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Circular and sustainable smart textiles for buildings and living: Challenges, pathways, and perspectives

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A R T I C L E I N F O

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Roadmap

A B S T R A C T

Over the past three decades, smart or functional textiles have gradually been introduced to the sectors of building and living, fulfilling a plethora of new applications. Although their show great promise for current and future applications in these domains, their application is often limited and hampered by a significant number of factors. Among these factors, a couple stand out in terms of their significance: sustainability and circularity, and functionalization (interactivity), including certification and standardization. A roadmap in these domains is proposed to remove barriers to the implementation and application of smart textiles in buildings and living. This is done by examining the state of the art in smart textile technology, analyzing the developments, setting the ambitions for the future, investigating the feasibility of options, and making choices and setting priorities. The roadmap can be used by industry and the wider community to make smart textiles a societal and commercial success story.

1. Introduction

The fields of architectural design, real estate development, and construction are in a continuous cycle of research and development aimed at improving the quality of buildings and the built environment – for instance, in terms of cost-effectiveness, speed and ease of construction, as well as sustainability and functionality. One of the innovations in the domains of building and living is smart and functional textile, which over the past thirty years has seen new applications of traditional textiles in the built environment (Venturini Degli Esposti et al., 2022; Priniotakis et al., 2022a, 2022b). These innovations include a plethora of new applications which range from the more obvious acoustic and thermal insulation and shading systems, which are an extension of the traditional applications of textiles in the form of furnishing materials such as carpets and curtains, to more advanced such as smart flexible thermo-insulation or for energy harvesting applications. Advances in technical or high-performance textiles have given significant, though often unseen, momentum to the building sector (Hamza et al., 2018). Despite popular belief, and perhaps popular misunderstanding, high-performance textiles are not visible in the form of curtains and furnishings inside buildings, but actually come as types of fibers that are mixed with concrete, as fiber glass reinforcement meshes and insulators (Libotean et al., 2018). As Priniotakis et al., 2022a, 2022b and Venturini Degli Esposti et al. (Venturini Degli Esposti et al., 2022) have shown, textiles pose a highly relevant area for future innovations that could profoundly impact the quality of indoor environments in buildings, including dwellings, office buildings, military facilities, schools and health care facilities. According to Gehrke et al. (2019), the term “smart textiles” has reached the general public and has significantly increased the demand for new, functional textile products. Still, when speaking of smart textiles, it is important to provide a definition of this terminology. The term smart textiles emerged in the late 1990s when intelligent materials were introduced into textiles and textile products. Smart

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List of abbreviations

AA –	Ascorbic Acid
CE –	Circular Economy
CEN –	European Committee for Standardization
EoL –	End of life
e-textiles –	Electronic textiles
GOTS –	Global Organic Textile Standard
IoT platforms –	Internet of Things platforms
ISO –	International Organization for Standardization LCA
LCA –	Life Cycle Assessment
LCC –	Life Cycle Cost
LEED –	Leadership in Energy and Environmental Design
PCM –	Phase Change Materials
PS –	Polystyrene
PU –	Polyurethane
RCS –	Recycled Claim Standard
SMEs –	Small and Medium Enterprises
TR –	Technical Report
TRL	Technology Readiness Level

textiles can be defined as textiles that are able to sense stimuli from the environment, to react to them, and adapt to them by integration of functionalities in the textile structure (Van Langenhove et al., 2007). Both stimuli and response can be electrical, thermal, chemical, magnetic or of another kind. The European Committee for Standardization (CEN) defined smart textiles in the withdrawn technical report (TR) 16298:2011 (European Committee for Standardization, 2011), and later in the TR 23383:2020 (European Committee for Standardization, 2020), as intelligent systems consisting of textile and non-textile components that actively interact with their environment, a user, or an object. Data are recorded and processed via sensors, and a defined reaction is generated via actuators or an information display on an additional device. Additionally, there are three distinct degrees of intelligence that can be identified (Tao, 2015). There are passive smart textiles that can only sense the environment, and they serve as sensors. Then, there are active smart textiles that can sense the stimuli from the environment and react to them. They also serve as an actuator. And last, so-called very smart textiles can adapt their behavior to dynamic conditions. For a textile structure to be considered a smart textile, both sensor and actuator components must be present in the material, which a processing unit can then supplement to control the exchange between these components.

As smart textiles promise support in almost all situations, including applications in sports, health, home and living, mobility, or building, new markets and business models may be opened for both consumer and technical products (Priniotakis et al., 2022a). There is a predicted market for smart textiles of approximately €2.8 billion for 2026, with an average annual growth rate of 34% (Beh et al., 2023). Although smart textiles hold great promise for current and future applications in the domain of building and living, their application is often limited and hampered by a significant number of smaller and larger factors. Among these factors, there are two factors that stand out in significance, which can be described as challenges to the mass or large-scale implementation and application of smart textiles in building and living. These are sustainability and circularity on the one hand, as well as functionalization (interactivity) on the other hand. Each of these innovations is at different technology readiness levels (TRL) and are related to elements as the certification and standardization of new products.

To remove barriers to the implementation and application of smart textiles in buildings and living, we propose a roadmap for these two domains. We do so by analyzing the state of the art in smart textile technology (current situation), analyzing the developments (what lies ahead of us), setting the ambitions for the future (where do we want to go?), analyzing feasibility of options (how can be get there?), and making choices and setting priorities (which route do we follow/take?). A comprehensive roadmap for the industries and the wider community can help move the smart textiles agenda and practice forward, making smart textiles a societal and commercial success story.

2. Sustainability and circularity

Considering sustainability and circularity, we need to consider the environmental impact and customer demands related to the enhanced performance of smart textiles. Designing textiles with circularity in mind promotes recycling, reuse, and waste reduction, aligning with broader sustainability goals. By minimizing waste and maximizing resource efficiency, they can contribute to a more sustainable building and living ecosystem (Brydges, 2021). With growing awareness and concern about environmental issues, consumers increasingly seek out sustainable products. Incorporating sustainability into smart textile solutions can enhance their market appeal and encourage adoption (Seock et al., 2024). Further, functionalization and interactivity enable smart textiles to perform a wide range of tasks beyond traditional fabrics, such as sensing, actuating, and communicating (Lymberis and Paradiso, 2008). Interactivity allows for customization and personalization, whether it is adjusting temperature, lighting, or providing health monitoring, interactive smart textiles offer tailored experiences for users (Sheng et al., 2024; Labbaf et al., 2023). One of the most significant challenges for textiles is the increasing amount of waste coming from textile production and second-hand textiles, most of which ends up either in landfill or gets incinerated. About 73% of the materials entering the textile system are lost after the final use of the clothes, the main application domain of textiles (Khairul Akter et al., 2022). A large proportion of these textiles can still be reused, and a significant proportion can be recycled into new products, including for the construction sector.

European Union requirements mandate that from January 1, 2025 onwards, textiles will be collected separately (European Commission, 2023). Municipalities are responsible for organizing the municipal waste management system, including the collection of textile waste. They currently apply various measures to collect this waste. The European Commission's Circular Economy Action Plan - the EU Textile Strategy, aims (1) to strengthen the EU market for sustainable and circular textiles, including the textile reuse market, (2) to tackle fast fashion, and (3) to introduce new business models. The strategy aims to promote the sorting, reuse, and recycling of textiles by encouraging industrial adaptation and regulatory measures such as extended producer responsibility (Huang et al., 2024).

The circular economy is one potential solution to ensure sustainable economic development. The basic idea of the circular economy is about reducing the use of resources and waste through intelligent product design – circular design, reuse of products and raw materials, product repair, recycling, responsible consumption, and innovative business models (Saskia et al., 2019). The aim is to integrate circularity and sustainability into all stages of the value chain, from the design phase to production and ultimately to the consumer (Tokede et al., 2022). The key is implementing life cycle sustainability assessment to understand the sustainability impacts of building projects across their entire life cycle. Here, the selection of materials is crucial for building structural systems that are able to contribute to achieving net-zero emissions in the environment (Tokede et al., 2022).

