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SMART TEXTILES: PAVING THE WAY TO SUSTAINABILITY[1]

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As an emerging technology, smart textiles can bring solutions to many problems, but also create new ones, especially related to their disposal and their impact on the environment. That is why it is important to address this problem at this stage of technological development when smart textiles have not yet pervaded the mass markets. In this article, first, an attempt is made to understand the chronological development of smart textiles: the reasons for a weak breakthrough in the commercial markets throughout the decades, starting from the 1990s until today, but also the emergence of new driving forces that should inevitably lead to a bright future for smart textiles. In addition, we explore the contemporary possibilities for sustainable materials, manufacturing techniques, and end-of-life solutions for developing sustainable smart textiles based on a broad literature review, online sources, and a questionnaire survey among textile experts. Finally, an overview of the latest developments related to the standardization of smart textiles is given. This research was spurred by participation in CONTEXT COST Action (CA17107 - European Network to connect research and innovation efforts on advanced Smart Textiles).

Keywords: smart textiles; sustainability; circular economy; end-of-life; eco-design

ПАМЕТЕН ТЕКСТИЛ: ПОПЛОЧУВАЈЌИ ГО ПАТОТ КОН ОДРЖЛИВОСТ

Како технологија во подем, паметниот текстил може да донесе решенија за многу проблеми, но и да создаде нови, особено тие поврзани со нивното отстранување и влијанието врз животната средина. Затоа е важно овој проблем да се реши во оваа фаза од технолошкиот развој кога производите од паметен текстил сè уште не се нашле на широкиот пазар. Во овој труд, пред

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сè, е направен обид да се разбере хронолошкиот развој на паметниот текстил: причините за слабиот пробив на комерцијалните пазари низ децениите, почнувајќи од 1990-тите до денес, но и појавата на нови движечки сили кои неизбежно водат кон негова просперитетна иднина. Дополнително се истражени современите можности за одржливи материјали, техниките на производство и решенијата за рокот на траењето за развој на одржлив паметен текстил, користејќи широк литературен преглед, онлајн извори и прашалник дистрибуиран меѓу експертите за текстил. На крајот е даден преглед на најновите случувања поврзани со стандардизацијата на паметниот текстил. Истражувањето беше поттикнато од учеството во Акцијата CONTEXT COST (CA17107 – Европска мрежа за поврзување на активности и иновации во областа на напреден паметен текстил).

Клучни зборови: паметен текстил; одржливост; циркуларна економија; рок на траење, еко-дизајн

1. INTRODUCTION

The textile and clothing industry is going through a transformation under the influence of technological progress, globalization, and sustainability concerns.[1] Textiles nowadays, besides the conventional functionalities, are expected to exhibit a level of “smartness”[2] and improve our daily experiences, general well-being, and wear-comfort.[3] With advances in chemistry and materials and in the age of the internet of things (IoT), a new era of smart textiles has opened up in which they can store and harvest energy,[4,5] sense,[6,7] display,[8] actuate,[9] and compute.[10] There are a few main drivers that encourage this development. One is the socio-demographic situation in Europe and other developed countries, where there is a shift in demographics toward growing geriatric populations. Another arises from the modern lifestyle, as it relates to exercise; the increasing incidence of chronic lifestyle diseases; and the growing tendency to provide a comfortable environment (at home, in the car, and at work). Also, the outbreak of COVID-19 put a new light on telemedicine and smart personal protective equipment (PPE) and positively influenced the accelerated development and implementation of smart textiles.[11,12]

Smart wearable devices are becoming a feature of Europeans’ lives. In 2020, 19 % of individuals in the EU used a smart watch, fitness band, connected goggles or headset, safety tracker, smart clothing, accessories, or shoes,[13] and this market is forecasted to increase to 150 billion dollars by 2026.[14] It is expected that there will be more than 8 billion consumers of internet and media devices worldwide by 2030, making this area by far the most common use case of the IoT as a whole.[15]

There are already wearable non-textile products on the commercial market, for instance, smart watches and wrist bands, but electronic devices integrated into textiles can offer several advantages, such as enhanced mobility and comfort for the user. Textiles and clothing are omnipresent in our daily life and, being the layer closest to our body, they provide an ideal platform for the integration of electronics to monitor physiological processes. Nevertheless, besides the initial enthusiastic beginnings during the IT boom of the late 90s, there was little commercial progress. This tendency began to change due to the above-mentioned driving forces, additionally boosted by the rapid development of the gaming industry and the metaverse, along with the maturation of manufacturing technologies. Therefore, in the years to come, we should expect the rapid development and greater market presence of smart textiles.

In light of sustainability, smart and especially electronic textiles pose a challenge toward their further processing when they reach their end-of-life. If this challenge is not tackled in time, the increasing market prevalence will result in new problems. In smart textile products, the level of integration has a remarkable influence on the materials’ recyclability and the end-of-life solutions of the product.[14] Since the maturity of the technological processes is at the stage of enabling full integration of functionality at the fiber level, it is vital to address the problem early when smart textiles have not yet pervaded the mass markets and waste prevention by design can still be successful.

This research was spurred by participation in CONTEXT COST Action (CA17107 – European Network to connect research and innovation efforts on advanced Smart Textiles), which ended in April 2023. In general, the CONTEXT objective was to create a network of European researchers and main relevant stakeholders in order to develop joint ideas and initiatives that can be turned into advanced smart textile products. The study was based on a broad literature review and online sources about contemporary sustainable innovations in the field of smart textiles; the discussions held at the two-day event organized by CONTEXT, Smart Textiles: Marketplace and Forward-Looking Opportunities, held in April 2023 in Prato and Florence; and a questionnaire survey delivered to all CON-TEXT participants. The aim of this study is to generate ideas on how to pave the way for the development of sustainable smart textiles.

