e-textile has sufficient quality to continue fulfilling its functions after a certain number of washes.

The fact that there are different standards for e-textile washing processes and that none of them is agreed upon by the scientific community is a difficulty for the textile sector and for this type of product. This lack of consensus means that there is no homogeneous regulation recognized by everyone and, therefore, means that the same product can be suitable and functional after a certain number of washes according to one procedure, but be unsatisfactory according to another type of procedure or standard that requires other criteria to be met [1].

The unification or universalization of the criteria used to certify that an electronic textile is suitable, not only in the first moment after its manufacture but for the daily life of the user (and this implies a certain number of daily washing) [1].

15.2 E-textiles deterioration during the washing process

During the washing of an e-textile, the fabric can suffer various damages related to the ageing of the piece, as well as changes in its shape or colour (beyond the loss of properties already mentioned) [1].

Due to experiencing one or more of the already mentioned damages, an e-textile may suffer the following secondary effects:

- Changes in its electrical properties, such as loss of conductivity.
- Changes in its functionality, such as one or more of its components (such as LEDS) ceasing to function.
- Changes in its characteristics, such as, for example, changes in the sensors.
- Changes in its appearance, such as darkening of the surface, wrinkles or shrinkage.

The appearance of these changes, or not, after a certain number of washes is used as an indicator to evaluate the profitability of electronic textiles.

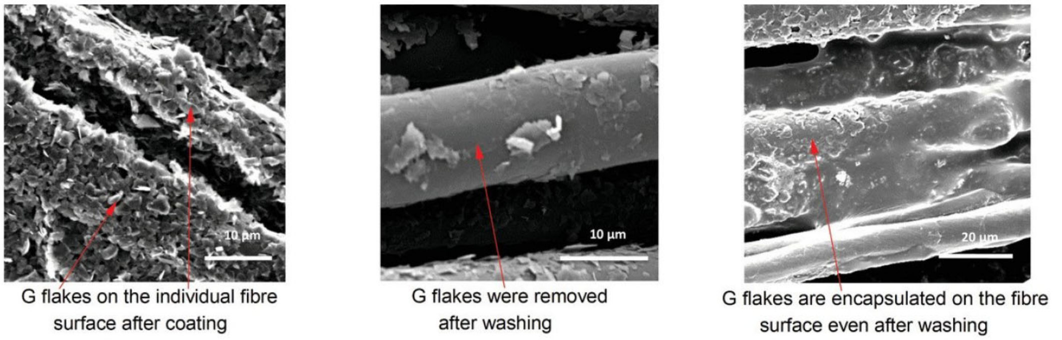
15.3 Vulnerability characteristics of electronic textiles

Washing e-textiles can cause errors and failures, and their previous characteristics will define what vulnerabilities or resistances they will have to one or more washing processes.

A key element is the type and composition of the product, that is, the material it is made of and how the fabric and thread relate to the components that make up the garment. For example, an electronic textile that is integrated by conductive elements between device and device (directly exposed to water) will be highly susceptible to degradation. Or, a conductor that has this function, but is not protected, will also be exposed to rapid degradation.

At the same time, it is worth saying that electronic textiles that integrate components that are protected, encapsulated in some way, are much more resistant to washing and avoid degradation much more often than conductive parts.

In addition, these components are resistant enough to avoid detaching from the piece in whole or in part. Examples of deterioration of electronic textiles:



G flakes on the individual fibre surface after coating

G flakes were removed after washing

G flakes are encapsulated on the fibre surface even after washing

Figure 15.1 Example of damages to conductive textile coatings after washing [2]

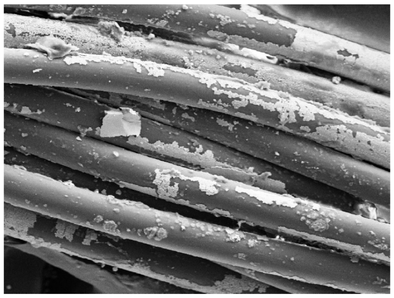


Figure 15.2 Depleted silver layer on nylon filaments [3]

15.4 Current situation of standardisation

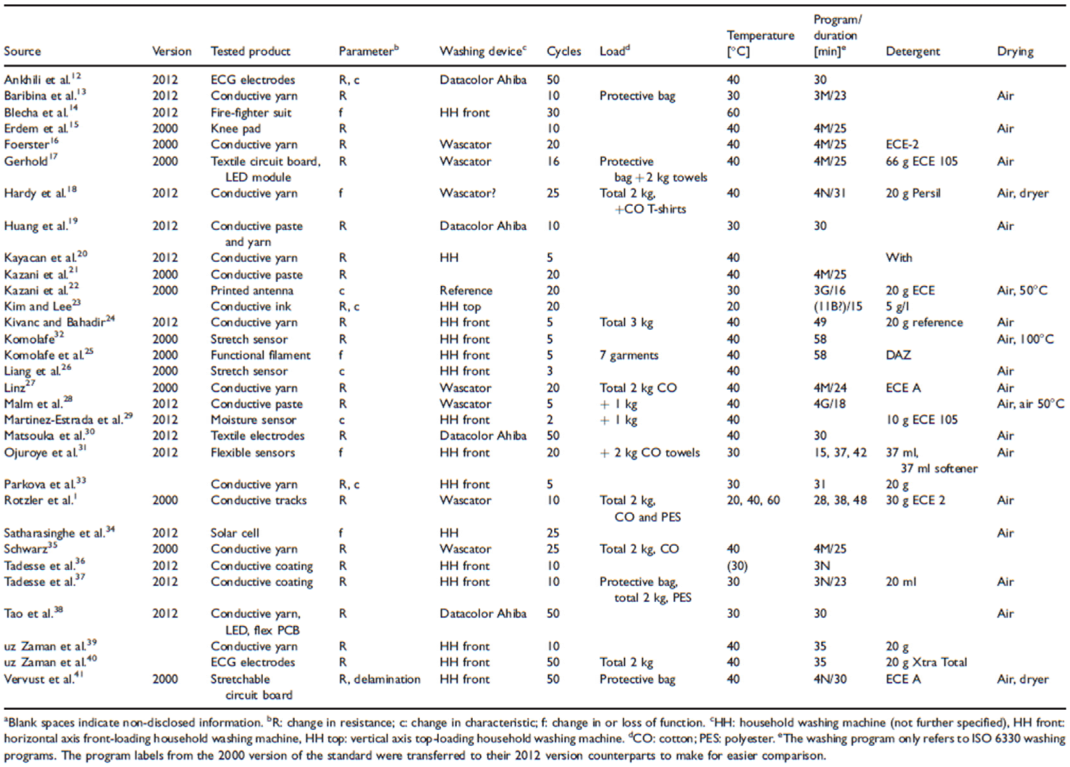
As mentioned, standards for the washability evaluation and several and there is not any general rule or indication for a global standardisation [4].

Still, several standards and methods have been tested and they are the reference for the evaluation of many electronic textiles. The main items they consider indicating the way the product should be washed and so, preserving its characteristics are the following [4]: the type of washing device, the program duration, the amount of wash load, the washing temperature, the type of detergent or the drying method [4].

The number of existing standards especially conceived for hybrid e-textiles to date is very low. Of the existing ones, most cover either terminology and/or definitions like ISO/PRF TR 23383 and ASTM D 8248:2020. Others give test methods for resistance measurement of textile-based products: AATCC 76 for fabrics, AATCC 84 for yarns, and CSN EN 16812 for conductive tracks on textiles.

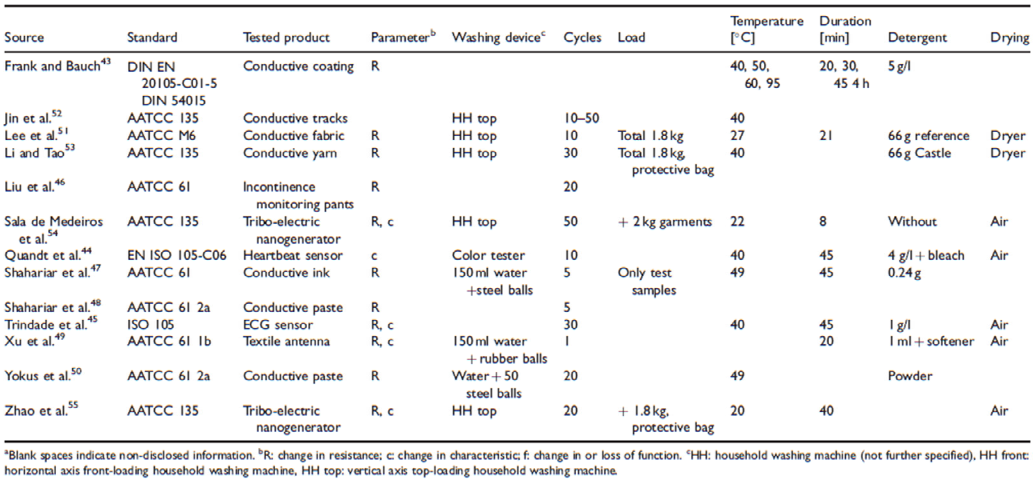
The most commonly used standard from adjacent fields when testing the washability of e-textiles is ISO 6330 Textiles—domestic washing and drying procedures for textile testing. The scope of the standard includes not only textiles, but also “other textile articles”—a term that can be applied to hybrid smart or e-textiles—allowing for the standard to be extended for their testing. Not included in the standard are guidelines or recommendations concerning the number of wash cycles that should be conducted nor criteria on how washing reliability can be assessed after testing.