Smart textiles are a rapidly growing field with the potential to revolutionize many industries. However, the lack of standardization and certification can hinder their development and adoption. There are only a few existing standards and certifications that are relevant to smart textiles, but they are not specific to this field. For example, the OEKO-TEX Standard 100 (Standard OEKO, 2025; OECD Publishing, 2025) certifies that textiles are free from harmful substances, however, it does not address the safety or performance of electronic components.

Future developments related to sustainability and circularity in the smart textile sector should cover two main aspects. Firstly, there are different ways to increase the level of sustainability of different products and services. Bearing in mind that these goods can be constantly improved by many technical and organizational approaches, it does not seem suitable to define at the moment which way should be followed. However, there is one common element accepted by the scientific community, which is the way to measure the level of sustainability. This metric is an ecological footprint, which calculates how much of the Earth's biocapacity (or "regenerative capacity") is consumed by a specific activity, considering the whole life cycle of a good (Wackernagel et al., 2019). Both research and practice in ecological footprint calculations are advanced enough to apply to many products, and some organizations are calculating it already without legal regulations that make it obligatory. During the United Nations Biodiversity Conference, which was held 7-19 December 2022 (COP15), “footprints” (i.e., ecological footprint, carbon footprint, water footprint, etc.) were widely discussed as one of the basic indicators for monitoring biodiversity health (GFN, 2022) (Conference of the parties to, 2022). Therefore, allowing the application of all technologies and organizational approaches, the ambition in terms of sustainability in smart textiles should be to produce goods with a reduced ecological footprint, preferably with a lower ecological footprint than the products that they replace.

Secondly, in terms of circularity, there is a need to assign a proper order of ecological actions to implement the bioeconomy concept. For that purpose, the 6Rs approach (Retiring, Retaining, Rehosting, Replatforming, Refactoring, and Re-architecting) is necessary to apply, which sets the hierarchy of steps. Starting from redesign, followed by reduce, remove, reuse, recycle, and ending with the recover phase (European Commision, 2018), representatives of the smart textile business should follow circularity actions according to their environmental priority. It is a good sign that the recycling of materials is becoming more and more common in the textile sector, however, redesigning products in an environmentally-friendly manner, reducing the amount of its production, which is more balanced with real needs, or promoting reusing existing products has a greater impact on the state of the environment. Therefore, an ambition in terms of circularity of smart textiles should be connected not only with the end of the cycle but mostly starting from the very beginning of the whole process of smart textile production.

The sustainability and circularity of smart textiles can be achieved by thinking outside the box. Based on experiences in the textile sector in general, the smart textiles industry should ideally tailor eco-design approaches (Edwin et al., 2021) to minimize its negative environmental impact during the initial phase. There is still a capacity for re-engineering the textile industry, which can be defined as something that can be rethought, re-evaluated, renewed, and restructured within the context of conventional textile processes while considering eco-friendly solutions for increased environmental sustainability (de Oliveira et al., 2021). Once this step is taken care of, other aspects should also be considered like recycling, which was in the scope of the latest research for some years. However, three elements could be considered in parallelly. One is recycling old textiles into new textiles (Kahoush and Kadi, 2022), the second is recycling other materials to produce textiles (Shukla et al., 2008), and the third is recycling textiles to produce other goods (Vera et al., 2023; Cho et al., 2023). The synergy effect of all these actions together can bring the smart textile industry closer to the goal of a sustainable and circular sector.

Recyclability is one of the key challenges of the textile industry because of the generation of large amounts of waste and pollution. To address this issue, researchers are developing methods for the recyclability of textile materials, including the use of recycled fibers, biodegradable materials, and closed-loop production processes. The recyclability of textile materials is a growing concern as the fashion and textiles industry is one of the largest polluters in the world, both in terms of water usage and waste generation. However, significant efforts are being made to increase the recyclability of textile materials and to reduce their environmental impact.

The corpus of the literature in this field is growing. For instance, Sandin and Peters (2018) provided a comprehensive overview of the current state of textile waste recycling and upcycling. They presented the current challenges and potential solutions to improve the sustainability of the textile industry, including reducing textile waste and maximizing the use of recycled materials. There also exist many different techniques which focus on various mechanical, chemical, and biological methods for recycling textile materials, providing an overview of the advantages and disadvantages of each method and making recommendations for improving the efficiency of textile recycling (Juanga-Labayen et al., 2022; Tadesse et al., 2025; Ribul et al., 2021). Tripathi et al. (2024) provided an overview of the current state of textile recycling, including technologies to recycle textile wastes. Furthermore, Juanga-Labayen et al. (2022) reviewed the current state of textile waste recycling, including the challenges and opportunities for improving the efficiency of the recycling process. These aforementioned studies highlight the challenges and potential solutions to improve the sustainability of the textile industry.

One approach is to use more sustainable fibers, such as organic cotton, linen, hemp, and bamboo, which are biodegradable and compostable. Another approach is to use recycled fibers, such as recycled polyester, which is made from post-consumer plastic waste. This not only helps to reduce waste but also reduces the need for virgin petroleum, a finite resource. In addition to using sustainable fibers, there are also efforts to improve textile recycling processes. This includes developing new technologies for separating and purifying different fibers, as well as for breaking down textiles into their constituent materials so that they can be reused or repurposed. However, despite these efforts, the recycling of textile materials remains a challenge due to the complex nature of textiles and the various materials and dyes used in their production. Nevertheless, it is important to continue exploring new and innovative solutions for improving the recyclability of textiles and reducing their environmental impact (see Fig. 1).

The priority for sustainability and circularity in the textile materials industry depends on several factors, including the current state of the industry, the availability of resources and technologies, and the level of consumer demand for sustainable products. In general, there are several priorities that are commonly recognized as important for promoting sustainability and circularity in the textile materials industry. In Fig. 2, we have included the reduction of waste, the use of sustainable fibers, the improvement of recycling, the enhancement of products' lifecycle, and the encouragement of consumer education with the description:

Reducing waste: Reducing the amount of waste generated in the production and use of textiles is a critical priority. This includes reducing the amount of water and energy used in production, as well as the amount of waste generated during the lifecycle of a textile product.

Using sustainable fibers: Using sustainable fibers, such as organic cotton, linen, hemp, and bamboo, helps to reduce the environmental impact of textiles by reducing the use of non-renewable resources.

Improving recycling: Improving the recycling of textiles is important for reducing waste and promoting circularity in the industry. This includes developing new technologies for separating and purifying different fibers, as well as for breaking down textiles into their constituent materials so that they can be reused or repurposed.

Enhancing product lifecycle: Enhancing the lifecycle of textile products by making them more durable and easily repairable helps to reduce waste and promote sustainability.

Encouraging consumer education: Encouraging consumer education about the environmental impact of textiles and promoting sustainable choices is an important priority. This includes promoting awareness of sustainable fibers and recycled materials, as well as encouraging consumers to recycle and reuse textiles.