2. HISTORY AND FUTURE PERSPECTIVES OF SMART TEXTILES

2.1. *Twenty-five years of working hard*

The term "smart textiles" started to emerge in the 1990s when the microelectronics and ICT (information and communication technologies) markets experienced a rapid growth phase spurred by the advent of the Internet, connected desktop computing, and mobile phones. The first product prototypes included the Levis-Philips phone jacket or the first sports shirt with an integrated heartrate measurement device developed by Clothing+ in Finland. Apart from communication, entertainment, and sports, the health market also saw their first versions of wearable textiles or clothing integrated monitoring devices such as the LifeShirt by Vivometrics[16] in the US or some prototypes produced by the large EU-funded project MyHeart,[17] led by Philips. Other testing grounds for smart textile products were the defense and civil personal protection markets, mostly driven by public funding led by institutions such as the U.S. Army's Natick Soldier Systems Center. However, despite great hope and bold announcements (the Levis-Philips joint venture's mission goal was "Philips technology in every shirt and skirt"[18]), commercial success was very difficult to come by, and many ground-breaking ideas were quietly abandoned in the post IT-bubble years in the early 2000s.[19]

While large industry, consumer brands and investors lost their appetite to venture much further into prototyping, production, and marketing at large scale, researchers and technology developers soldiered on, mostly supported by public grants such as those of the European Union's research and innovation framework programs. In 2008, the Smart Fabrics and Intelligent Textiles cluster was formed, bringing together some 10 EU-funded smart textiles research projects. Up to that point, Europe, through EU and national public funding, and the US, mostly through defense-related projects, dominated the global smart textiles innovation landscape, with some interesting work also taking place in Japan, Korea, and Taiwan.

Despite many such promising developments, no real broad commercial breakthrough for smart textiles happened in those years. Still, national and European research funds kept supporting leading edge applied research. Flagship projects of this period including Pasta,[20] PowerWeave,[21] and 1DNeon[22] pushed smart electronic or optical functions deeper into the core of textile materials such as fibres and filaments, thus enabling manufacturing of such materials in more conventional textile processes such as weaving, knitting, embroidery, or printing. Also, some smaller industry innovators from the textile technology and microelectronics sectors kept developing solutions with some niche market adoption potential, witnessed through many smart textiles exhibits at leading sectoral trade fairs such as Techtextil, ITMA, LOPEC, or JEC between 2015 and 2019.

At the same time (in the 2010s), another boost came from the introduction of consumer wearables (smart watches, fitness trackers, etc.) by consumer electronics companies (Apple, Samsung, Polar, Garmin, Fitbit, etc.). This renewed the commercial attention and, at the same time, spurred the technological progress (e.g. flexible and low-power electronics); this was combined with the possibility to capture more reliable and relevant data, transfer them to cloud-based databases, and analyze them through powerful algorithms. By far, not all of these concepts relied on smart textiles, but the idea of integrating smart functions into clothing or accessories that people use naturally on a daily basis was always an attractive proposition.

The early 2020s were marked by the outbreak of the COVID-19 pandemic, and this shed a new light on telemedicine and smart protective equipment[11,12] as successful tools for coping with the emerging situation and affected their accelerated development. Furthermore, as the world becomes more immersed in digital experiences and there is growing industry excitement around the metaverse, smart textiles may find their "killer application" that would finally bring the mass market breakthrough, precisely in the enabling of richer interactions between the digital and physical worlds.

2.2. *Why most smart textiles innovations failed*

2.2.1. *Complexity*

The smart textiles value chain is a complex one consisting of multiple actors from three distinctive industries, namely electronics, textiles, and ICT. This implies the need for cross-sectoral partnerships and converging competencies, priorities, and strategies based on three very different industries, viewpoints, and mindsets. Currently, product development is predominantly driven by a technological push. Many products only reach the prototype stage because of the absence of (large-scale) manufacturing capabilities and the challenges related to the difficulty of finding the right long-lasting partnerships. Figure 1 shows the complexity of the full value chain map of smart textiles.[23]

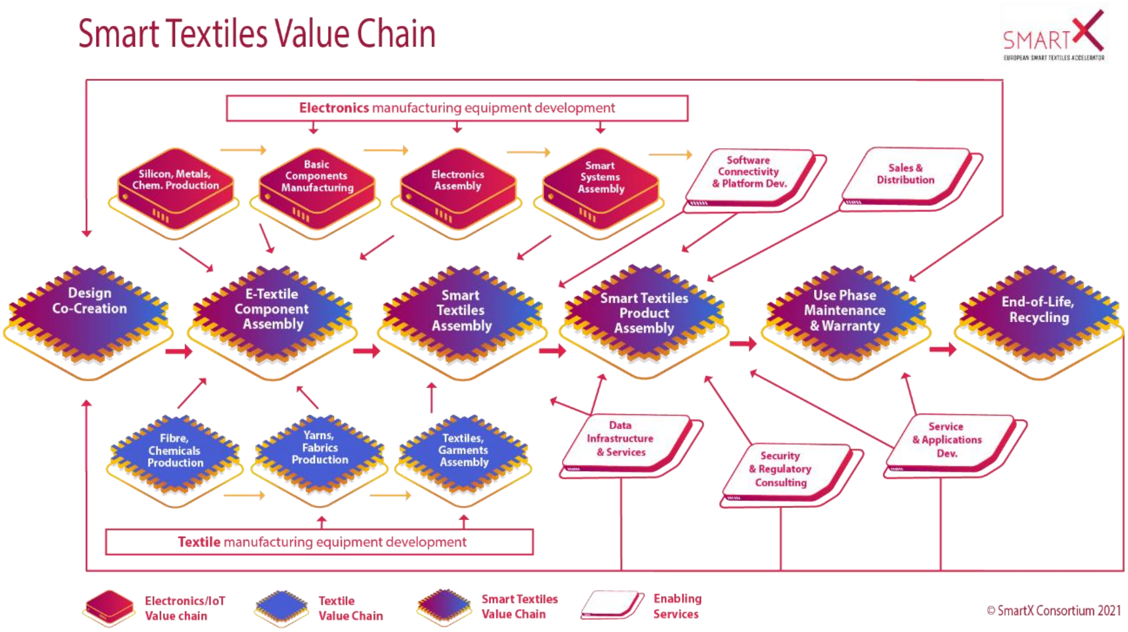

Fig. 1. Full smart textiles value chain map by SmartX[23]

Many of the fundamental problems that botched the early smart textile dreams remain headaches today. These include:

2.2.2. *Technological barriers*

- The complexity of the products for both manufacturers and end users.
- Limited technical capacities and the fragility of textile-based electronics.
- Difficult connectivity between textile and (non-textile) electronic parts.
- Lack of large-scale production of smart textile materials and components and a related lack of affordability for mass-market adoption.
- Lack of automated assembly technologies creating costs and quality issues.
- Limited washability.
- Lack of standards, testing, and certification, often driven by the fundamental difficulty of classifying the end product as either a textile/clothing product or an electronic device.