Figure 15.3 Wash testing according to ISO 6330 [4]



Source	Version	Tested product	Parameter[b]	Washing device[c]	Cycles	Load[d]	Temperature [°C]	Program/ duration [min][e]	Detergent	Drying
Ankhili et al.[12]	2012	ECG electrodes	R, c	Datacolor Ahiba	50		40	30		
Baribina et al.[13]	2012	Conductive yarn	R		10	Protective bag	30	3M/23		Air
Blecha et al.[14]	2012	Fire-fighter suit	f	HH front	30		60			
Erdem et al.[15]	2000	Knee pad	R		10		40	4M/25		Air
Foerster[16]	2000	Conductive yarn	R	Wascator	20		40	4M/25	ECE-2	
Gerhold[17]	2000	Textile circuit board, LED module	R	Wascator	16	Protective bag + 2 kg towels	40	4M/25	66 g ECE 105	Air
Hardy et al.[18]	2012	Conductive yarn	f	Wascator?	25	Total 2 kg, +CO T-shirts	40	4N/31	20 g Persil	Air, dryer
Huang et al.[19]	2012	Conductive paste and yarn	R	Datacolor Ahiba	10		30	30		Air
Kayacan et al.[20]	2012	Conductive yarn	R	HH	5		40		With	
Kazani et al.[21]	2000	Conductive paste	R		20		40	4M/25		
Kazani et al.[22]	2000	Printed antenna	c	Reference	20		30	3G/16	20 g ECE	Air, 50°C
Kim and Lee[23]		Conductive ink	R, c	HH top	20		20	(11B?)/15	5 g/l	
Kivanc and Bahadir[24]	2012	Conductive yarn	R	HH front	5	Total 3 kg	40	49	20 g reference	Air
Komolafe[32]	2000	Stretch sensor	R	HH front	5		40	58		Air, 100°C
Komolafe et al.[25]	2000	Functional filament	f	HH front	5	7 garments	40	58	DAZ	
Liang et al.[26]	2000	Stretch sensor	c	HH front	3		40			Air
Linz[27]	2000	Conductive yarn	R	Wascator	20	Total 2 kg CO	40	4M/24	ECE A	Air
Malm et al.[28]	2012	Conductive paste	R	Wascator	5	+ 1 kg	40	4G/18		Air, air 50°C
Martinez-Estrada et al.[29]	2012	Moisture sensor	c	HH front	2	+ 1 kg	40		10 g ECE 105	
Matsouka et al.[30]	2012	Textile electrodes	R	Datacolor Ahiba	50		40	30		Air
Ojuroye et al.[31]	2012	Flexible sensors	f	HH front	20	+ 2 kg CO towels	30	15, 37, 42	37 ml, 37 ml softener	Air
Parkova et al.[33]		Conductive yarn	R, c	HH front	5		30	31	20 g	
Rotzler et al.[1]	2000	Conductive tracks	R	Wascator	10	Total 2 kg, CO and PES	20, 40, 60	28, 38, 48	30 g ECE 2	Air
Satharasinghe et al.[34]	2012	Solar cell	f	HH	25					Air
Schwarz[35]	2000	Conductive yarn	R	Wascator	25	Total 2 kg, CO	40	4M/25		
Tadesse et al.[36]	2012	Conductive coating	R	HH front	10		(30)	3N		
Tadesse et al.[37]	2012	Conductive coating	R	HH front	10	Protective bag, total 2 kg, PES	30	3N/23	20 ml	Air
Tao et al.[38]	2012	Conductive yarn, LED, flex PCB	R	Datacolor Ahiba	50		30	30		Air
uz Zaman et al.[39]		Conductive yarn	R	HH front	10		40	35	20 g	
uz Zaman et al.[40]		ECG electrodes	R	HH front	50	Total 2 kg	40	35	20 g Xtra Total	
Vervust et al.[41]	2000	Stretchable circuit board	R, delamination	HH front	50	Protective bag	40	4N/30	ECE A	Air, dryer

[a] Blank spaces indicate non-disclosed information. [b] R: change in resistance; c: change in characteristic; f: change in or loss of function. [c] HH: household washing machine (not further specified), HH front: horizontal axis front-loading household washing machine, HH top: vertical axis top-loading household washing machine. [d] CO: cotton; PES: polyester. [e] The washing program only refers to ISO 6330 washing programs. The program labels from the 2000 version of the standard were transferred to their 2012 version counterparts to make for easier comparison.

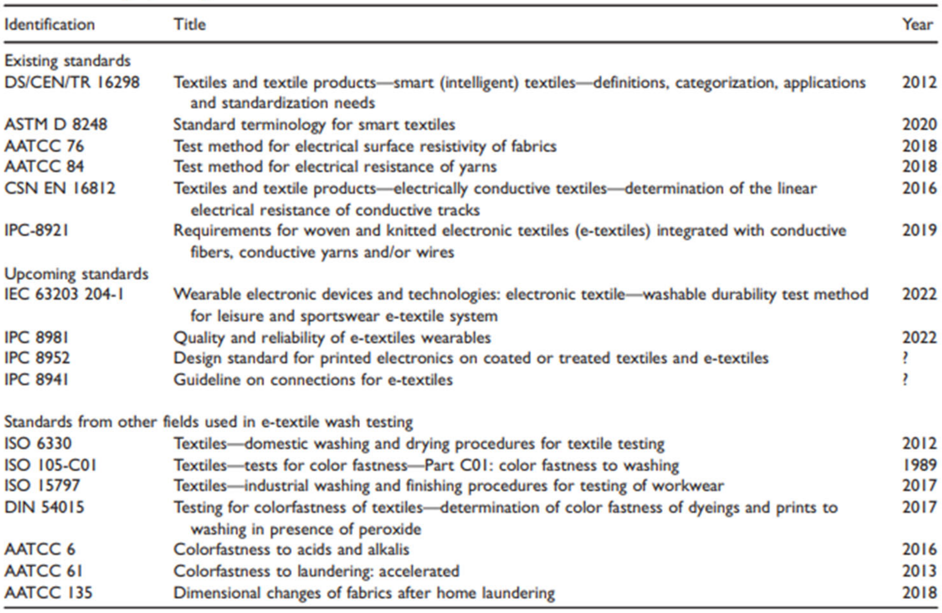


Source	Standard	Tested product	Parameter[b]	Washing device[c]	Cycles	Load	Temperature [°C]	Duration [min]	Detergent	Drying
Frank and Bauch[43]	DIN EN 20105-C01-5 DIN 54015	Conductive coating	R				40, 50, 60, 95	20, 30, 45 4 h	5 g/l	
Jin et al.[52]	AATCC 135	Conductive tracks		HH top	10–50		40			
Lee et al.[51]	AATCC M6	Conductive fabric	R	HH top	10	Total 1.8 kg	27	21	66 g reference	Dryer
Li and Tao[53]	AATCC 135	Conductive yarn	R	HH top	30	Total 1.8 kg, protective bag	40		66 g Castle	Dryer
Liu et al.[46]	AATCC 61	Incontinence monitoring pants	R		20					
Sala de Medeiros et al.[54]	AATCC 135	Tribo-electric nanogenerator	R, c	HH top	50	+ 2 kg garments	22	8	Without	Air
Quandt et al.[44]	EN ISO 105-C06	Heartbeat sensor	c	Color tester	10		40	45	4 g/l + bleach	Air
Shahariar et al.[47]	AATCC 61	Conductive ink	R	150 ml water +steel balls	5	Only test samples	49	45	0.24 g	
Shahariar et al.[48]	AATCC 61 2a	Conductive paste	R		5					
Trindade et al.[45]	ISO 105	ECG sensor	R, c		30		40	45	1 g/l	Air
Xu et al.[49]	AATCC 61 1b	Textile antenna	R, c	150 ml water + rubber balls	1			20	1 ml + softener	Air
Yokus et al.[50]	AATCC 61 2a	Conductive paste	R	Water + 50 steel balls	20		49		Powder	
Zhao et al.[55]	AATCC 135	Tribo-electric nanogenerator	R, c	HH top	20	+ 1.8 kg, protective bag	20	40		Air

[a] Blank spaces indicate non-disclosed information. [b] R: change in resistance; c: change in characteristic; f: change in or loss of function. [c] HH: household washing machine (not further specified), HH front: horizontal axis front-loading household washing machine, HH top: vertical axis top-loading household washing machine.

Figure 15.4 Wash testing according to other standards [4]

In the following figure some of the standards related to e-textiles are shown, classified depending on their current state. From the European point of view, it is important to mention that no ISO standards are used for e-textiles currently.



Identification	Title	Year
Existing standards		
DS/CEN/TR 16298	Textiles and textile products—smart (intelligent) textiles—definitions, categorization, applications and standardization needs	2012
ASTM D 8248	Standard terminology for smart textiles	2020
AATCC 76	Test method for electrical surface resistivity of fabrics	2018
AATCC 84	Test method for electrical resistance of yarns	2018
CSN EN 16812	Textiles and textile products—electrically conductive textiles—determination of the linear electrical resistance of conductive tracks	2016
IPC-8921	Requirements for woven and knitted electronic textiles (e-textiles) integrated with conductive fibers, conductive yarns and/or wires	2019
Upcoming standards		
IEC 63203 204-1	Wearable electronic devices and technologies: electronic textile—washable durability test method for leisure and sportswear e-textile system	2022
IPC 8981	Quality and reliability of e-textiles wearables	2022
IPC 8952	Design standard for printed electronics on coated or treated textiles and e-textiles	?
IPC 8941	Guideline on connections for e-textiles	?
Standards from other fields used in e-textile wash testing		
ISO 6330	Textiles—domestic washing and drying procedures for textile testing	2012
ISO 105-C01	Textiles—tests for color fastness—Part C01: color fastness to washing	1989
ISO 15797	Textiles—industrial washing and finishing procedures for testing of workwear	2017
DIN 54015	Testing for colorfastness of textiles—determination of color fastness of dyeings and prints to washing in presence of peroxide	2017
AATCC 6	Colorfastness to acids and alkalis	2016
AATCC 61	Colorfastness to laundering: accelerated	2013
AATCC 135	Dimensional changes of fabrics after home laundering	2018

Figure 15.5 State of e-textiles standardisation

15.5 Conclusions

Washability is one of the key questions for e-textiles. Equally to what they are able to offer when the conductivity and devices are added in the product.