These priorities can vary depending on the specific needs and challenges of the industry and the region, but they all play an important role

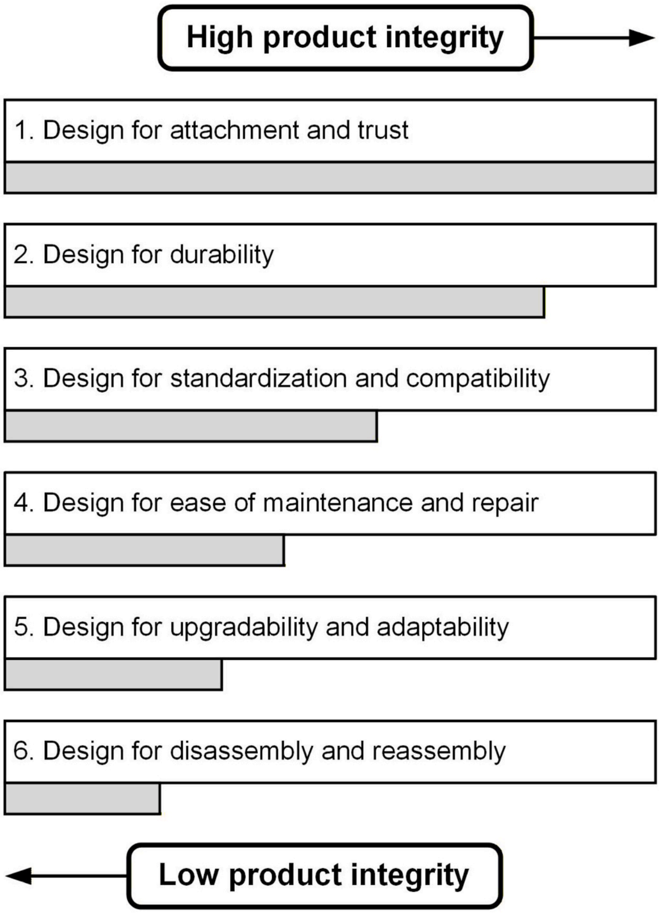

Fig. 1. Six design strategies for longer lasting products (The Ministry of Infrastructure and, 2016; Fifield et al., 2016).

in promoting sustainability and circularity in the textile materials industry. One of the promising ways forward is through so-called green chemistry. The use of hazardous and toxic chemicals in the production of textiles is a major environmental concern. Green chemistry aims to replace these chemicals with safer, more sustainable alternatives, such as bio-based solvents and dyes, to reduce the environmental impact of textile production (Mouro et al., 2023). Valuable information on the application of green chemistry in the textile industry, including textile processing, dyeing and finishing, and wastewater treatment, can be found in the literature that highlights the principles and practices of green chemistry and their implementation in these processes, as well as the challenges and opportunities for the implementation of green chemistry in the textile industry. Roy Choudhury (Roy Choudhury, 2013) published a comprehensive overview of the application of green chemistry in textile processing, including the principles and practices of green chemistry and their implementation in the textile industry. The scholars also discussed the challenges and opportunities for the implementation of green chemistry in textile processing. Additionally, Gaikwad (Gaikwad et al., 2022) reported that the application of green chemistry in textile dyeing and finishing, including the principles and practices of green chemistry and their implementation in these processes, had been studied. The authors made recommendations for the implementation of green chemistry in textile dyeing and finishing. Shuchita et al. (Tomar et al., 2023) reported a comprehensive overview of the application of green chemistry in textile wastewater treatment, including the principles and practices of green chemistry and their implementation in textile wastewater treatment processes. It shows how the application of green chemistry in textile production has a direct impact on the safety, sustainability, and health impacts of textile products, especially when used in enclosed, near-human environments, i.e., built environments. This contributes to healthier, greener, and more responsible interior solutions. Textiles in the built environment, such as carpets, upholstery, insulation, and wall coverings, often involve dyes, finishes, and coatings that can release hazardous chemicals and affect indoor air quality. Applying green chemistry helps replace these with safer, bio-based alternatives, improving durability and performance while reducing toxicity. Research on green chemistry in textile processing, dyeing and finishing, and wastewater treatment shows how sustainable practices can lower environmental impact and promote healthier indoor environments when textiles are integrated into buildings.

In addition to green chemistry, sustainable developments in the textile industry can be found through improved water treatment and overall energy savings. The textile industry is a significant contributor to water pollution, due to the discharge of toxic chemicals into rivers and lakes. To address this issue, methods are being developed for the treatment of textile wastewater, including biological and chemical treatments, to reduce the environmental impact of textile production. Energy consumption is a significant issue in the textile industry, particularly in the areas of fiber production, spinning, weaving, and finishing. Energy-efficient textile production, including the use of renewable energy sources, energy-saving technologies, and closed-loop production processes, may be part of the solution towards a more sustainable future. Several articles focus on water treatment and textile materials, providing valuable insights into water treatment in the textile industry. These articles cover various methods for treating textile wastewater and the challenges associated with treating textile wastewater. Furthermore, they highlight the importance of water treatment in the textile industry and provide a useful overview of the field (Catarino et al., 2025; Farhana et al., 2022). Concerning the energy saving in textile production, the literature provides valuable information, including the current state of energy consumption and the various methods for reducing energy consumption. They highlight the importance of energy saving in the textile industry and provide a useful overview of the field (Hasanbeigi and Price, 2012).

Another innovation is a more thorough application of life cycle assessment (LCA) in the textile chain. LCA is a comprehensive approach to evaluating the environmental impact of a product, from raw material extraction to disposal. LCA is used to identify the most sustainable materials, technologies, and production processes for smart textiles, ensuring they have a minimal environmental impact. Several studies have been conducted on the LCA of textile materials, and the results have shown that the production of textile materials is associated with significant environmental impacts, such as greenhouse gas emissions, energy consumption, water usage, and waste generation. To address these issues, researchers are developing new materials and technologies that have a lower environmental impact, and are exploring ways to minimize waste and increase the sustainability of textile production (Fernández-González et al., 2023). These studies highlight the importance of conducting LCAs for textile materials and the need for more sustainable materials, technologies, and production processes. There are some limitations to these LCAs that should be considered. First, the scope of the LCAs may not include all aspects of the life cycle of textile materials. For example, some LCAs may not consider the impact of transportation or the end-of-life disposal of textiles. Second, the data used in the LCAs may not be complete or accurate, which can impact the validity of the results. For example, the data used to calculate greenhouse gas emissions may not be representative of the entire life cycle of the textile. Finally, the interpretation of the LCAs' results may be subjective and depend on the authors' perspective. For example, some authors may place more weight on specific environmental impacts, such as energy consumption, while others can prioritize the impact on water usage. In conclusion, the LCAs of textile materials presented in the two articles provide valuable information on the environmental impact of textile production. However, it is important to consider the limitations