2.2.3. *Application/market barriers*

- Wrong use cases / end markets – search for ‘killer application’ in consumer markets.
- Lack of understanding of true user needs.
- Lack of standards, testing, and certification.

2.2.4. *Business model barriers*

- Poor economics
- No good product-service concepts
- No data strategy / exploitation
- No user stickiness
- Seller / payer / user conflicts

2.3. *Why there is hope for the future*

With the correct design, engineering, and manufacturing approach, a well selected end application, and an appropriate business model, it would be possible to successfully launch smart textile products on the market. Textiles have a number of advantages over other material solutions, which smart textile developers should especially attempt to harness. They:

- can drape smoothly on irregularly shaped, soft and deformable surfaces such as the human body - especially knitted fabrics;
- can cover large surface areas and can easily provide the smart functionality on many points across this large surface;

- are light, breathable and otherwise comfortable to wear and touch;
- are easy to use – most people from age 3 on know how to put on a t-shirt or wear a glove;
- can be durable and relatively easy to clean.

Another thing that goes in favor of the smart textiles bright future is that many technology bottlenecks have already been solved. For one, textile technologies such as conductive yarns suitable for weaving, knitting, and embroidery, automated placement, insertion and connection of electronic components on textile materials, printing of conductive inks on textile substrates, and coating, gluing, or lamination processes have all advanced massively in recent years and make true industrial production of smart textiles a reality. Miniaturized, low-energy, flexible, low-cost microelectronic components are available for many functionalities. There is better connectivity (4G/5G) and better data management (cloud-based service, security, general data protection regulation – GDPR).

Now, what remains in order to ensure a successful future for smart textiles is to actively involve in the projects, as early as possible, all relevant stakeholders, including the designers, manufacturers, end users, and experts on end-of-life treatment, as well as experts on service and application development. Building a successful community is of crucial importance to ensure that all talents, capacities, and knowledge work in better synergy throughout the industry toward one goal, successfully bringing smart textile products to market.[19]

3. SMART TEXTILES AND SUSTAINABILITY. WHERE ARE WE GOING?

There are serious doubts about the sustainability of smart textiles,[24,25] and it is not difficult to see where such suspicions originate. Both the textile and microelectronics industries do not have the best records on sustainability. Additionally, the combination of electronics with textile materials, and especially their high level of integration, results in new challenges for sustainability.

It is estimated that 92 million tons of textile waste are produced annually,[26,27] and although 95 % of textiles are fully recyclable,[28] ~85 % of all textiles are still dumped into landfills.[29–31] Incorporating electronics into existing textiles to introduce smart functionalities will therefore make end-of-life processing even more complicated and challenging.[32] It entails the presence of scarce raw materials, heavy metals, nanoparticles, and toxic chemical compounds in the textiles. Moreover, the presence of yarns coated with silver or copper metal depositions makes it impossible to remove and reuse the electrical parts, nor to mechanically recycle these materials.[33] Therefore, combining textiles with electronics adds new, unprecedented challenges from a sustainability point of view.

In addition to the consequences of materials on products' sustainability, there is another trend that applies to both electronics and textile products, which is that they usually have rather short service lives, and their end-of-use is much shorter than their end-of-life.[34] This hyper consumption of both types of products, accelerated by fleeting fashion trends in the apparel sector, has a profound environmental impact. Therefore, it can be expected that if serious measures are not taken now, in the near future the old smart textiles will cause large waste streams similar to today's e-waste and textile waste.[25]

Therefore, in order to pave the way to sustainability for smart textiles, there is a clear unmet need for an integrated product design, the use of eco-friendly materials, the development of sustainable manufacturing processes, and an effective end-of-life strategy to encourage the manufacture of the next generation of smart and sustainable textiles that can either be recycled into value-added products or decomposed in the landfill without any negative environmental impacts. Future waste problems can only be mitigated by environmentally conscious and circular design of smart textiles. Waste prevention by design can be successful at an early stage of technological development, and it is important to outline the possible sustainable design choices that can be made at the early stage of smart textiles' innovation process.

In order to do a strategic analysis allowing for the identification of the directions of development of the key elements of sustainable smart textiles, a questionnaire survey was conducted among the CONTEXT participants. This questionnaire, consisting of 21 questions based on the relevant issues identified in the literature review, was sent to all CONTEXT participants (more than 200) to share their vision for the development of smart textiles. Regarding the background, 72.4 % of the participants in this survey came from academia and 27.6 % from industry. Of those coming from industry, 40 % were from big companies, 20 % from SMEs, and others from non-profit organizations, R&D, higher school education in the textile industry, services for industry, and collective research centers – in between academia and industry.

In the following sections the important issues related to the sustainability of smart textiles will be covered through a literature review intertwined with an analysis of the questionnaire survey results.