A simple wash can destroy the whole technology the product has been endorsed for, so, the way the textile is confectioned and the way it is washed will play a relevant role in the success of its cleaning (that means no loss of properties).

For that, a common standardisation is key. General rules would facilitate the development of this kind of products, as they would be developed following certain standards from the beginning and all producers would play with the same rules.

The main limitation found up until now, is about the policy makers. Even the investigations done until the moment guide a significant part of the e-textiles producers and it can be said around a 60% follow the existing standards, the institutions that have competences to regulate these standards have not set them.

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Chapter 16. ECO-DESIGN FOR SMART TEXTILE DEVELOPMENT

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16.1 Introduction

The ongoing process of innovation in the smart textiles sector could clash with the purposes of policies concerning environment and waste. It can be expected, considering contemporary examples of e-textiles, that existing systems for take-back and recycling of e-waste or old textiles are not designed to process raw materials of this kind.

16.2 Recent trends in the innovation process

E-textiles can be conceived as a forerunner of smart technologies that will permeate our lives in the future. These products are described as "*fashionable technology*" which main features are uniqueness and advanced functionality combined with a sense for fashion and aesthetics. [1] Wearable computing evidences a far-reaching vision of computing devices being embedded into garments in an inconspicuous way. Researchers and enterprises from the electronic and the textile sectors pursue the development of e-textiles. The figure below (16.1) represents the convergent technological innovation as materials and devices from distinct domains of technology are mixed in the same product.

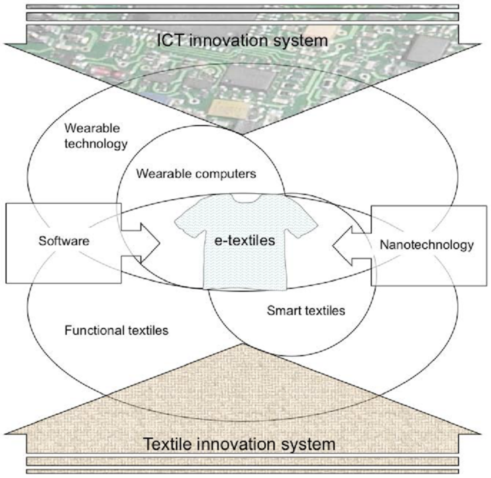


Figure 16.1 E-textiles in the innovation system of textiles and electronics sector [2]

The organisation of new design concepts is required by the convergence of textiles and electronics, especially for materials composition and configuration of components. The main features of textile integrated electronics should be flexibility, stretchability, and foldability. E-textiles must become comfortable, fashionable, and washable while retaining their smart functionality over many use-cycles for a better user experience. Successful realisation of e-textiles therefore necessitates new design and configuration paradigms as well as new materials and technologies. An interdisciplinary community of designers, crafters, and fashion artists branch out the development of e-textiles as they handcraft textile-electronic components and make their concepts openly accessible via blogs, websites, and workshops [3].

16.3 End-of-life impacts of e-textiles

One of the phenomena that makes high-tech products turn to waste is known as progressive obsolescence: they are replaced by newer models after a relatively short lifespan. E-textiles are subject to this kind of obsolescence in that they combine short-lived electronics with the fleeting fashion trends that govern the apparel market. The findings of a technology assessment study suggest that old e-textiles will emerge as a new category of waste soon after their introduction on the consumer mass markets [4]. These products could also lead to increasing consumption of batteries, which need to be disposed of when exhausted. In that, they resemble the contemporary e-waste problem. But discarded e-textiles also pose new issues that result from their unique properties: the dispersion of electronic materials within large amounts of textile waste will make it difficult to recover valuable materials from a low-grade feedstock [5]. Moreover, potentially hazardous substances are also dispersed and therefore hard to separate for safe disposal. From today’s perspective environmentally benign management of waste e-textiles is not guaranteed for the following reasons:

(1) Large mass flows of waste e-textiles can be expected if e-textiles experience breakthrough on mass markets [6].

(2) The emissions of hazardous substances could be a consequence of landfilled or incinerated e-textiles but also occupational health risks when e-textiles undergo recycling processes.

(3) Textile-embedded electronic components contain small amounts of scarce materials which are scattered across large textile surface areas and hard to recover. It appears hardly feasible to process such blended feedstock by means of existing recycling facilities. Recovering minute amounts of valuable materials from a large mass flow of textile bulk materials is technically and economically difficult. Without recycling, there exists a risk that mass application of e-textiles accelerates the depletion of scarce resources, such as technology metals and resources for fibre production.

16.4 Eco-design of e-textiles: the challenges

The goal of e-textile developers is to seamlessly integrate electronics into textiles, however until that goal is not completely achieved, exact e-textile qualities are yet unknown.

Because of this, it is challenging to predict potential end-of-life issues and to develop waste minimization design recommendations. For instance, the recommendation made by Design for Recycling to utilise snap-fit fasteners (instead of screws) for plastic electrical device covers is useless if the they are sewn or embroidered onto fabrics [7]. If electronic components are to be bonded onto cloth, it will also be challenging to design them for simple disassembly in the conventional manner. The DfR principle, which restricts the use of plastic parts with surface metallization, it is in contradiction with the usage of metal coated yarns for e-textiles. This means that innovative design ideas must be created in combination with e-textiles' innovation process.

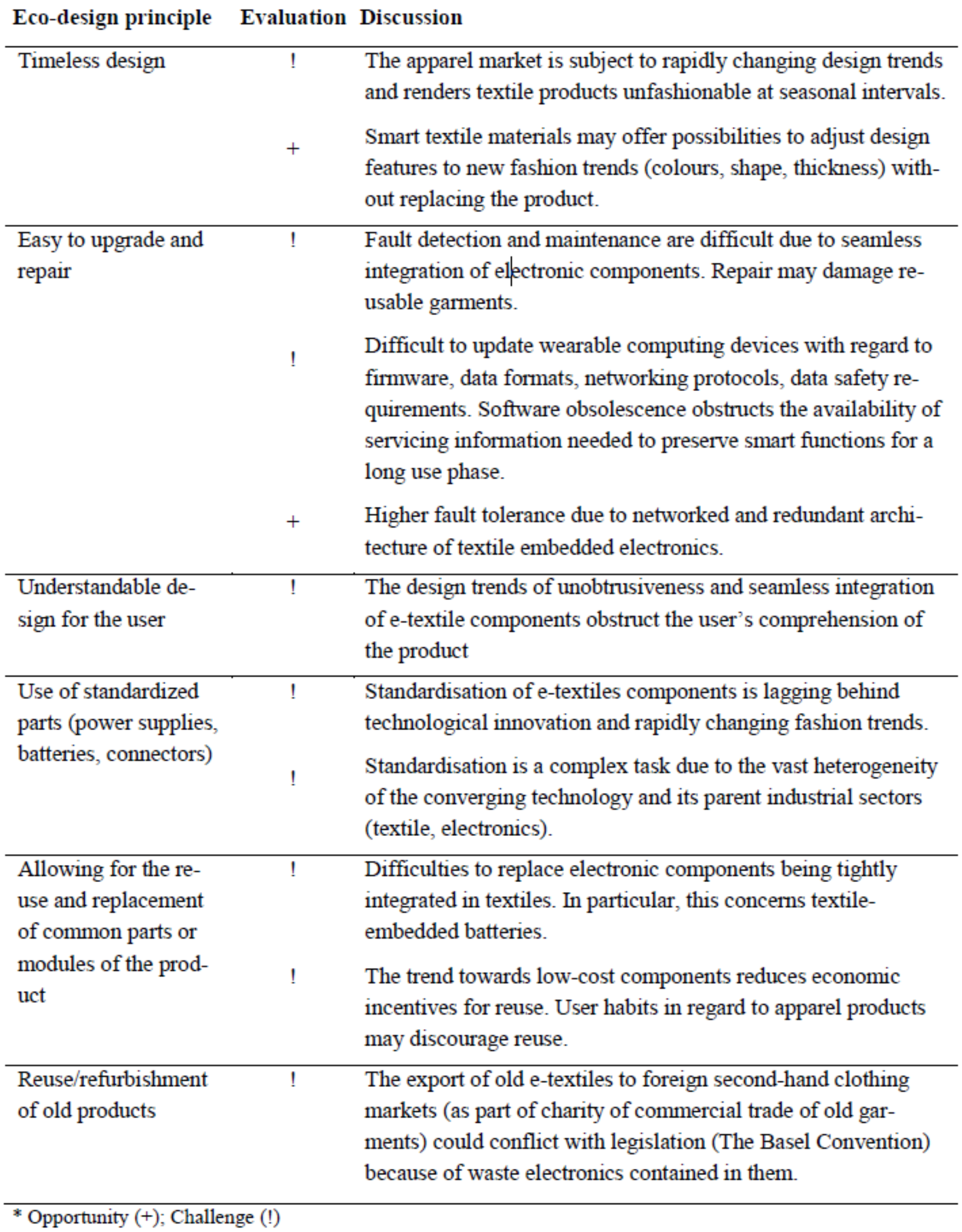
The Tables 16.1–16.2 show eco-design principles related to waste prevention and end-of-life treatments. They were adopted from the ECMA-standard 341 [8] and the Green Electronics Council [9].