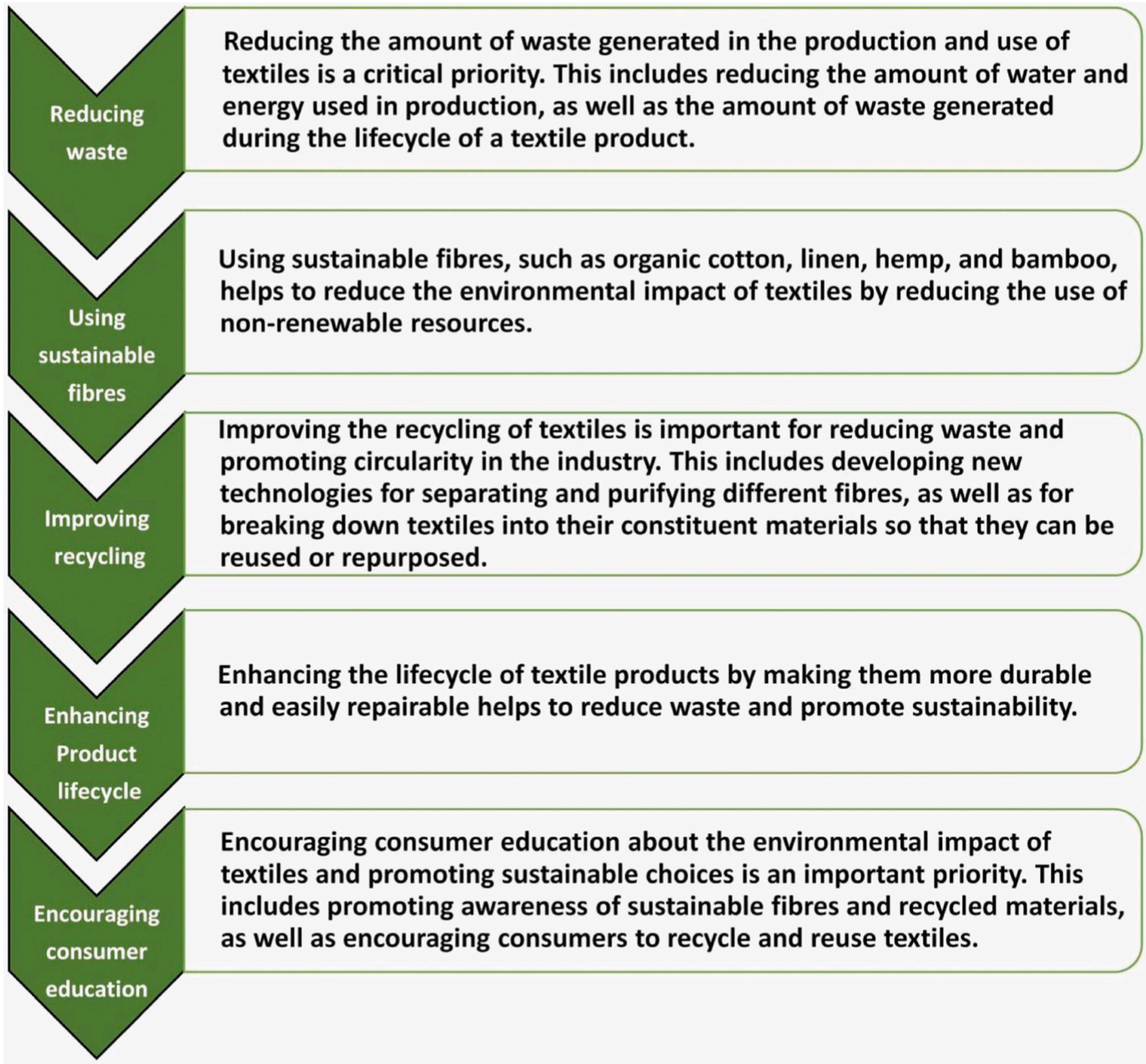

Fig. 2. The listed main priorities recognized in promoting sustainability and circularity in the textile materials industry.

of these LCAs and to continue to improve the methodology and data used in such assessments.

The durability and recyclability of textiles applied in building and living are the key features for obtaining the circularity and sustainability of textile technologies. The textile industry, including textiles for interior design, is very complex and diverse, which is challenging in terms of the global value chain. The supply chain challenges are currently related to energy prices, the security of raw material supply, and impacts on the exporting segments of the textile ecosystem. Small and medium enterprises (SMEs) to strengthen their resilience should focus on innovations, creativity, know-how, and quality textile products to deliver sustainable and more attractive products (European Commission, 2022). There is an urgent need and a strong potential for the transition to sustainable and circular production while looking to improve the product design to allow the application of current recycling technologies.

The remaining challenge is in designing multifunctional and smart building textiles without blending too many synthetic components, which makes recycling more difficult due to the limitations of technologies to separate textile waste (Yousef et al., 2019; Navone et al., 2020). Building and living textiles based on synthetic fiber also play a role in microplastic pollution. To design products for building textiles with less environmental damage, we need to follow the eco-design principle. The eco-design requirements involve following a few key principles. The first is the selection of materials that should be ecological, reusable, recyclable and non-toxic for the environment, and recoverable. The second is using environment-friendly technologies to produce them, which requires little energy consumption, material, and fuel. The third is corresponding to optimal and aesthetic functions that follow color selection, which is not harmful to users and the environment. To fulfill the demand for the increasing applicability of textile technologies in building and living, the priority route is not only to rethink conventional technologies but also to make them sustainable at every step of technical textile production. The remaining challenges are also related to certification systems for eco-friendly construction materials.

The global textile value chain represents a highly complex and interconnected system based on the production and transformation of natural and artificial fibers that serve functional, cultural, and industrial purposes across apparel, household, and technical applications. As one of the world's largest employers and a key contributor to international trade, the textile industry plays a central role in global economic development. At the same time, it faces mounting structural and material challenges that threaten its long-term sustainability, resilience, and capacity for value creation. Historically, the sector has operated predominantly under a linear “take–make–dispose” model, characterized by intensive resource extraction, energy- and water-heavy manufacturing processes, and accelerating product turnover. Over the past 15 years, average garment wear-time has declined by approximately 36%, while less than 1% of textile materials are currently recycled into new clothing, resulting in substantial material value loss and escalating environmental pressures. This linear paradigm has exposed the industry to significant risks, including resource scarcity, waste accumulation, regulatory tightening, and volatility in global supply chains.

Addressing these challenges requires a fundamental transition toward circular economy models in which textile materials are retained at their highest possible value for as long as possible. Circularity in the textile sector is structured around three interdependent loops. The first focuses on reuse, enabling products to be transferred to second or multiple users in order to extend their functional lifetime. The second emphasizes repair and repurposing, supporting maintenance, refurbishment, and upcycling strategies that delay disposal and reduce demand for virgin resources. The third loop involves recycling, relying on both mechanical and chemical technologies to recover fibers or molecular building blocks and reintroduce them into production as high-quality secondary raw materials.

This systemic transformation must also be understood within the global geography of textile production and consumption (Table 1). While demand for textile products is widely distributed across regions, manufacturing remains highly concentrated in Asia, with China playing a dominant role in the intermediate stages of the value chain, particularly in yarn and fabric preparation. This concentration creates critical geographical bottlenecks, amplifying supply-chain vulnerabilities and underscoring the need for more diversified, resilient, and circular production ecosystems. Together, these dynamics frame sustainability and circularity not as optional improvements, but as strategic imperatives for the future of the global textile industry.

The environmental impacts of the global textile industry are concentrated in key hotspots, particularly during raw material extraction and energy-intensive manufacturing. The sector generates approximately 3.3 billion metric tons of greenhouse gas emissions annually, and if current trends persist, this figure is expected to increase by 49% by 2030. The most significant manufacturing hotspot is wet processing, including dyeing and finishing, which accounts for 36% of total emissions due to its reliance on fossil fuels for heating large volumes of water. In parallel, the growing dominance of synthetic fibers, now representing 62% of global textile production, links the industry directly to carbon-intensive fossil fuel extraction and chemical processing. The consumer use phase also contributes substantially, with laundering responsible for 24% of the overall climate footprint (United Nations, 2025). Water use represents a second major environmental pressure, with the textile sector consuming approximately 215 trillion liters of water per year. Cotton cultivation is the primary contributor due to irrigation demands, while frequent consumer laundering further increases freshwater withdrawals. Water scarcity impacts are unevenly distributed, with China accounting for 34% and India for 12% of the global water scarcity footprint, where textile production directly competes with human and ecosystem water needs (Tlatlaa et al., 2023). Land use and ecosystem degradation form a third critical hotspot. Although cotton occupies only 2.5% of global arable land, it accounts for 16% of pesticide use and 4% of synthetic fertilizer consumption. Additionally, regenerated cellulosic fibers such as viscose and modal can contribute to deforestation and biodiversity loss when raw material sourcing is not strictly managed (Kooistra et al., 2006).

Table 1
The list of major countries of textile production and consumption (Notten, 2020).

Region	Share of Fiber Production	Share of Yarn/ Fabric Production	Share of Assembly	Share of Consumption (by GHG)
China	57%	64%	35%	11%
India	13%	9%	7%	1%
European Union	7%	7%	4%	3%
North America	4%	-	-	23%
Bangladesh	1%	-	28%	-

3. Functionalization and interactivity

Functionalization and interactivity of textile materials is a rapidly growing field that is at the forefront of innovation in the textiles and materials science industries. In recent years, there have been numerous advances in the development of functionalized and interactive textiles, see the schematics in Fig. 3, including the advances, which are described as follows.