3.1. *Implementation of risk-preventions measures and environment design principles in the innovation process*

Our past experiences with the development and commercialization of technological innovations show that technologies can cause adverse side effects.[35] Harm to human health or environments can arise at various stages during the lifecycle of products. In this context, side effects can be seen as an unintended deviation from the objectives of a new technology and thus represent a risk as defined in ISO 31000.[36] Environment, health, and safety (EHS) risks are defined as the probability that 'safeguard subjects' (human health, the environment) may suffer damage due to exposure to hazardous emissions.[37,38] While, for established technologies, the EHS risks are usually tangible, for emerging technologies, these cannot be exactly determined because research on EHS risks is lagging behind the technological development.[38]

Making products safe and sustainable by design has the potential to improve product safety, prevent pollution, mitigate climate change, and enable a circular economy.[39] This entails assessing product performance against requirements for safety and sustainability at the design stage of product development, rather than after a product has reached the market and starts commercialization. During the design phase, it is more feasible to meet performance objectives for safety and sustainability.

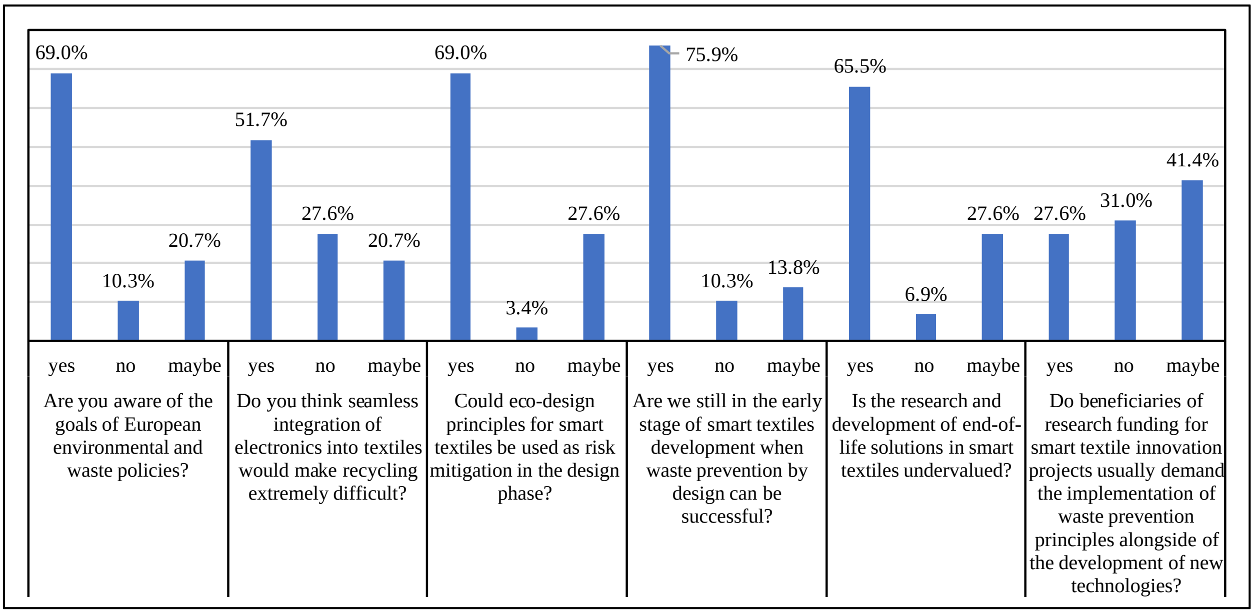

Fig. 2. Summarized results of answers to questions related to the sustainability of smart textiles

An analysis of the results of the questionnaire (Figure 2) shows that a high percentage (69 %) of the CONTEXT participants are aware of the goals of the European environmental and waste policies; even higher, 75.9% believe that we are still in the early stage of smart textiles' development when waste prevention by design can be successful. 69 % of the participants have the opinion that eco-design principles for smart textiles could be used as risk mitigation in the design phase and, at the same time, 65.5 % find end-of-life solutions in smart textiles undervalued. 51.7 % find the seamless integration of electronics into textiles to be the reason that will make the recycling process extremely difficult, while 27.6 % declared that beneficiaries of research funding for smart textile innovation projects demand the implementation of waste prevention principles alongside the development of new technologies. 69 % of the participants declared that they do implement risk-prevention measures and environmental design principles in the current innovation process (Fig. 3).

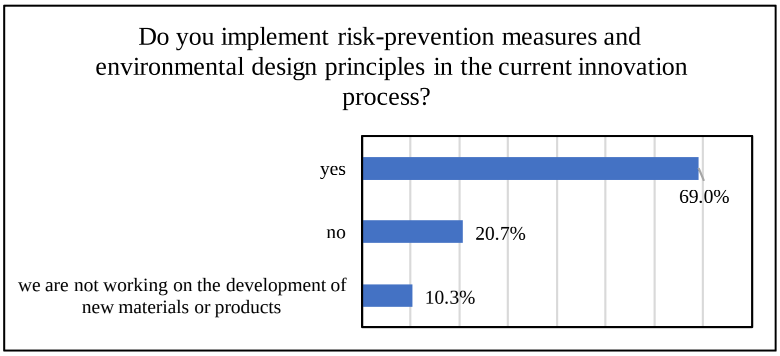

Fig. 3. Percentage of smart textiles experts (CONTEXT participants) that implement risk-prevention measures and environmental design principles in the innovation process

3.2. *The most prosperous application area of smart textiles*

Where should the most prosperous application of smart textiles be sought? The mass fashion market is not the place to look for the most prosperous future uses of smart textiles. The reason is that this market is too fickle and price-sensitive, and there is actually no room here for the real application of intelligent innovations that smart textiles can offer that can be reduced to some cheap gimmickry. The applications for monitoring some basic functionalities (such as heart rate, movement, or position tracking) related to consumer health, sports, and gaming applications also does not offer a big future because these can be realized with simpler non-textile solutions.

The greatest commercial opportunities for smart textiles should be sought in professional markets, such as personal protection and defense, professional care, and professional sports as far as wearable applications are concerned, and various niche industrial markets in the non-wearable part of the market. Innovators who know very well not only the needs of users but also the weak points of these markets can come up with cost-effective and useful solutions based on smart textiles.