Table 16.1 Challenges and opportunities for eco-design referring to material efficiency

Eco-design principle	Evaluation	Discussion
Reduce the diversity of materials in the product	!	The amalgamation of electronic and textile components increases the variety of materials found in a product.
	+	The use of conjugated polymers (conductive or semi-conductive plastics) can reduce the amount of metallic components. Innovations in organic electronics can stimulate the design of e-textiles free of metals and silicon.
Reduce the weight of the product	+	Trend towards flexible thin-layer electronic components can pave the way for to weight savings and increased resource efficiency,
	+	Lightweight textile materials can replace solids (plastic, metals) as casing or backing material in devices,
	!	Increasing number of devices used per person can outweigh savings.
Using renewable materials	+	Natural fibres (e.g. cotton, hemp, kenaf, bamboo) can replace plastics as casing or backing material. This helps in reducing the consumption of fossil resources and lowers the carbon footprint of products.
Using recycled materials	+	Textile materials can, by virtue of their flexibility, be easier refurbished or remanufactured into new products than those rigid materials typically found in electronics.

* Opportunity (+); Challenge (!)

Table 16.2 Challenges and opportunities for eco-design referring to product obsolescence



Eco-design principle	Evaluation	Discussion
Timeless design	!	The apparel market is subject to rapidly changing design trends and renders textile products unfashionable at seasonal intervals.
	+	Smart textile materials may offer possibilities to adjust design features to new fashion trends (colours, shape, thickness) without replacing the product.
Easy to upgrade and repair	!	Fault detection and maintenance are difficult due to seamless integration of electronic components. Repair may damage reusable garments.
	!	Difficult to update wearable computing devices with regard to firmware, data formats, networking protocols, data safety requirements. Software obsolescence obstructs the availability of servicing information needed to preserve smart functions for a long use phase.
	+	Higher fault tolerance due to networked and redundant architecture of textile embedded electronics.
Understandable design for the user	!	The design trends of unobtrusiveness and seamless integration of e-textile components obstruct the user's comprehension of the product
Use of standardized parts (power supplies, batteries, connectors)	!	Standardisation of e-textiles components is lagging behind technological innovation and rapidly changing fashion trends.
	!	Standardisation is a complex task due to the vast heterogeneity of the converging technology and its parent industrial sectors (textile, electronics).
Allowing for the reuse and replacement of common parts or modules of the product	!	Difficulties to replace electronic components being tightly integrated in textiles. In particular, this concerns textile-embedded batteries.
	!	The trend towards low-cost components reduces economic incentives for reuse. User habits in regard to apparel products may discourage reuse.
Reuse/refurbishment of old products	!	The export of old e-textiles to foreign second-hand clothing markets (as part of charity of commercial trade of old garments) could conflict with legislation (The Basel Convention) because of waste electronics contained in them.

* Opportunity (+); Challenge (!)

16.5 Eco-design techniques for e-textile durability and recycling

Sustainable design concepts for e-textiles should focus on waste prevention. Designers should search for possibilities to prolong the useful life of e-textiles. This could be achieved by designing products for repair, refurbishment, and re-use. The couture sector has brought about examples of upcycling old garments [10]. These experiences can inspire the design of high-tech apparel to be future vintage clothing rather than waste. If fashion changes, smart materials and technologies can be deployed to make products reconfigurable in that they adjust their looks. This would help in delaying obsolescence and prevent waste. Design for upcycling of e-textiles implies that faulty electronic components can be replaced without damaging the fabric. The environmentally conscious application of advanced technologies and materials can expedite the innovation process in sectors such as polymer electronics.

There are opportunities to reduce the consumption of primary resources by using recycled fibres and to avoid the use of hazardous substances. Textile materials can replace problematic components in electronic products. The use of miniaturised ICT-devices can pave a way to reduce resource consumption if small devices replace the functions of larger ones. Moreover, opportunities exist for decreasing the consumption of scarce metals if polymer electronics replace silicon-based electronics.

During the use phase, it's crucial to keep battery and electrical usage to a minimum. In the housing and packaging of electronics, for instance, environmentally friendly textile materials could take the place of conventional materials. Push-buttons, Velcro strips, or sewn-in pouches are examples of common textile accessory parts that can be used to install electronics on textiles in DfR-friendly methods (aiming at minimising the disassembly time).

Smart materials and bio-inspired design principles can achieve many desired tasks without the usage of electronic components [11]. The biomimetic design principles of smart textiles, such as self-healing fabric and wrinkle- or tear-resistance, are discussed by Singh et al.

Self-healing nanotechnology enables the development of products that can repair themselves and are less likely to be damaged. Switchable materials open up new design options for recyclable artefacts since they enable self-disassembly methods [12]. Destructible yarns or adhesives that break down when exposed to heat, microwaves, or magnetic fields could be created using stimuli-responsive polymers [13]. Such technologies might be able to economically deconstruct significant quantities of wasted post-consumer e-textiles if they are placed in automated recycling plants.

16.6 Conclusion

There are still concrete challenges that hamper the mass breakout of e-textiles. Among them the need for a new design and configuration paradigms able to assure comfort and washability while retaining the smart functionalities over many use cycles. New technologies and innovative techniques to recover the material once the products are disposed, to efficiently separate the components and save large amounts of material and to avoid the dispersion of potentially hazardous substances. In order to do so it would be important to follow specific eco-design principles focused on waste prevention, designing products for repair, refurbishment, and re-use.

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Chapter 17. ORGANIC AND INORGANIC SMART TEXTILE MATERIALS

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17.1 Introduction

The so-called smart and interactive textile industry has grown significantly during the past thirty years. With the introduction of novel fibres, new fabrics, and cutting-edge processing techniques, demand for smart textile materials and their applications is expected to increase. Additionally, washable, flexible, light-weight, and strong e-textiles are in high demand. These characteristics are influenced by the initial material's characteristics, the post-treatment, and the integration methods.

An e-textile can be created by using various surface techniques to apply a conductive component to the surface of a textile substrate or by creating a textile substrate from metals and naturally conductive polymers and using them to create fibres, yarns, and textiles. Additionally, it is possible to include conductive filament fibres or yarns onto traditional textile substrates both during and after the creation of the textile fabric by embroidering. The complete smart textile component can be printed in 3D, layer by layer, and the idea of 4D could be crucial in elevating the prestige of smart textiles to a new level [1].

17.2 Classification of smart textiles

Smart textiles are materials and structures that sense and react to environmental conditions or stimuli and they can react on themselves. The expressions of “smart” and “intelligent” textiles or “wearable electronic” textiles are used like synonyms. This is why the definition is determined only by the context, in fact smart or intelligent textile materials are functional materials actively interacting with their environment. On the other hand, smart or intelligent textile systems are systems exhibiting an intended and exploitable response as a reaction either to changes in its surroundings or to an external input. Figure 17.1 shows an illustration of a bionic bra created by Steele et al. that uses artificial muscle technology and electro-material sensors to detect an increase in breast motion and then respond by providing more support for active living.

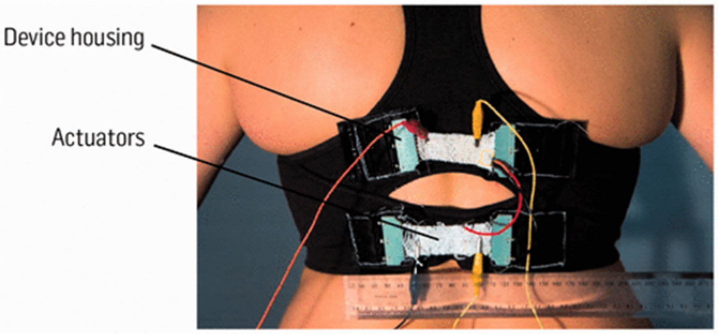

Figure 17.1 Bionic bra

Smart textiles can be divided into three subgroups:

- Passive
- Active
- Very smart or intelligent smart textiles.

Smart textiles can be divided into three categories:

Electronic components, conductive polymers, encapsulated phase change materials, shape memory materials, and other electronic sensors and communication tools can all be used to create them. According to Dadi's 2010 research, these materials respond to their surrounding stimuli in accordance with how they were constructed [3]. The first generation of wearable motherboards has already been created. These motherboards contain sensors built into clothing that can detect injuries and health information about the wearer and transfer that information remotely to a hospital.

17.3 Smart Textile Systems' Components

Smart textiles with sensing and actuating capabilities for the desired use have been produced as a single-purpose textile. However, the entire smart textile system could have specific function building blocks such as sensor, actuator, interconnection, a controlling unit, communication device, and power supply. In Figure 17.2 we can see a schematic representation of a smart textile system.

Figure 17.2. Function of smart textiles [4]

Sensors: A sensor is an electronic component that detects a physical property and recording or responding to it. Typical textile-integrated sensor types include textile electrodes for strain, humidity, temperature, pressure, light, molecule detection, electrocardiography, electromyography and electroencephalography.

Actuator: Actuators perform actions including moving objects, releasing materials, and creating sounds by acting on an effect supplied from the sensor, potentially after first sending this effect through an information processor. Common examples of textile actuators introduced are, organic light-emitting diodes, phase changing materials, temperature regulating textiles, and sound-generating textile [5].

Data processing: A processor appropriate for the intended use is needed in smart textiles in order to process the parameters acquired by the sensors and provide the necessary output. Only when the textile is actively processing information is the information processing element required.

Communication Device: This is a unit integrated to transmit and receive electronic data and/or information from and to another system, respectively.

Storage: The power supply unit is a part that is used to power the system. Due to their compact ease, lithium polymer (LiPo) batteries are frequently utilised for smart textiles. However, recently developed capacitors and energy harvesting systems based on textiles might be able to take their place in some applications [6].