1.) **Smart Textiles:** The development of smart textiles has been a major area of focus, with researchers developing new ways to embed technology, such as sensors, actuators, and electronics, into textiles. This has led to the creation of textiles that can respond to changes in their environment, such as temperature, light, and pressure, and be used in a wide range of applications, from healthcare and sports to architecture and design. Electronic textiles (e-textiles) are one of the most developing areas as they refer to textiles having electronic components (Zangani et al., 2015). The electrical conductivity in textiles is facilitated by including conductive yarns containing conductive material or coatings based on carbon, silver, or other metals (Chen et al., 2022; Krysiak et al., 2022). The created material functions as a multifunctional conductive textile sensor, capable of detecting pressure, motion, respiration, and temperature while maintaining high flexibility, breathability, and durability. The breathable and porous composite structure based on PVDF fibers coated by carbon nanotubes serves as a foundation for smart wearable electronics, enabling real-time monitoring of physiological and environmental signals without sacrificing comfort (Kopacz et al., 2025a, 2025b).

We discover their importance in health and fitness sensing by the possibility of incorporating electrophysiological, temperature, and strain resistors, able to measure electrical activity produced by muscle, brain, and heart (Jung et al., 2007, 2014; Dagdeviren et al., 2016; Kim et al., 2011). Additionally, wearable sweat sensors enable the non-invasive measurement of biomarkers in human sweat, providing a promising approach to address the shortcomings of conventional hospital-centered healthcare. A wearable sweat sensor that integrates a 3D $Ni_3(HITP)_2$ electrochemical sensor with a bioinspired Janus fabric, capable of detecting ascorbic acid (AA) and glucose in human sweat (Yang et al., 2026). Similarly, other studies using ampere-responsive molecularly imprinted polymer-based electrochemical sensors and bionic microchannels have demonstrated rapid, selective detection of biomarkers such as cortisol, glucose, and lactate, highlighting the expanding potential of wearable, biomimetic sweat sensors in dietary health management, exercise monitoring, and disease prevention (Liao et al., 2025a, 2025b). Another aspect is communication that is achieved via wireless systems, enabling continuous monitoring (Du et al., 2024). Importantly, a huge part of tissue engineering lies in the fiber-based meshes, patches, and biodegradable scaffolds used as biomaterials (Jiang et al., 2021a, 2021b; Pattnaik and Swain, 2022; Kaniuk and Stachewicz, 2021). The sensing features in scaffolds are often based on piezoelectric polymers, enhancing the regeneration process in tissues (Szewczyk et al., 2019a, 2019b, 2023). For us, thermal comfort due to the thermal conditions of the human body is crucial for all psychological functions and efficient body energy management. The regulation of our thermal comfort has a prominent impact on the energy consumption of building heating, cooling, and ventilation (Peng et al., 2021).

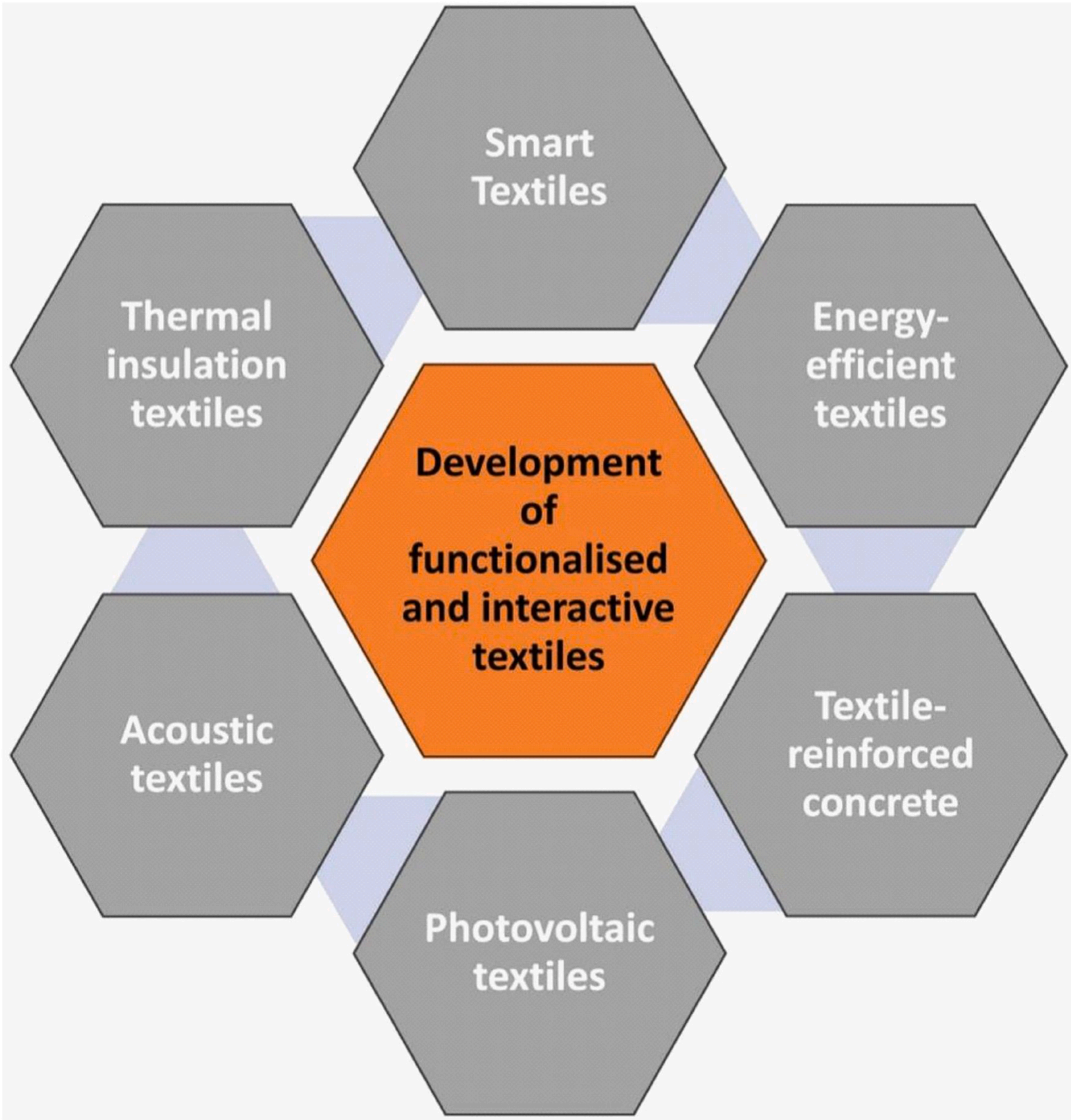

Fig. 3. The selected advances in the development of functionalized and interactive textiles.