Constant monitoring of the health status and performance for patients, professional athletes, and those who first respond to new situations such as firefighters, soldiers, or workers in dangerous work environments is not only a need but a necessity. Applying the intelligent solutions that smart textiles can offer in such situations will mean savings in terms of lower costs for hired labor, fewer manual checks, and, most importantly, lower rates of accidents and injuries, which will lead to lower insurance premiums. Some of these markets are regulated or at least require adherence to strict standards and complex certifications, but these are barriers that can be overcome, especially for companies that already provide conventional solutions in these markets.

The responses of CONTEXT participants are in line with this, finding that the most prosperous applications of smart textiles are in healthcare and medicine, personal protective equipment, and sports and wearables (Fig. 4).

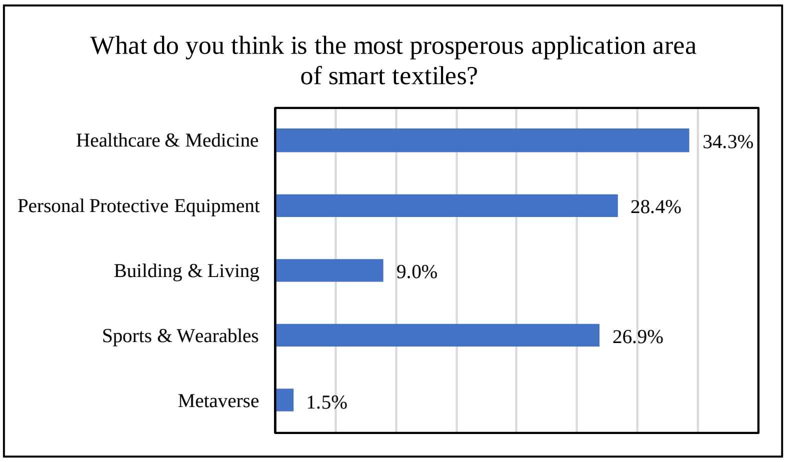

Fig. 4. Percentage representation of the most prosperous application of smart textiles according to textiles experts (CONTEXT participants)

3.3. *Future development of smart textiles elements*

The development of smart textiles in the context of sustainability should be based on the appropriate selection of materials and production processes, and products should be designed in line with circularity. This implies using materials that can be produced and processed in a closed-loop manner, avoiding toxicity and scarcity. Products should be designed in a manner to be energy self-sustaining with a well-defined end-of-life treatment.

3.3.1. *Future development of conductive fibers*

Conductors are the most important component in smart textiles, operating the electronics and facilitating added functionalities.

Metal inks based on silver,[40] copper,[41] or gold[42] are the most frequently used conductive materials due to their high electrical conductivity. However, they are neither cheap nor environmentally friendly.[32] It is of paramount importance to develop "green" electronics by using biodegradable "metallic" component materials. In this manner, Zn,[43] Mg, Fe, W, and Mo have demonstrated excellent dissolution performance for many applications, including health monitoring devices, flexible electronics, energy storage, and electronic sensors. Further studies are needed to evaluate their compatibility and interactions with sustainable textile fibers for smart textile applications.[44,45] Additionally, suitable end-of-life solutions have to be established to either separate such materials from bulk textiles or achieve complete biodegradation of the entire product.

Intrinsically conductive polymers are electrically conductive materials composed of a conjugated covalent backbone and functional groups with pseudocapacitive characteristics, together giving rise to conductive properties.[46] The most common conductive polymers are polypyrrole (PPy), polyaniline (PANI), polythiophene (PT), and PT derivatives such as poly(3,4-ethylene dioxythiophene) (PEDOT), which have been used satisfactorily as electrode materials.[47] Such conductive polymers have mechanical flexibility greater than that of metal contacts, which makes them ideal for developing flexible and conformal electronics for health monitoring systems. Additionally, they have demonstrated excellent biocompatibility within biological systems.[47] From a sustainability point of view, intrinsically conductive polymers are suitable for products that are designed to be disassembled and re-used at the end-of-life due to their non-biodegradability.

Carbon-based conductors are intensively being investigated for obtaining soft, sustainable electronics both in the form of fibers (embedded in polymers) or inks. Recognized for their outstanding properties (mechanical strength, thermal conductivity, and electrical conductivity) carbon-based materials are an excellent candidate for smart textile applications.

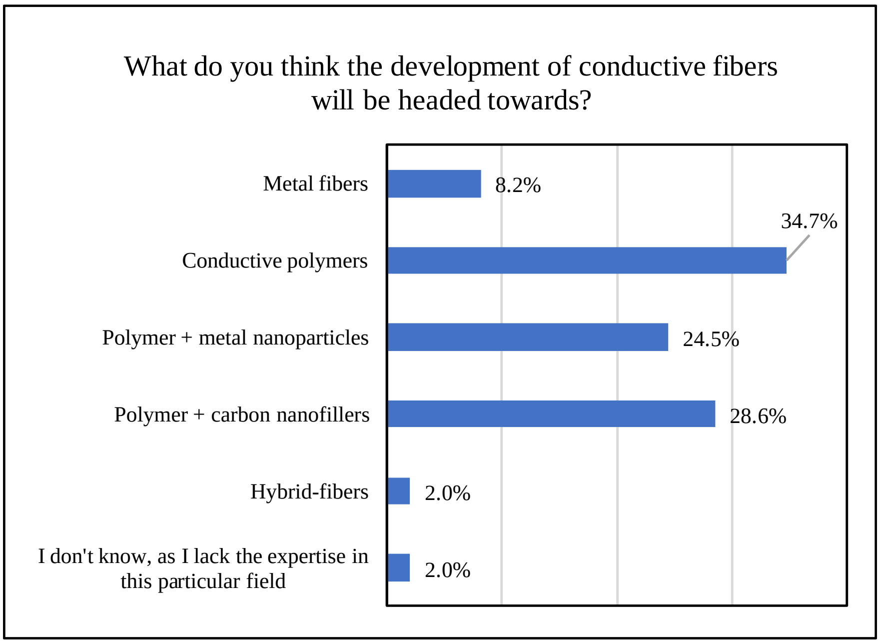

Fig. 5. Percentage representation of the future development of conductive fibers, as seen by textiles experts (CONTEXT participants)

Recently, it has been reported that washable, durable, and flexible graphene-based wearable e-textiles are highly scalable, cost-effective, and potentially more environmentally friendly than existing metals-based technologies.[48–51] Additionally, integrated graphene-based wearable smart textiles may be capable of dealing with both sustainability and the current technical challenges associated with various applications.[32]

As can be seen from Figure 5, the predictions are that conductive fibers will develop in the direction of internally conductive polymers (34.7 %), followed by polymer nanocomposites with either incorporated metal nanoparticles (24.5 %) or carbon nanofillers (28.6 %).