17.4 Conductive Materials

Electrically conductive textiles are used in many applications of smart textile materials but conventional textile materials are usually insulating ones so they cannot be used directly for smart textile applications that require electrical conductivity. However, it is possible to obtain electrically conductive textiles by integrating metallic wires, conductive polymers, or other conductive compounds into the textile structure. To impart conductivity, non-textile metallic filament wires made from silver, stainless steel, nickel, aluminium, and copper can be inserted into the textile structure. Metals provide high conductivity which is very important for some smart textile applications but increases the weight of the material and affects their flexibility. Moreover, some metals are prone to corrosion. Metal-based conductive textiles can also be produced by coating metal ink on the surface of textile materials, but these have limitations in wash stability. Looking for alternative conductive compounds is fundamental to know how to produce reliable conductive textiles with better flexibility. The conductive materials for textile materials can be categorised as:

1. Conductive inks.
2. Carbon-based conductive polymers.
3. Intrinsically conductive polymers.
4. Conductive polymer composites.

17.5 Conductive Inks

The development of functional printable inks with various nanoscale sizes and architectures is considered as a key factor in the success of inkjet printing for printed electronics. Conductive inks may have the appearance of plates, nanowires, nanotubes, or other three-dimensional nanostructured materials. There are many options available for the printable ink, including conductive, semi-conductive, and dielectric inks. Conducive metal nano- and micro-particles can be used to create conductive inks. Organic polymers, inorganic semiconductors, and metal oxides can all be used to create semi-conductive inks. Organic polymers in solvents, organic polymer thermosets, or organic polymers packed with ceramics are the dielectric inks. Metals, metal oxides, conductive polymers, organometallic inks, graphene, carbon nanotubes, and mixtures of the various inks can all be used to create useful conductive inks [7].

17.6 Carbon-Based Conductive Materials

The development of electrically conductive fabrics has been studied using carbon-based materials like graphene, carbon nanotubes (CNT), carbon black, graphene oxide, and reduced graphene oxides. These carbon materials are ideal for creating conductive textiles due to their characteristics; flexibility, corrosion-resistance, and affordability. A conductive polyester fabric made of graphene was created and used for bio potential monitoring applications [8]. Depending on the load content, these materials can be utilised to create conductive textiles with a variety of conductance ranges. Zhu et al. used dip-coating and spray coating to create machine-washable conductive fabrics made of single-walled carbon nanotubes [9]. The created electrically conductive textiles have a high conductivity of up to 7.4 102 S/m.

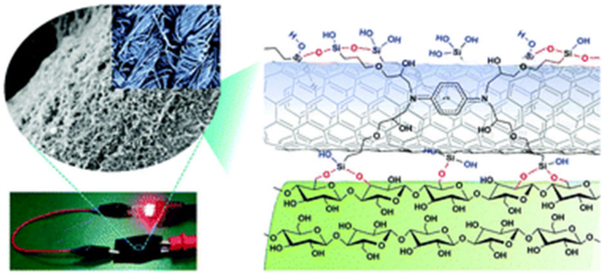

Figure 17.3 Carbon-based nanomaterial composition [10]

17.7 Intrinsically Conductive Polymers

Currently, the creation of electro-conductive textiles makes extensive use of inherently conductive polymers. Polymers with a conjugated molecular structure—which includes alternate single and double bonds between carbon atoms—are known as conductive polymers. They are the perfect option for textile-based electrodes because they may combine the electrical properties of metals or semiconductors with the advantages of ordinary polymers. The most effective conductive polymers for making conductive textile are polypyrrole (PPy), polyaniline (PANI), and polythiophene derivative poly (3,4-ethylene dioxythiophene): poly (styrene sulfonate) (PEDOT:PSS) [11]. Organic solvents known as dopants can be added to the polymers to increase their conductivity, for example, by using polar organic solvents such ethylene glycol, dimethyl sulfoxide, and glycerol, the conductivity of PEDOT:PSS can be increased by a factor of one to three [12]. Since a variety of electrical properties may be obtained by experimenting with the polymer add-on and the amount of dopant, these conductive polymers can therefore be used to design all of the structural components of the smart textile system. The chemical composition of several conductive polymers is shown in Figure 17.4.

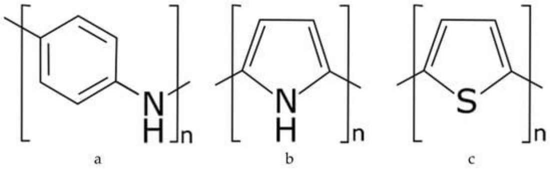

Figure 17.4. The most successful conductive polymers: a – polyaniline; b – polypyrrole; c – polythiophene [1]

17.8 Conductive Polymer Composites

The highest conductivity is found in metal-based conductive textiles, although they are frequently too rigid. Existing conductive polymers exhibit encouraging conductivity, but they still require enhancements to their mechanical properties. As a result, conductive polymeric composites have better mechanical stability and electrical conductivity. Composites made of carbonaceous, metallic, and conducting polymeric fillers, either alone or in combination, are known as electrically conductive polymer composites. They can be created using a single polymer or a multi-phase blend, depending on the electrical and mechanical qualities needed. The use of conductive polymer composites in academic and professional settings has been continuously increasing. In order to create conductive textiles, numerous conductive polymer composites have been developed and employed.

17.9 Conclusion

Smart textiles are materials that can sense and react to environmental conditions or stimuli. The technological advancements that allow for the constant performance improvements of these materials, are driving the market demand for these products. Electrical conductivity is an important property for many applications of smart textile materials. There are different techniques that can be applied to obtain electrically conductive textiles; the most suitable depends on the functions we desire to obtain and the type of material used.

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Chapter 18. HOW TO DEAL WITH SMART TEXTILE WASTE

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18.1 Introduction

Textile waste is recognized as the fastest-growing waste stream in municipal solid waste (MSW). All over the world, the rising clothing consumption and production caused the development of a textile waste generation which led to many challenges in a lot of countries. One of them is waste collection through economically viable sorting infrastructure which is difficult to find. Another significant challenge is represented by variations in fibre blends that make the sorting of textile waste demanding and complicated. However, automation for sorting and innovations in textile recycling are fields of growing interests [1]. The most preferred option is textile reuse but it suffers a shrinking market due to banning imported used clothing in some countries. The production of new clothes via textile reuse and recycling should be driven by economic incentives to make it feasible for the area of concern. In order to reduce the environmental impact, sustainable blended materials made from recycled fibres have to be used innovatively. Furthermore, it is fundamental to work on the characterization of the structure and properties of cellulosic fibres regenerated from cotton-based waste. An additional key action could be the investigation of recycling technologies to sustainably manage other textile waste, such as man-made cellulosic fibre (MMCF) and other fibres like polyamide. Behind polyester and cotton, MMCFs are a class of fibres made mostly from wood and other cellulose-containing materials. They are the third most widely used fibre globally. They account for an equivalent of around 7.1 MT of fibre annually, or about 6.4% of all fibre produced [2]. Sustainability is additionally encouraged by the creation of non-traditional fibres and a chemical-free binding process. When compared to traditional plant-based fibres, natural fibres can offer substantial advantages because of their lesser environmental impact. Recycling technologies that can create new fibres that are comparable to virgin fibres are among the innovations that promote the circular economy and closed-loop recycling systems. The fashion sector gains greatly from the transition from the existing linear economy to a circular economy while minimising the negative repercussions of the global population increasing that is causing a bigger demand for clothing [3].

18.2 Smart Textiles Recycling Benefits

E-textiles are expected to be extensively used and can produce significant waste streams. It will be difficult to collect and recycle old e-textiles without cutting-edge collection and recycling schemes. E-textiles may also affect human health and social justice concerns generally related to electronic waste. We can have unlimited benefits by recycling smart textiles in the proper way. Some facts are:

- Synthetic fibre products do not decompose and natural fibres may release greenhouse gases so less landfill space is needed.

- Avoided use of virgin fibres.
- Reduced consumption of energy and water.
- Pollution avoidance.
- Lessened demand for dyes.
- Reduced greenhouse gas emission [4].

18.3 Smart Textiles Recycling Possibilities

Figure 18.1 Smart Textile recycling

Old e-textiles ‘fate depends on the waste management schemes that are established at the place of their disposal. However, the recycling schemes currently in use are inappropriate to collect and process textiles with integrated electronic components. According to recycling experts, it is difficult to recycle e-textiles because of various technical problems. For example, textiles could jam shredders and crushers such as those currently used in waste electrical and electronic equipment recycling (WEEE) [5].

The separation of fluffy, light materials like metalized plastic foils and textile threads was thought to be beyond the capabilities of automated separators. We know from existing WEEE recycling technology that mechanical shredding causes significant precious metal losses. These materials are transmitted in substantial amounts into output fractions, where they cannot be retrieved. Additionally, the valuable metals (such as silver) would be transferred into the dust fraction during the destruction of e-textiles. The experts predicted that manual e-textile waste sorting and processing was feasible, albeit challenging. Because the rich metals are not concentrated in e-textile wastes as they are in traditional electrical waste, the processing costs were predicted to be unaffordable.

The solution to smart textile recycling still needs to be developed. These are the results coming from some research: [6-9]

- The technology should be used to produce items with a longer life cycle.
- Technology developers and product designers of e-textiles should not simply assign the recycling industry accountability for their inventions' end-of-life phase.

- Transforming challenges into opportunities by constructing technological artefacts in order to have long-term sustainability benefits over their entire product life cycle.
- Sustainability benefits must be searched for and put into practice.
- Industrial designers can play a vital role by creating showcases of sustainable e-textiles to inspire consumers and decision-makers to focus their attention on sustainable alternatives.
- Eco-design of the new product must be imposed by every research institution.
- Waste prevention should be made an explicit goal of innovation strategies.
- More use of smart textiles for simple and coarse sensors, like resistive or capacitive sensors can help in obtaining precision through the use of multiple sensors and data extrapolation.
- Increased use of surface fabrics that currently exist to reduce the requirement for tiny sensors and electronic components.
- Make sure that multiple data paths and parallel lines ensure reliability and secure fail circuitry.
- Consider minimal use of materials, such as mono-materials.
- Fossil fuels usage can create new possibilities for a sustainable future.
- Disassembling of controlling circuits from the smart textile for longevity and longer usage.
- Improving the durability of the products by focusing on the quality, disposability, wear, reparability and obsolescence.