2.) **Thermal insulation textiles:** Thermal insulation materials are designed to reduce the transfer of heat between objects and spaces. The ideal characteristics of thermal insulation materials are having low thermal conductivity, which minimizes heat transfer, such as trapped air or gas pockets, inhibiting the movement of heat (Ijjada and Nayaka, 2022). Air can be trapped between materials or inside pores offering high resistance to heat flow, meaning they impede the transfer of heat effectively. However, a non-porous structure can prevent the circulation of air within the material, which can reduce heat transfer through convection. Additionally, insulation materials should be chemically stable and durable to ensure long-term performance and resistance to degradation from exposure to moisture, environmental factors, and chemicals, while withstanding mechanical stresses and maintaining their insulating properties over time. Besides, low-density materials are often preferred for insulation applications because they are lightweight and easier to handle, transport, and install. Common materials used for thermal insulation include glass fibers (fiber glass) insulation (Cao et al., 2015), which is widely used due to its affordability, fire resistance, and effectiveness in trapping air pockets. Similarly, mineral wool is made from natural or synthetic minerals and offers excellent thermal insulation properties along with resistance to fire, moisture, and pests (Raja et al., 2023). Here, cellulose insulation can also be used from recycled paper or plant fibers treated with fire retardants (Pal et al., 2021). It is eco-friendlier and offers good thermal performance. However, the most popular are extruded or expanded polystyrene (PS) foam boards, which provide high thermal resistance and are suitable for insulating walls, roofs (Gaidhani et al., 2023), and floors. Further, spray polyurethane (PU) foam expands to fill cavities, providing an effective air barrier and high insulation value and it's commonly used in hard-to-reach areas (Gama et al., 2018). Moreover, reflective insulation materials, such as foil-faced insulation, reflect radiant heat, reducing heat transfer through radiation. Selecting the right insulation material depends on factors such as the application, desired thermal performance, budget, and environmental considerations. The nontechnology research, including the smart textiles, has a large field of development of new and lightweight materials with high thermal insulation properties (Syduzzaman et al., 2023). Example are highly porous aerogel materials with a gel-like structure and extremely low density. Aerogels can be made from various materials such as silica, carbon, and polymers and exhibit extremely low thermal conductivity and good transparency (Guo et al., 2022, 2023). Aerogels have the lowest refractive index and dielectric constant of all solid materials. These remarkable properties create opportunities for their application in buildings, with potential uses ranging from insulation to novel construction materials (Balaji et al., 2022). Ongoing research continues to explore new developments and applications for aerogels in the field of building materials (Nguyen et al., 2022). Nanocomposites, which can be composed of a matrix reinforced with nanoparticles such as carbon nanoparticles, nanotubes, graphene, or nanoclay into polymers or other matrices, can reduce thermal conductivity, leading to improved insulation performance. The properly selected insulation materials, including various foams and textiles, can save approximately 65% of energy (Hadded et al., 2016). Nature-inspired research (Metwally et al., 2019) in thermal management is contributing to the development of new and sustainable solutions to reduce heat losses in buildings (Hu et al., 2019). To improve energy efficiency, sustainable, flexible insulation materials inspired by nature, such as polar bear hairs and cactus fibers, have been developed to minimize heat loss. A bioinspired one-step fabrication method enables the creation of nanogroove polymer fibers via humidity-controlled electrospinning, replicating the nanoscale structure of Old Man Cactus hair to enhance insulation performance (Ura et al., 2025). Similarly, hollow double-shell fibers inspired by polar bear fur achieve low thermal conductivity ($0.031\ W\ m^{-1}\cdot K^{-1}$) while maintaining flexibility and adaptability to different surfaces (Knapczyk-Korczak et al., 2024). Together, these advances demonstrate how nanoscale morphology engineering and biomimetic fiber architectures can deliver lightweight, efficient, and eco-friendly thermal insulation materials, supporting global efforts to reduce energy consumption and carbon emissions.

3.) **Energy-efficient textiles:** Researchers are also exploring new ways to use textiles to improve energy efficiency in buildings and other applications. This includes developing textiles that can regulate temperature, reduce heat loss, and improve insulation. Further by incorporating the phase change materials (PCM), composite materials are capable of storing and releasing thermal energy during phase transitions (Das et al., 2024, 2025). Nanoparticles can be added to PCMs to enhance their thermal properties, such as increasing heat transfer rates or improving thermal stability (Moradi et al., 2023). The temperature-controlling textiles are based on the phase change materials, such as paraffin waxes that change phase from solid to liquid. It is accompanied by the absorption and storage of large amounts of thermal energy. The release of stored heat energy happens in the reverse transition from liquid to solid state. The embedding of phase change materials in textiles can help to maintain a consistent temperature (Pielichowska and Pielichowski, 2023). Energy-efficient textiles are revolutionizing the way we approach clothing, home fabrics, and industrial materials by reducing energy consumption throughout their entire lifecycle. Among the most innovative developments are smart and adaptive textiles, low-energy production materials, and self-cleaning, anti-stain finishes (Dejene, 2025). Additionally, low-energy production materials significantly contribute to sustainability. Fibers made from recycled or bio-based sources often require far less energy to produce than conventional synthetic fibers. Examples include recycled polyester, which repurposes post-consumer plastic bottles, as well as bamboo and hemp fibers, which are naturally renewable and biodegradable. By utilizing these materials, manufacturers can minimize the environmental impact of textile production while maintaining high-quality performance (Ahmed et al., 2025). Finally, self-cleaning and anti-stain finishes help conserve energy by minimizing the need for frequent washing. Advanced coatings, such as TiO_2 nanoparticles, create hydrophobic surfaces that repel water and dirt, enabling fabrics like cotton to remain cleaner for longer periods. This reduces both water and energy consumption, extending the life of garments and textiles while maintaining hygiene and appearance (Taliantzis and Ellinas, 2025).

4.) **Textile-reinforced concrete:** The integration of textiles into concrete has become a popular approach for improving the strength and durability of concrete structures. This involves incorporating textile materials into the concrete mix to provide additional reinforcement and improve its performance. Textile-reinforced composites, including concrete, are used to strengthen the constructions and increase their flexibility and fire resistance by replacing the traditional steel reinforcement (Venigalla et al., 2022). In natural composites, nonwoven fibers, such as keratin or collagen (Metwally et al., 2019; Stachewicz, 2021; Szewczyk and Stachewicz, 2020) are used for reinforcements, reducing cracks and improving the ductility behavior of materials which is the case in textile-reinforced concrete (Raupach and Morales Cruz, 2016). Here crucial is the bonding strength between fibers and matrix, apart from applying fibers with high elastic modulus to increase the toughness of composites (Sun et al., 2022). From the materials design strategies, the length of the fibers used as reinforcements and their arrangements affect the composite's performance (Rajak et al., 2021; Priyanka et al., 2017). Here high-performance carbon and glass fibers and textiles are incorporated in concrete to obtain lightweight structures. The advantage of flexibility in shape and resistance to corrosion of the textile fabrics is used to achieve a high degree of composite material utilization. In concrete, the reinforcing fibers can be distributed uniformly and oriented randomly and can be woven into pure textiles to form shells, bridges, or sandwich panels (Hong et al., 2021). Still, there are many challenges to overcome in terms of materials design. However, the performance and reliability of various pilot projects show great potential for the textile industry to be involved in civil engineering (Raupach and Morales Cruz, 2016).

5.) **Photovoltaic textiles:** The development of photovoltaic textiles, which can generate electricity from sunlight, has also been a growing area of interest. These textiles offer a unique way to incorporate renewable energy sources into building and living spaces. Wearable electronics have extended into solar textiles (Mather and Wilson, 2017). The development of photovoltaic textiles, which enable the generation of electrical energy from solar radiation, has emerged as a significant research direction in the field of sustainable and wearable technologies. These innovative materials offer a novel means of integrating renewable energy sources into both architectural environments and everyday life. Photovoltaic fabrics are increasingly incorporated into wearable electronics, enabling garments and accessories to supply power to various low-energy devices, such as fitness trackers, smartwatches, and compact medical instruments. Additionally, these textiles hold potential in outdoor and off-grid applications, for instance, in camping equipment such as backpacks and tents, where they provide energy autonomy in remote settings. In the context of the built environment, photovoltaic textiles may be employed in architectural elements, including awnings, blinds, and roofing structures, thereby contributing to the decentralized generation of electricity and enhancing building energy efficiency. Although still in the early stages of technological maturity, photovoltaic textiles represent a transformative innovation with the potential to reshape energy consumption and distribution practices on both individual and structural levels. Ongoing research efforts are focused on improving the efficiency, durability, and adaptability of these materials, and continued advancements in this domain are likely to result in a broader spectrum of practical applications in the near future.