3.3.2. *Future development of bonding elements*

Bonding elements in smart textiles, just like other electronic components, must withstand harsh conditions during the use phase (washing, drying, mechanical abrasion, sweat, UV radiation, etc.). Here are the state of the art technologies for electrical contacting:

• Soldering: based on lead-free solders (alloys of tin, silver, copper, antimony, bismuth).

• Mechanical connections: embroidery of conductive yarn.

• Metallic snap fasteners or metalized hook-and-loop fasteners are used for detachable connections.

• Conductive adhesives that contain metallic particles (typically silver) or carbon black dispersed in monomers, polymers, or biocmponent epoxy resins.

• Non-contact solutions.

The CONTEXT participants find that the development of contacting and bonding elements will lead toward the conductive adhesives that contain metallic particles, carbon fillers, or nanofillers dispersed in monomers or polymers. 60 % of respondents decided on this, followed by mechanical connections like embroidery with 28.6 % (Fig. 6).

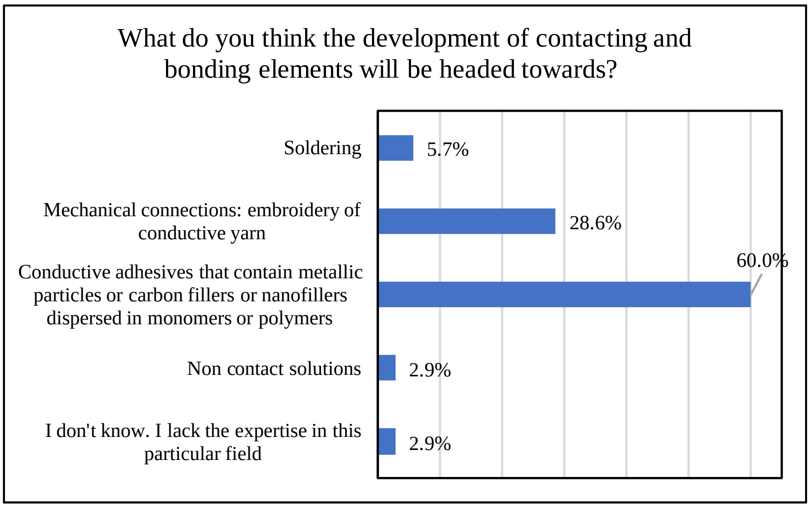

Fig. 6. Percentage representation of the future development of contacting and bonding elements, as seen by textiles experts (CONTEXT participants)

3.3.3. *Future development of power supply units*

Energy harvesting systems are key to sustainable development in smart textiles.[52] Relevant energy harvesting technologies include photovoltaic (harvesting solar energy)[53–55], piezoelectric[56–58] and triboelectric[59–61] (capturing mechanical energy from physical movement), and thermoelectric (harvesting thermal energy, although the power levels demonstrated to date are very small).[62–64] Large progress has been achieved over the last few years toward the development of flexible systems with a higher power output.[65] However, many challenges remain: insufficiency of power output; issues with robustness, reliability, and durability; an inability to preserve textile aspects such as flexibility, drapability, touch, breathability, heat and moisture management characteristics; high cost; processes being difficult to scale up; and potential toxicity of certain compounds.[65]

According to the questionnaire survey results (Fig. 7) in forecasting the development of power devices, priority is given to photovoltaics with 42.1 %, followed by piezoelectric elements with 28.9 % and thermos-generators with 21.2 %.

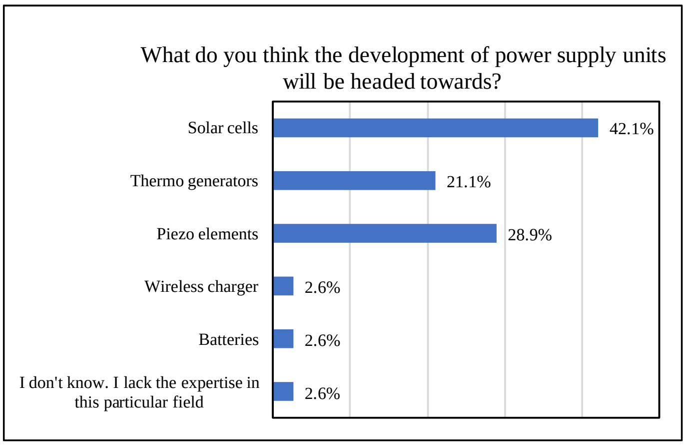

Fig. 7. Percentage representation of the future development of power supply units, as seen by textiles experts (CONTEXT participants)

3.3.4. *Sustainable manufacturing and end-of-life solutions*

The sustainability of smart textiles depends on the sustainability of the textile substrate and the individual electronic elements as well as the sustainability of the manufacturing process. In other words, the textile itself and the electronic elements (insulators, conductors, semiconductors, etc.) need to be fabricated through sustainable fabrication methods and also need to be sustainable themselves in terms of being recyclable and/or biodegradable. The development of environmentally friendly fabrication methods for smart textiles requires actively assessing and minimizing the environmental consequences of the manufacturing.