18.4 Conclusion

In order to enhance the textile market's sustainability and close the circular loop, recycling should be increased. The use of blended and man-made materials that are chemically based hampers recycling possibilities. The recycling of e-textile waste is even more complicated; the current recycling schemes are inappropriate, and an effective solution is still to be developed. For these reasons the introduction of new technologies should be sustained by economic incentives, while eco-design, the use of mono-materials, natural fibres, and chemical-free binding processes should be encouraged.

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Chapter 19. CONSERVING SMART TEXTILES RESOURCES BY 3R CONCEPT

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19.1 Introduction

The concept of conserving smart textile resources through the 3R concept refers to the principles of reducing, reusing, and recycling in the context of smart textiles. Smart textiles are fabrics or materials that have integrated technology, such as sensors, actuators, or connectivity features.

The concept of conserving smart textile resources revolves around the responsible and sustainable management of resources associated with the production, use, and disposal of smart textiles. It involves various strategies and practices aimed at minimising waste, reducing environmental impact, and maximising the efficiency and longevity of these technologically advanced materials.

By embracing these principles and implementing sustainable practices, the concept of conserving smart textile resources aims to minimise waste, reduce environmental impact, and promote the long-term viability and sustainability of smart textile technologies.

Our life is surrounded by textiles and because we are in the era of technology, it is not surprising that textiles also have intelligent functions. Nowadays there are a lot of intelligent and innovative fabrics, smart textiles which can be used in the fashion industry.

Smart textiles are also called electronic textiles or e-textiles and are textiles with electronic components to perform some functions. The integration of digital components should not modify the clothing functions such as comfort, softness, resistance, durability.

The market of smart textiles is growing in developing nations and the worldwide smart fabrics market will grow from $943 million in 2015 to $5369 million by 2022 [1].

Literature provides several types of smart textiles, and the common classification is based on the aesthetic and performance functions of the clothing. The aesthetic intelligent fabrics are used in the fashion industry, and they can change colour, may light up. These fabrics are using thermochromic, solvatochromic, photochromic, and electrochromic materials. The performance functions refer to the capacity of the material to protect against the radiations, to monitor the body functions such as heart rate, to control the body temperature.

Intelligent textiles could transform stimuli into responses that interact with all 5 senses: tactile, visual, auditory, olfactory, haptic. Besides the clothing and apparel industry, smart textiles have other applications like medicine, automobiles, military, aviation, robotics.

Smart textiles are not necessarily more sustainable than ordinary ones and according to literature there are some doubts about the sustainability of smart textiles [2]. Both industries, textile and microelectronics, have some problems regarding sustainability.

The term "sustainability" has become increasingly popular in recent years in all industries and in consumer’s language. Sustainability has different definitions, but the most common is "Quality of an anthropic activity to be carried out without exhausting the available resources and without destroying the environment, so without compromising the possibilities of meeting the needs of future generations” [3]. Sustainability can be described as the intersection of the "three pillars" that constitute the solutions to environmental, social, and economic problems.

19.2 The 3R Concept

From an environmental point of view, the textile industry was not very friendly, but thanks to advanced and innovative technologies, this has changed in recent years. Technological progress, process improvement, care for the environment, all aim to move the industry towards sustainable development.

From an economic point of view, the sustainable development of European industry can be achieved through competitiveness - being one step ahead of the competition. Due to unfair export restrictions, competitors from other third countries can purchase low-priced products, which makes it difficult to maintain a competitive advantage on the world market.

From a social point of view, certain aspects must be followed: ensuring the welfare of animals, improving the image of the industry, and attracting investments, supporting education and specialised training, as well as not exploiting the workforce.

For a long period of time, sustainability and the circular economy was approached through the prism of the 3"Rs" concept: **Reduce, Reuse, Recycling**.

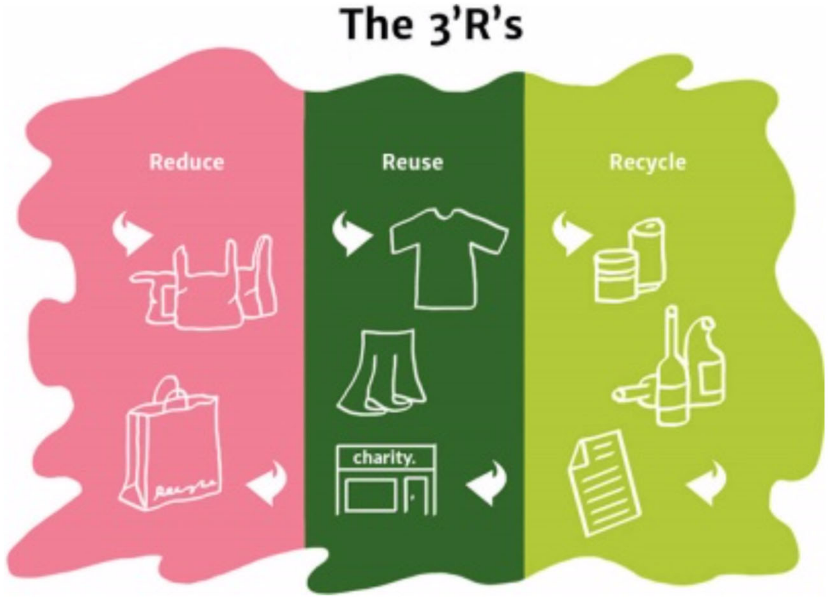

Figure 19.1. 3"Rs" concept, source: https://www.solarschools.net/knowledge-bank/sustainability/reduce-reuse-recycle

Reduce

Refers to limit the number of purchases in order to reduce the amount of waste generated. This is the most effective component of the waste hierarchy.

Reuse

The second ”R” means that the products should be used as much as possible before replacing them. The textile products are usually replaced because they are not fashionable anymore even if they are still functional and aren’t damaged.

Recycle

The third ”R” refers to giving a new purpose to the product or to some parts of it.

The goal of the 3"Rs" is to minimise the amount of waste produced, reusing products as much as possible, and recycling any materials that can be used for a new purpose.

McDonough and Braungart proposed a new approach to "R": Re-thinking or Re-design. This new "R" is based on the reorganisation behaviour of the society, focused on Eco-design and design processes closely related to sustainable development and the emergence of a new type of consumer, namely the conscious consumer [1, 4].

19.3 The 6R concept

The latest concept is the "6R" which forms the basis for sustainable production (reduce, reuse, refuse, reimagine, repair, recycle) as this allows the transformation from a single traditional open life cycle to a closed one [5].

Figure 19.2. The 6 ”R”, source: https://reimagineco.ca/blogs/news/the-6-rs

Reimagine or Rethink

Refers to consumer’s lifestyle and their purchase habits. Before buying something, they should ask themselves if they really need that product and rethink their everyday choices.

Reuse

Instead of buying a new product, reinvent and find an alternative use for the existing one.

Reduce

The goal is to reduce the amount of waste created by buying only the important products and limit the purchases.

Repair

Before throwing away a product it should extend the life of it by fixing it.

Refuse

It refers to the fact that you refuse to pay extra for something that would end up generating more waste, such as a big packing filled up with paper.

Recycle

The raw materials from textiles products can be reclaimed and reused to obtain another product, which means the conservation of the natural resources and contributing to sustainable development.

Each of these" Rs" describes an action that can be taken to reduce the environmental impact of products.

The capacity to recycle smart textile products depends on the materials used and the level of integration between the textile and technological components [5]. Another aspect is the way the electronic devices are placed: stitched, buttoned, Velcro, zipped. Not removing electronic devices at the time of recycling makes the process more difficult. Even if the electronic hardware is removed, they are difficult to recycle. The best method of disposal of textile waste is recycling but in terms of smart textile the process is very complicated, difficult, expensive and sometimes impossible.

19.4 Conclusions

By integrating these principles into the design, production, use, and disposal of smart textiles, the 3R concept promotes resource conservation, waste reduction, and environmental sustainability. It helps to maximise the value derived from these materials and minimise their impact on the environment.

Smart textiles often incorporate electronic components that require energy to operate. By conserving resources and implementing energy-efficient designs, we can reduce energy consumption and reliance on fossil fuels, thereby lowering greenhouse gas emissions and combating climate change.

Conserving resources promotes sustainable innovation in the field of smart textiles. It encourages the development of eco-friendly materials, efficient manufacturing processes, and recycling technologies. By focusing on resource conservation, the industry can drive advancements that align with environmental stewardship and social responsibility.

Emphasising resource conservation in smart textiles aligns with the principles of a circular economy. By reducing, reusing, and recycling materials, we can create a closed-loop system where resources are used efficiently, waste is minimised, and valuable materials are continually circulated back into the production cycle.

Overall, conserving resources in smart textiles is essential for minimising environmental impact, reducing waste, promoting sustainability, and driving economic and technological advancements in a responsible and efficient manner.

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Chapter 20. SUSTAINABLE SMART TEXTILES DEVELOPMENT

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20.1 Introduction, definitions

Smart textiles can be defined as textiles able to sense and react to environmental conditions and external stimuli (e.g., mechanical, thermal, and chemical stimuli) thanks to a number of sensors incorporated in the textiles.

Sustainability means meeting our current needs without compromising the ability of future generations to meet their own needs. In addition to natural resources, sustainable development also needs social and economic resources. Sustainability is not just environmentalism. In most sustainability definitions, we find concerns for social equity and economic development.