6.) **Acoustic textiles:** The use of acoustic textiles to control sound and reduce noise levels in buildings is another growing area of focus. Researchers are exploring new ways to create textiles that can absorb or deflect sound waves, providing an effective and aesthetically pleasing solution for controlling noise pollution. As noise pollution increasingly affects our lives, materials science and engineering in sound absorption and scattering are gaining more interest. The acoustic properties of materials depend on their structure and porosity. Especially textiles can reduce noise and vibrations, especially in cars, trains, air, and spacecraft and ships. Soundproofing in buildings is important for maintaining the health and well-being of the residents (Padhye and Nayak, 2016). Thermal insulation materials often combine acoustic insulation properties. These products can also be obtained by using recycled textiles. This sustainable approach plays an important role in energy savings and the reduction of environmental pollution. Many conventional acoustic and thermal materials, such as polyurethane foam or mineral wool, adversely affect the ecosystem. Textile products designed by considering the life cycle of production can provide multifunctional properties and solutions to current environmental issues.

Overall, the functionalization and interactivity of textile materials is a rapidly evolving field, and researchers are continuously exploring new and innovative ways to integrate technology into textiles and create new applications for these materials. The functional textile market and sectors are continuously growing. Smart textiles can be developed in a sustainable way giving the benefits of adjustable functions according to specific needs (Dulal et al., 2022). One of the most promising are flexible triboelectric (Busolo et al., 2021) and thermoelectric (Sun et al., 2020) generators converting the energy generated by the human body into electrical energy. Additionally, the on-body monitoring and analysis of our health via blood pressure and heartbeat, but also sweat using patches that realize the real-time monitoring of biomarkers (He et al., 2019).

As shown in the previous paragraphs, the ambitions for future smart textiles are vast and varied, driven by the desire to enhance functionality, comfort, sustainability, and connectivity in clothing and various other applications. Future smart textiles may integrate advanced sensors capable of monitoring various physiological parameters such as heart rate, body temperature, and hydration levels. These textiles could provide real-time feedback on health and performance metrics (Meena et al., 2023).

Moreover, the adaptive properties such as shape-changing or color-changing capabilities could dynamically respond to environmental stimuli or user preferences, offering enhanced comfort and utility (Ruckdashel et al., 2021). Here, the active heating or cooling can optimize thermal comfort in different environments, reducing reliance on traditional systems (Peng and Cui, 2020). Similarly, moisture-wicking fabrics can enhance comfort during physical activity or in humid conditions (Zhang et al., 2022).

Ambitions include adopting sustainable production methods such as dyeing techniques that minimize water usage and energy consumption, as well as utilizing renewable materials in textile manufacturing. Textiles designed for easy disassembly and recycling can contribute to a circular economy by minimizing waste and reducing the environmental impact of textile production (Baloyi et al., 2024). Future smart textiles should seamlessly integrate with Internet of Things (IoT) platforms, enabling connectivity with smart devices and systems in the home, workplace, or healthcare settings (Soori et al., 2023; Fernández-Caramés and Fraga-Lamas, 2018). Overall, the ambitions for future smart textiles are driven by a desire to push the boundaries of innovation, sustainability, and user experience, with the goal of creating garments and products that are not only functional and practical but also environmentally friendly and aesthetically appealing. In-depth technical perspective on smart and functional textiles by extending their classification beyond levels of intelligence to functional categories is driven by user needs and environmental stimuli, including protective, medical, sports, and cosmetotextiles. It further differentiates functionalization strategies at the fiber, surface, and biotechnology levels, enabling a clearer comparison of technological approaches (Zhang et al., 2023). Quantitative performance data demonstrate the effectiveness of these techniques in real-world applications. For example, layer-by-layer functionalization of polypropylene fabrics significantly improved static charge decay (from 46 to 5.7 min), thermal stability (degradation temperature increased from 330 °C to 420 °C), and moisture transport (capillary rise increased eightfold). Advanced thermal management solutions, such as bioinspired hollow fibers, achieved low thermal conductivity (0.031 $W\,m^{-1}\cdot K^{-1}$) and enabled building energy savings of up to 65%. Functional ingredient efficacy was also quantified, with insect-repellent textiles reaching over 90% effectiveness, immobilized enzymes retaining up to 87% activity, and deodorant textiles requiring a minimum of 80% photocatalyst fibr content for optimal performance. Detailed application cases, including wearable sensors, textile-reinforced concrete, and cosmetotextiles, illustrate the technological maturity of these solutions. The rapid market growth of functional textiles, reaching USD 4.72 billion in 2020 with CAGR values exceeding 30%, confirms the transition of smart textile technologies from experimental research stages to commercially viable solutions for both apparel and built-environment applications (Kumar et al., 2020; Nistorac et al., 2024).

4. Certification and standardization

In this context, we propose certification and standardization as essential factors for integrating advanced textiles into buildings and living environments. These systems provide a reliable way to ensure quality, safety and interoperability. For example, the CE marking under the EU Construction Products Regulation and sustainability labels such as the Recycled Claim Standard (RCS) build trust among consumers and professionals. They also open the door to a wider market and regulatory compliance, especially as smart textiles move from concept (TRL 1-3) to commercialization (TRL 7-9) (Fig. 4).

Finally, the integration of certified, standardized smart textiles into buildings and living spaces will be critical to creating more sustainable and resilient environments. Whether it's energy-efficient curtains, responsive wall coverings, or health-monitoring bedding, smart textiles offer untapped potential to reimagine how we build and inhabit spaces. By focusing our efforts on implementation through certification and supporting scale-up across the sector, we can move smart textiles from the lab into everyday life, helping us build and live in smarter, more sustainable ways.

These ambitions outlined above are clear, but how can we get there? How feasible are the options? Our overview of the domains of sustainability and functionality have shown that many innovations exist, sometimes on the lower rungs of the technology readiness scale. Nevertheless, a range of products (varying from prototypes to products that can be both on the consumer market) are available. The scale at which such innovations are implemented varies, but it is clear that the need for a more sustainable future, as outlined in a wide range of European Union guidelines and protocols, is an important stimulus here. Scaling-up is the major thing needed at this time, which it has in common with other trends in sustainable development, such as the

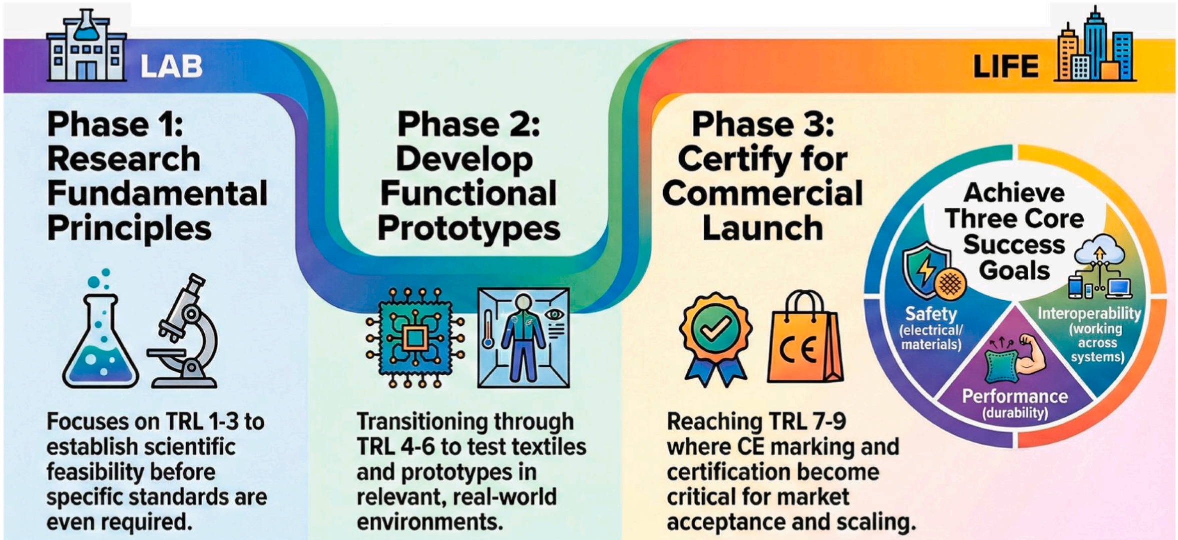

Fig. 4. Schematics of the phases of the smart textiles' product development. (AI generated).

decentralized generation of sustainable energy, the electrification of mobility, and the protein transition, to name a few. To achieve the goals stated above, clear choices and priorities need to be made. This is generally done by follow certain routes. We would like to propose the route of certification and standardization as a route towards the implementation of smart textiles. It is a pathway often chosen in the European Union to improve the quality of products. Certification ensures that smart textiles meet specific quality and safety standards, reassuring consumers about the reliability and performance of these products. Standardization also facilitates quality assurance; thus, different smart textile products can work together seamlessly. All building materials in the European Union use CE certification, as do textiles. The CE mark is the visible mark of approval on the product, which certifies that the product complies with the relevant harmonized European standards and regulations.