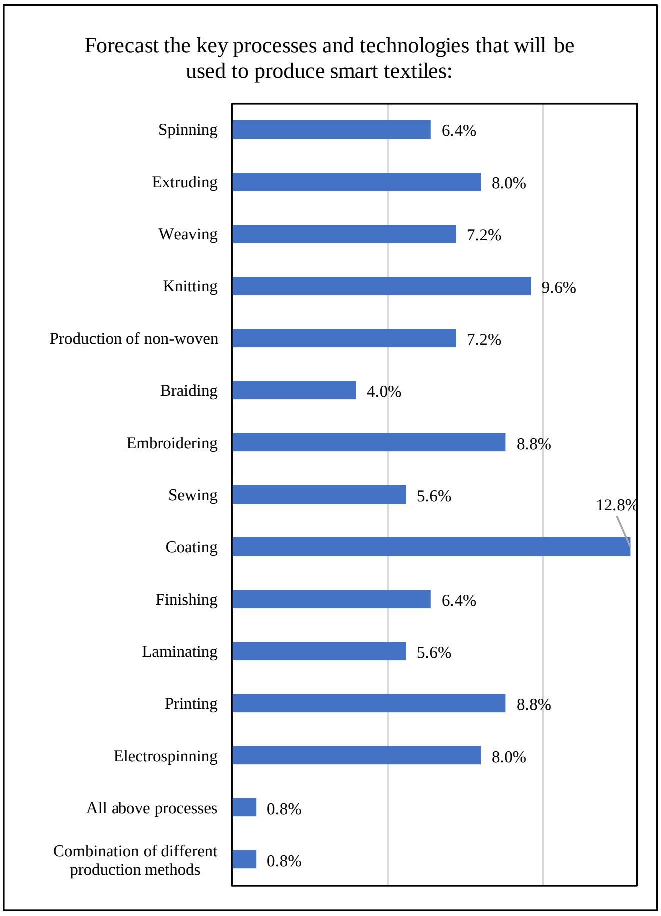

Fig. 8. Percentage representation of the key processes and technologies that will be used to produce smart textiles, as seen by textiles experts (CONTEXT participants)

There are many methods for smart textiles production; the results of the questionnaire survey (Figure 8) show the experts do not prefer a certain type of technology, but almost all methods of production are more or less equally represented in the forecast of the key processes and technologies that will be used to produce smart textiles.

Furthermore, the disassembly of various electronic components needs to be considered to fully recycle wearable electronics at the end of their useful life, and the product recyclability needs to be considered originally in the design phase. The waste and recycling methods are highly dependent on the application area, design, and construction of smart textiles, as well as consumer awareness on waste separation. Hence, the procedures for recycling are truly undeveloped. The wide range of application areas for smart textiles, healthcare and medicine, automotive and aeronautics, personal protective equipment, building and living, and sports and wearables inevitably leads to several waste streams.[14,25,38,39]

A total of 41.3 % of the respondents think that smart textiles should be recycled, 30.4 % think that they should be remanufactured, 26.1 % reused, and only 2.2 % think that they should end up in landfills (Fig. 9).

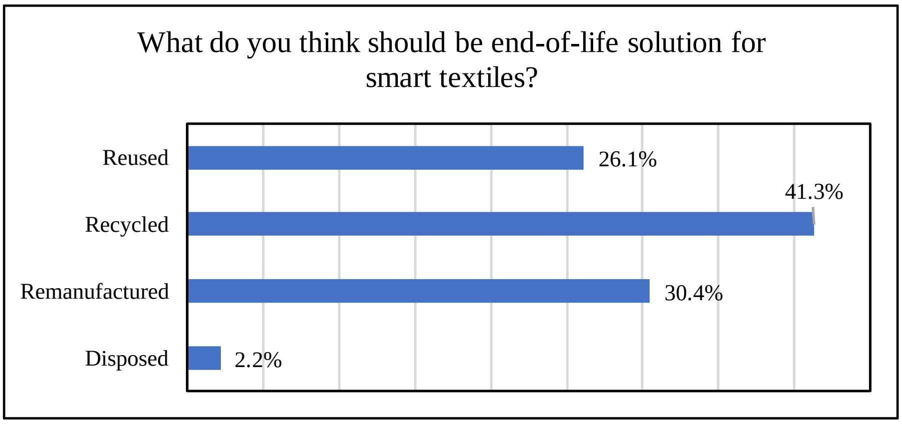

Fig. 9. Percentage representation of the end-of-life solution for smart textiles, as seen by textiles experts (CONTEXT participants)

Currently, three principles are suggested according to which the end consumer will dispose of smart textiles: down cycling at home (using textile parts), recycling as electronic waste, or recycling as an old textile product.[25] International levels of waste stream systems are, however, irregular, and smart textiles, being in a multidisciplinary field, hinder one system implementation.

The results from the questionnaire survey show that the textile experts find recycling as electronic waste as the most plausible end-of-life solution for smart textiles with 46.2 %, followed up by recycling as an old textile product with 38.5 % and down cycling at home with 12.8 % (Fig. 10).

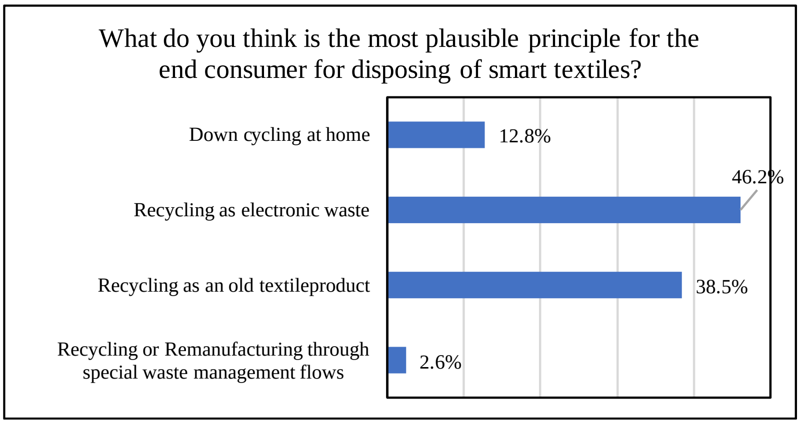

Fig. 10. Percentage representation of the most plausible principle for the end consumer for disposing of smart textiles, as seen by textiles experts (CONTEXT participants)

In the situation where many issues related to the recycling of smart textiles are not resolved, it is very important that designers should prolong the useful life of smart textiles. This implies designing products for repair, refurbishment, and reuse, thus giving preference to waste prevention over recycling. The reuse and repair strategies also reduce the consumption from primary resources.