The combination of the terms of smart textiles and sustainability, leads to the need of a new definition: the one of sustainable smart textiles. In a broad and general aspect, which would be defined as smart textiles that fulfil the demand for sustainability in every aspect of their functions and applications and through all their life cycle, from raw materials extraction till end of life, including the most important phases of fabrication and usage. What is of outmost importance for achieving the demands of sustainable smart textiles, is that they are designed and developed as such.

In the following, we will present the most important aspects of development of smart textiles that can be regarded as sustainable. The quest for sustainability is an eternally repeating process of continuous development, so the aspects presented below, should be regarded as not the only ones, but as the most important ones and a good starting point for anyone wishing to develop sustainable smart.

20.2 Energy consumption

Energy consumption is one of the most important aspects related to sustainability, especially excess energy consumption when this energy is based on non-renewable sources like fossil fuels. In terms of smart textiles, a characteristic that is extremely useful in order to avoid usage of energy is the self-cleaning ability. Several technological solutions can be used for this, like photo catalysts, microwaves, carbon nanotubes, metal oxide colloidal, silver nanoparticles and chlorine halamine [1]. The realisation of self-cleaning properties on textile surfaces by using nanotechnology, provides a vast potential for the development of new materials or new products and applications for known materials [2]

Furthermore, self-healing can extend the life cycle of a textile by several years. If we can achieve self-healing, that means we can prolong the replacement of a textile and that leads to less energy needed to produce a new one.

Self-healing fabrics, which are known as smart textiles with automatic self-repairing function, are considered a promising essential for the continuous expansion of the textile industry. The self-healing textiles have been conventionally developed with the use of chemical coating finishes in forms of microcapsules, hydrogels or other polymeric matrices [3].

Moreover, the self-thermoregulation ability of textiles is a real revolution for energy consumption. One can imagine clothes that have the ability to regulate the temperature of the body of the person that wears them, so there would be less or maybe none need for heating or cooling devices that consume a considerable amount of energy. Strategies for that approach include cooling/heating fabric, cooling/heating woven textile, coloured textile, dynamic textiles, PCM-Fibre-based textile, Metal Nanofiber-Based Hybrid Films/Textiles, Graphene and Carbon-Based Materials, Thermoelectric Device (TED) [4]

Figure 21.1 Sustainability leads to a green future

20.3 Materials

Sustainability of smart textiles must also refer to the kind of the materials used for the fabrication of the product. Materials that are too expensive or require sizable resources should be avoided for the favour of other materials and ideally for recycled materials that are considered sustainable, e.g., carbon neutral or recycled or recyclable.

It is even possible to think of a solution of electronic materials and components, which have come to the end of their life and could be possible to be integrated on smart textiles. An example is microprocessors that are considered obsolete for high tech (computing) applications but can work efficiently on low demand applications in smart textiles, ego controlling a limited number or input/output devices like sensors. In that way, significant amounts of dangerous electronics wastes are up cycled and remain in service instead of been a source of contamination [5]. The same can apply for small screens from mobile phones or radio communication equipment.

The possibility of electronic components that can be disassembled from the smart textile, by mounting the electronic hardware on the textile in an easily removable way, can provide for hardware upgrading and a longer life cycle and consequently reduction of electronic wastes.

20.3 Energy Production

We already referred to energy consumption with the meaning of decreasing the energy needed for the function of the smart textile. One step forward is the energy production from the textile itself.

That could happen with biomechanical energy harvesting from the textiles as the human body is a rich source of biomechanical energy. A quite mature technological solution for harvesting biomechanical energy is the piezoelectric effect that could be integrated with textiles for on-body electricity generation. Compared to intermittent biomechanical energy that requires body motions, another energy source is the body heat, that constantly exists on the human body even in stationary postures, which originates from metabolic by-products and has become an available energy source for continuous electricity generation over the past decades. Beyond the aforementioned electricity generation from biomechanical motions and body heat, biochemical energy is a type of on-body energy source that is generally available but usually ignored, which is presented in forms like body fluids, including sweat, tears, blood, and saliva [6].

Photovoltaics Textiles

The two major sectors for photovoltaic (PV) textiles are firstly to power sensors and other electronics integrated into a wearable fabric, and then the large-scale use of solar power from awnings, sunshades, covers, and similar installations. At present there are no purely textile solar power products but many laboratory-scale versions that are vying for development into commercial applications.

The first challenge in fabricating any PV cell, is to provide an electrically conducting base that does not have a resistive barrier to the flow of charges from the cell. For cells that deliver significant currents only metals are used, while lower performing thin film cells may use less conducting transparent oxides (e.g., indium tin oxide- ITO, or aluminium zinc oxide-AZO). Conducting polymers are not sufficiently conducting on their own [7]

Usage of natural fibres

Composites based on natural fibres are under intense study due to their environmentally friendly nature and unique properties. Its advantages are their continuous supply, easy and safe handling and biodegradable nature. Although natural fibres perform admirably physical and mechanical properties, it varies with plant source, species, geography among others [8].

Categories of natural fibres are:

- Plant fibres which include bast, leaf, stem, fruit, seed and other such as wood.
- Animal fibres which include hair such as wool, angora, mohair, cashmere, and alpaca, as well as silk.
- Mineral fibres like asbestos [9] could also be of use, but there are human health issues with them, and this is an inhibiting factor.

Most promising and novel category is the fibres obtained from fruit and seeds. Tons of fruits are wasted every year. If it becomes possible to produce fibres from it, that will lead to great environmental and financial results.

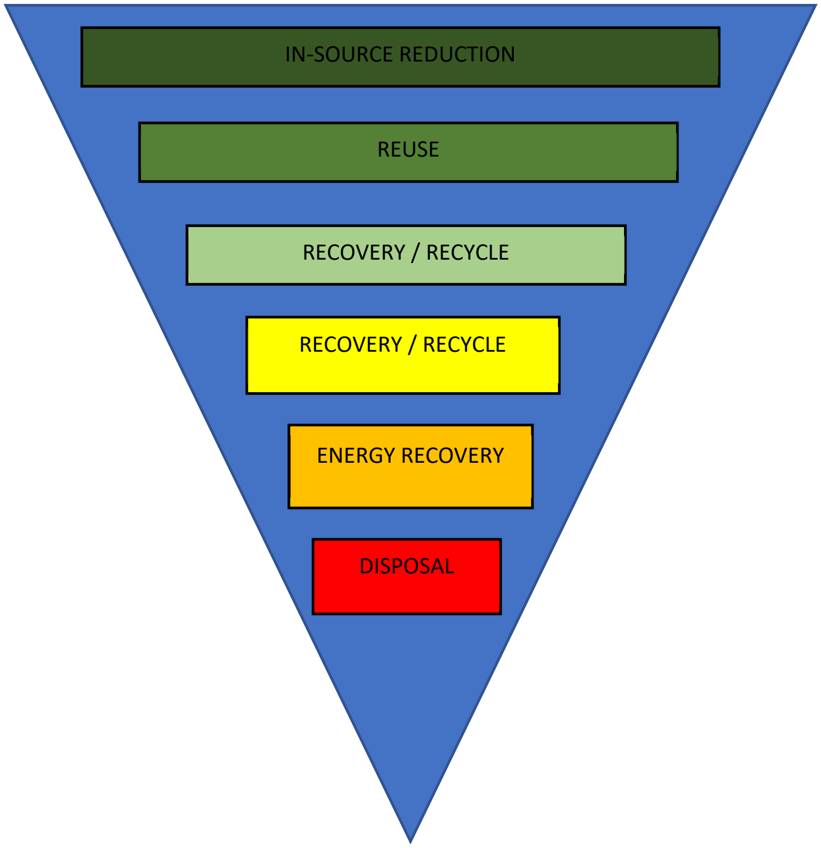

Figure 21.2 Waste reduction hierarchy

20.4 Conclusion

Although smart textiles do not have a mature market yet, they do have to fulfil the demand for sustainability, as every other product does. In order to be sustainable, smart textiles must be designed and developed as such. The relevant modifications and adjustments will be applied to every single part of the product (yarns and electronic parts) but should also be applicable through the whole of the life cycle. This means that aspects like energy consumption during the use phase should be minimised and/or counterbalanced, for instance by energy production by the smart textile itself.

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21. SMART TEXTILES TOXICITY

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21.1 Introduction

The textile industry is a fully developed and technologically advanced industrial sector with a substantial CO_2 footprint and contribution to water pollution, mainly due to dyeing processes [1,2]. A wide range of chemical agents are involved in the industrial textile manufacturing processes for sizing and desizing, bleaching, dyeing, finishing and softening [3]. Flame retardants and surface treatments with engineered nanomaterials should also be considered [1]. The toxicity of most of these chemicals employed in the production processes of traditional fabrics is well documented and the exposure limits have been determined by systematic studies over the past decades [1,3].

Apart from the conventional types of fabrics and the relevant hazards, the escalating use of nanomaterials, battery chemicals, heavy metals integrated with fabric in smart textiles has raised additional concerns on the potential health risks related to their use and maintenance as well as their end-of-life treatment. Some recent studies highlight the environmental impact of nanomaterials and describe the necessary procedures [4-6]. Toxicity aspects related to the lifecycle of smart textiles have a vast impact on human health and safety, the environment and the efficiency of existing waste management procedures and recycling [2,6]. There is a profound conflict between the unlimited functionalities and the overall sustainability of the smart textile products [2,6,7].

The following paragraphs provide an overview of the fundamental knowledge on potential toxicity of smart textiles aiming to inform innovation centers and researchers of this field, investors, SME and industrial manufacturers, end-users and policy makers.

21.2 Human health hazards related to smart textiles

According to Rovira et al. [1] the categories of chemicals of testified toxicity, widely used in the textile industry, include:

(a) Aromatic amines, primarily used for the production of azo dyes. Many of these compounds are characterized as allergens and most importantly as carcinogenic and genotoxic compounds.