Furthermore, the governments and higher authorities must support sustainability as they support innovative developments. The imposition of regulations may force integration of green thinking into the new designs and challenge the existing ones. The European initiative "European Green Deal"[66] provides an example of this guidance.

Lately, the European Commission – Joint Research Centre has published a paper on a techno-scientific assessment of the management options for used and waste textiles in the European Union. This document may awaken the awareness of the researchers, industries, and the public regarding to the bottlenecks and future work on textile circularity and sustainability. The document also gives information about waste management and points out the necessity of a well-functioning textile re-use and recycling market for a sustainable and circular textile economy.

The European Commission also proposed some policy measures for the waste management of textiles in the "2023 Waste Framework Directive revision", consisting of actions such as the amendment of relevant measures in related legislation to facilitate waste prevention.

The certifications and global labels given to the products on the market may also contribute to educate the consumer to the environmental impact and encourage industry to adapt their products. As an example, OEKO-TEX® STANDARD 100[67] is one of the world's best-known labels for textiles tested for harmful substances. In particular, smart textiles with passive properties like antibacterial effects may obtain this label if they don't contain harmful materials.

4. STANDARDIZATION ON SMART TEXTILES

Standards are used for different purposes, including (i) testing and characterizing materials and products and (ii) assessing them against certification schemes or legislative requirements. Smart textiles standardization started in 2009 with the establishment of a smart textiles working group under the European Committee for Standardization, which recently enlarged its scope to also include electronic textiles, thus it is now called CEN/TC248 WG31 smart textiles and electronic textiles. This committee developed a first review document on smart textiles, which was revised in 2020 together with its sister committee at ISO (ISO TC38 WG32 smart textiles).[68] In 2023, a document dedicated to electronic textiles was published.[69] While in the first document sustainability was only addressed at a rather high level, the need for developing standards to address sustainability and circular economy issues was identified as a high priority in the second document. While the needs of either textiles or electronics are already addressed elsewhere, they cannot simply be implemented individually for designing electronic textiles. It is therefore necessary to write a dedicated document.

This necessity is confirmed by the results of the survey made in the CONTEXT project, as shown in Figure 11.

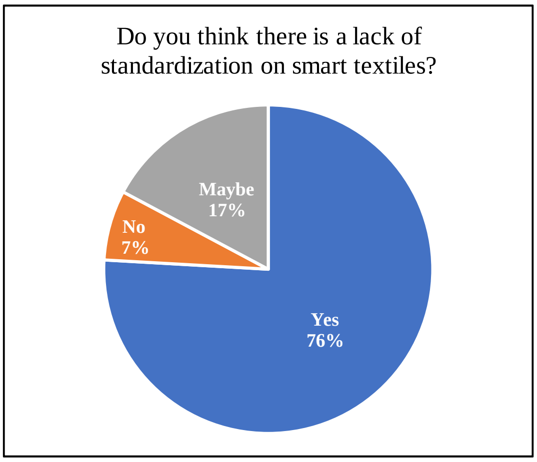

Fig. 11. Percentage of smart textiles experts (CONTEXT participants) that think that there is a lack of standardization on smart textiles

The two above-mentioned working groups therefore started working on a document with recommendations and guidelines on how to design smart textiles and electronic textiles which are sustainable and suitable for a circular economy. All elements listed in the previous sections of this document will be integrated into this document, together with references to other standards published or under development in the field of circular economies and sustainability. The recommendations and guidelines will be divided into three sections:

1. A general overview of all the different required criteria;

2. A decision tree to guide the designer with choosing and ranking the criteria applicable to the product they are designing;

3. Guidance on how to facilitate the working together among experts in textiles, electronics, and ICT.

The latter item has been identified as one of the most challenging, especially in the development of electronic textiles. In all these years of researching and developing electronic textiles it is still difficult for the different sectors to understand their terminology and a way of working toward design and product development.

The document will also demonstrate how to implement the recommendations and guidelines by providing examples of actual products and/or products under development which are in need of this guidance for finalizing their design.

5. CONCLUSIONS

Even though smart textiles have yet to find their "killer application" that will finally bring them a breakthrough into the mass market, they have a bright future ahead of them. On the one hand, it is the application in professional markets whose specific requirements will require true use of the intelligent innovations that smart textiles can offer. On the other hand, as the world becomes more immersed in digital experiences, smart textiles can enable a richer interaction between the digital and physical worlds. Additional support is the fact that many of the technological bottlenecks related to smart textiles production have already been solved, but also the sustainable solutions for the electronic components have matured, while still being in the early phase of the smart textile development when prevention through design can still be successful. Now, what remains in order to ensure a successful future for smart textiles is to actively involve in the projects, as early as possible, all relevant stakeholders, including the designers, manufacturers, end users, and experts on end-of-life treatment, as well as experts on service and application development. Building a successful community is of crucial importance to ensure all talents, capacities, and knowledge work in better synergy throughout the industry toward one goal, successfully bringing of smart textile products to the markets. Regarding the standardization, it is important that a document dedicated to electronic textiles was very recently published (in 2023), where the need for developing standards to address sustainability and circular economy issues was identified as a high priority. Also, working groups under the European Committee for Standardization were formed that developed a document with recommendations and guidelines on how to design smart textiles and electronic textiles that are sustainable and suitable for a circular economy. Interestingly, one of the biggest challenges, despite all these years of smart textiles development, is the problem to find a way to facilitate cooperation and mutual understanding between experts from the different sectors – textiles, electronics, and ICT.

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