(b) Toxic metals such as Co, Pb, Cr, Cu, Ni, Cd, Hg, AS, Zn (ingredients of organometallic complexes or inorganic pigments in dyes), toxic catalysts such as Sb_2O_3, metal and oxide nanoparticles added in textiles to obtain tailored properties.

(c) Phthalates, frequently encountered in the form of PVC prints, which are categorized as potential endocrine disruptors.

(d) Formaldehyde-based resins, used in textile finishing, are skin irritants and potential carcinogens in cases of high levels of released formaldehyde.

(e) Polybrominated diphenyl ethers (PBDE) and hexabromocyclodecane (HBCD) additives, employed as flame retardants. These chemicals, although not extensively studied in terms of particular intoxication mechanisms, accumulate on human tissues and have also been detected as domestic and major ecosystem pollutants.

The engineered nanomaterials enter the human body, mainly by inhalation, skin absorption and ingestion, with the first two being the most frequent pathways [3, 4].

In the case of functionalized textiles and wearables, the most common types of nanoparticles, nanofibers and nanocoatings employed to offer a wide range of properties - such electrical conductivity, self-cleaning and antibacterial performance, enhanced mechanical strength and abrasion resistance, UV blocking, flame retardation, water repellency and many more - are metal particles (Ag, Cu, Au), various carbon-based particles (CNTs, carbon black), nano-clays and inorganic oxides (TiO_2, Al_2O_3, ZnO), graphene oxide [2-4, 9, 8, 9]. Some typical integrated nano-devices and flexible fibers utilized as batteries are Al-NaOCl galvanic cells and ($LiFePO_4$/ Li4Ti$_5$O10/ solid polyethylene oxide/ PVDF), respectively. Polymer and copolymer layers, polymer photonic bandgap fibers, metal films deposited by sputtering and multi-component conductive yarns with supercapacitor function are also typical nano-dimension components of smart textiles [2]. All the above-mentioned chemicals and materials are related to various toxicity hazards. Figure 21.1 depicts the penetration of CNTs into a lung cell.

Figure 21.1 *Scanning electron microscope image depicting carbon nanotubes (CNTs) penetrating a lung cell (Source: Robert R. Mercer, Ann F. Hubbs, James F. Scabilloni, Liying Wang, Lori A. Battelli, Diane Schwegler-Berry, Vincent Castranova and Dale W. Porter / NIOSH; CC0 Public Domain).*

The health and safety risks are bound to all stages of the products lifecycle –the production of raw materials, the integration of nanomaterials and electronics with fabrics during manufacturing, the use phase and the end-of-life waste treatment and disposal. The highest exposure risk is faced by the workers of the textile industry during the production phase [3, 4]. The most common methods for integration of smart textile components are: (i) weaving, knitting, lamination or stitching of conductive yarns onto textiles, (ii) weaving and knitting for the production of two- and three- dimensional textiles, (iii) incorporation of electronics in the fabric substrate by the creation of electrical contacts [10].

The release of potentially toxic constituents from the final smart textile products can be generated by abrasion, sweat, temperature fluctuations, irradiation effects, washing treatments during use [9]. Skin absorption is considered as the primary health concern for smart textile end-users, but these effects are not well studied [4]. Many studies report possible mechanisms of adsorption and accumulation of nanoparticles, nano-aggregates and nano-agglomerates in human organs [4]. Particles of size lower than 100 nm penetrate cell membranes and create various disorders, including oxidative stress, inflammation, apoptosis, mitochondrial and lysosomal dysfunction and genotoxicity [15]. The specific hazards depend on the physicochemical properties of the particles (size, chemical composition, surface energy, charge etc.) [4, 6] and the two main consequences are toxic effects and DNA damages responsible for neurological diseases and cancer [4]. Periyasamy in his extensive review on the consequences of textile microfibers release, includes studies that have detected microfibers in human placenta samples [3]. The same author lists all heavy metals added in polymer fabrics, their functionality and the related health risks for humans, ranging from allergies to various types of cancers and organ failures. In Figure 21.2 the most common health problems and diseases caused by the intense or prolonged human exposure to nanomaterials are being summarised.

Figure 21.2 *Diseases and health conditions related to exposure and accumulation of nanoparticles in the human body (Source: Cristina Buzea; CC0 Public Domain).*

Almeida et al. report the EN ISO standards that have been evolved or adopted for the evaluation of the effects of skin contact with typical nanomaterials contained in textiles. Most of these test methods are designed as immersion tests in artificial perspiration solutions [9]. The integrated electronics in smart textiles require a different approach.

21.3 Environmental impacts of smart textiles toxic ingredients

The environmental risks and ecotoxicity impacts of toxic agents’ emission during washing processes and end-of-life disposal of smart textiles comprise a separate field that requires monitoring and control, so that future mass production of multi-component textiles, garments and wearables will not result in widespread pollution, as in the case of microplastics [5, 7].

Perhaps, the most frequently published data are results from washing tests of textiles with anti-odor and/ or anti-microbial properties. Extensive leaching of silver nanoparticles has been reported by several studies [2,4], a risk that was probably underestimated during the design of these products. Up to the present, there is only one available standard procedure for washing according to ISO 6330 and no specific guidelines for proper recycling or international regulations that would minimize the environmental impact [10]. The appropriate recycling practices is an additional issue to be addressed. The effectiveness of traditional textile recycling (reaching 100%), is not applicable to smart textile waste [6, 8]. Dolez et al. in their review work [11], mention some improvements on the recyclability of particular fiber categories used for the manufacturing of personal protective equipment, such highly extensible elastomeric fibers, cellulose-based fibers and commodity synthetic fibers. Some positive results regarding the partial recyclability of metal components (after metallurgical recovery or mechanical separation from polymer materials) have also been reported in case of conductive electronic textiles [6]. However, this is not a general trend and there are no available systematic practices through which the disintegration/detachment and separation of substrate fabrics from nanoparticles, electronics or other components would be possible.

As pointed out by Köhler [7], smart textiles with electronics and sensors at the end-of-life phase should be collected and treated as electronic devices. Until now, there is no specific legislation and regulations for the ecological design and waste management of wearables [5]. The systematic contamination of solid waste recycling systems, landfills and incineration sites, wastewater treatment with nanoparticles and other toxic agents and chemicals would inevitably lead to the ecosystem pollution through water, soil and air [3, 7].

21.4 Toxicity and ecotoxicity assessment methods - Required regulations and policies

Studies focusing on nanomaterials toxicity for humans are rather limited and mainly rely on the extrapolation of animal exposure models to humans. To achieve that, researchers have employed several animal and microorganism species for *in vivo* experiments, in order to assess the effect of various types of nanoparticles. However, no systematic protocols correlating the physicochemical properties of these materials and the intoxication mechanisms are available and thus, the experimental results are often inconclusive [4].

According to the review article of Saleem et al. [4], the latest research trend of toxicological studies is primarily the use *in vitro* techniques, employing epithelial cell lines or alternatively 3D cultures. The evaluation of this type of experiments could provide information about potential DNA damage (destruction or oxidation), mutations on genes and destruction of chromosomes [4]. In any case the selection of the suitable testing method depends on the nanomaterials unique properties and toxicokinetic factor of the examined biological system [12].

The environmental impact is mainly approached by risk assessment methodologies (lifecycle assessments designed to predict the toxic load resulting from washing processes or waste disposal), combined with end-of-life ecotoxicity case studies [3- 7]. This latter category involves analyses of toxic contaminants accumulation in aquatic sources, sediments, plants, soil bacteria and other living organisms [4]. For example, microfibers released from functionalized textiles have been detected in vegetable, fruit and fish samples by several studies [3].

Assessing the toxicity and ecotoxicity of smart textiles and addressing the washability and recyclability problems are challenges directly related with the overall sustainability of these innovative products [2, 4, 7, 10]. Targeted surveys conducted in 2011 by two experts, who interviewed researchers and managers of several European research institutes and SMEs involved with smart textiles technologies, revealed ignorance about side effects resulting from end-of-life waste disposal, lack of proper life cycle assessments and limited adaptation of waste prevention strategies according to EU policies [7].

Schischke et al [5] in a study published in 2020, mention very scarce literature sources with life cycle analyses data on wearable electronics and smart textiles. Even though significant progress is expected to have taken place within the last decade, it can be deduced that the design of specific standards and international regulations for safety and environmental engineering is way behind the technological progress in applied research and innovation, product design and manufacturing and industrial-scale production [5, 7, 10].

The published ISO series of standards on nanotechnology [13] and those under development [14] are positive steps towards concise terminology, materials characterization, risk analysis, toxicity testing and several other fields. Some guidelines for future standardization of smart textile products have been included in ISO/TR 23383:2020(en) [15].

Experts in the field highlight the responsibility of the investors and producers to comply with the existing health and safety regulations and the environmental regulations, undertake risk assessment analyses at all stages of the smart textile products lifecycle and provide clear information to consumers regarding the safe use and appropriate disposal of discarded products [2, 5]. Glisovic et al. [6] report generic methodologies for life cycle analyses of engineered nanomaterials that are applicable to industry of smart textiles and wearables.

An interdisciplinary approach with the synergy of experts from various fields -engineering, chemistry, materials and textile science, garment design, medicine, toxicology, safety, environmental sciences -is considered prerequisite, not only for the design of smart textiles but also for the establishment of international health and safety and environmental control systems, regulations and policies and the sustainable end-of-life waste management [6, 9, 11].

Summary

The most common toxic chemicals encountered on smart textiles and wearables, as well as on traditional fabric substrates are being presented along with health hazards and diseases reported for humans at various phases of the products lifecycle. The environmental impacts and the ecotoxicity related to end-of-life are briefly discussed. The chapter gives a general overview of the toxicity assessment methodologies and the existent regulations and policies, pointing out the weak aspects regarding the sustainability of smart textile products that have to be addressed in the near future.

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