The Construction Materials Directive 305/2011/EU was adopted in 2011 and entered into force in 2013. As of this date, all construction materials offered for sale in the European Economic Area must be manufactured in accordance with the relevant harmonized European standard and bear the CE marking. Recycled textiles are certified under the RCS label, which allows the marketing of textiles made from recycled raw materials. Having recognized certification and standards in place builds trust among consumers, encouraging wider adoption of smart textiles in building and living applications. Compliance with established standards is often a requirement for entering certain markets or industries. During the early stages of smart textiles research (TRL 1-3), the focus is on fundamental scientific principles and feasibility studies. At this point, there may not be specific standards or certification processes established for the technology. As smart textile technologies progress through mid-level TRL stages (TRL 4-6), researchers transition from laboratory-scale demonstrations to prototype development and testing in relevant environments. In the later stages of technology development (TRL 7-9), smart textiles are closer to commercial deployment and certification and standardization become critical for market acceptance and regulatory compliance (Fig. 4). Moreover, obtaining certification and compliance with established standards is essential for scaling up production (Hertleer and Van Langenhove, 2015). In standardization and certification, we see a route for adopting innovations into actual products that can help the domains of building and living on road which is more sustainable and makes use of a plethora of currently unlocked potential for functionality.

The field of smart textiles is relatively new and continually evolving. However, existing standards and certification systems are being applied, and efforts are underway to develop more specific standards for this growing market. In the current landscape, many existing sustainability standards can be applied to smart textiles, such as Oeko-Tex Standard 100, which ensures textiles are free from harmful substances, and the Global Organic Textile Standard (GOTS), which certifies organic fibers. These standards help ensure that smart textiles are produced with minimal environmental and health impacts. In case of building certifications like LEED (Leadership in Energy and Environmental Design) offer a framework for incorporating smart textiles into sustainable buildings. LEED points can be awarded for using materials that enhance energy efficiency or indoor air quality. Importantly, smart textiles contributing to these goals can be recognized under such certifications (Table 2).

Efforts are also underway to develop more specific standards for smart textiles (Hertleer and Van Langenhove, 2015). For instance, the International Organization for Standardization (ISO) is working on technical specifications for textiles with specific functionalities, such as electrical conductivity or energy harvesting. In summary, the benefits of standardization and certification for smart textiles include:

Increased consumer confidence: Certification can give consumers peace of mind that smart textiles meet certain safety, performance, and sustainability standards.

Fairer competition: Standardization can help to level the playing

Table 2
Key Existing Standards and Certifications applied to smart textiles to ensure safety, quality, and environmental compliance.

Standard/Label	Focus Area	Description/Purpose
CE Marking	Regulatory Compliance	Mandatory for construction materials in the European Economic Area; certifies compliance with harmonized European standards.
RCS (Recycled Claim Standard)	Sustainability	Certifies textiles made from recycled raw materials.
Oeko-Tex Standard 100	Health & Safety	Ensures textiles are free from harmful substances.
GOTS (Global Organic Textile Standard)	Sustainability	Certifies textiles made from organic fibers.
LEED (Leadership in Energy and Environmental Design)	Building Certification	Award points for materials that improve energy efficiency or indoor air quality, including smart textiles.
IPC Standards	Technical	Specifically covers printed electronics on textiles.

field for different manufacturers and ensure that all products are competing on the same basis.

Innovation: Standards can help to accelerate innovation by providing a common framework for developing and testing new smart textile products.

Overall, standardization and certification are crucial for developing the smart textiles market. As the field matures, more specific standards and certification systems will likely emerge to address the unique needs of this innovative technology. The development of specific standards and certifications for smart textiles is essential to ensure their safety, quality, and interoperability. Standards should address the following issues related to:

Safety: Smart textiles need to be safe to wear, both in terms of electrical safety and the safety of any materials used.

Performance: Standards can ensure that smart textiles meet performance requirements for things like conductivity, durability, and washability.

Interoperability: Standards can help to ensure that smart textiles from different manufacturers can work together seamlessly.

Several organizations are working on developing standards for smart textiles. The IPC - Association Connecting Electronics Industries, for example, has published a series of standards on printed electronics on textiles. The Smart Textile Alliance is another organization that is working to advance the development of standards for smart textiles. The development of standards and certifications for smart textiles is still challenging, but it is essential. It can be achieved by working together with the industry stakeholders to ensure the safety, quality, and interoperability of smart textiles.

5. Roadmap and future perspectives

Textiles are deeply embedded in our daily lives and are widely used in clothing, industry, healthcare and home environments. In this article, we have highlighted the current state of advanced textiles in the context of construction and living, describing ongoing technological developments and future prospects. A key goal for research, industry, and society is to gain access to sustainable, functional, advanced textiles that are also economically viable. These materials must meet performance requirements while simultaneously meeting pressing environmental and economic demands. The roadmap is underpinned by strong economic momentum, with the global functional textile market reaching USD 4.72 billion in 2020 and demonstrating sustained growth rates of approximately 30–33%. This expansion is driven by demand from automotive, healthcare, military, and sports sectors, alongside rapid growth in emerging markets such as India, China, and Brazil. Within this context, the market for textile finishing agents is projected to reach USD 4.52 billion by 2025, highlighting a clear incentive for industrial scaling and commercialization (Kumar Singh and Kumar, 2021).

From a technological perspective, the roadmap moves beyond generic innovation narratives by identifying specific implementation routes that facilitate the transition from laboratory-scale prototypes to market-ready products. Advanced coating and surface modification strategies form a first phase, including the adoption of micro- and nanoencapsulation techniques to protect sensitive active substances and enable their controlled release in response to external stimuli such as heat or pressure. Layer-by-layer deposition is highlighted as a key approach for producing ultrathin functional films that preserve fabric breathability while imparting properties such as UV protection or water repellence. In parallel, chemical grafting techniques using multifunctional crosslinkers establish covalent bonding between functional agents and textile fibers, significantly improving durability and wash fastness, see Fig. 5.

The roadmap also defines clear functional diversification goals for next-generation textiles, targeting high-value applications such as cosmetotextiles with integrated skincare and aromatherapeutic functions, smart sensing textiles incorporating wearable sensors and heating elements, and protective or adaptive fabrics that combine flame retardancy, insect repellence, and thermal regulation through phase-change materials.

However, advanced textiles face challenges. Sustainability remains a major issue, as textile production requires significant amounts of water and energy, and non-renewable, non-biodegradable materials are often used. Durability, performance limitations and high production costs further hinder their widespread deployment (Table 3). Overcoming these challenges,–increasing material durability, improving comfort and functionality, and reducing production costs, is essential if textiles are to make a significant contribution to building a sustainable future.

While the goals are clear, their implementation requires practical, adaptable strategies. There are many promising innovations, but they are often at an early stage of technological readiness. Nevertheless, more and more solutions are emerging along the value chain, from prototypes to market-ready products. Along with broader sustainability efforts, such as renewable energy and the transition to electric mobility, the development of these textile innovations is now essential. To ensure market viability and user acceptance, these technological advances are embedded within a structured assessment and quality framework. This includes low-stress mechanical testing to preserve fabric handle and comfort, standardized physiological performance evaluations for

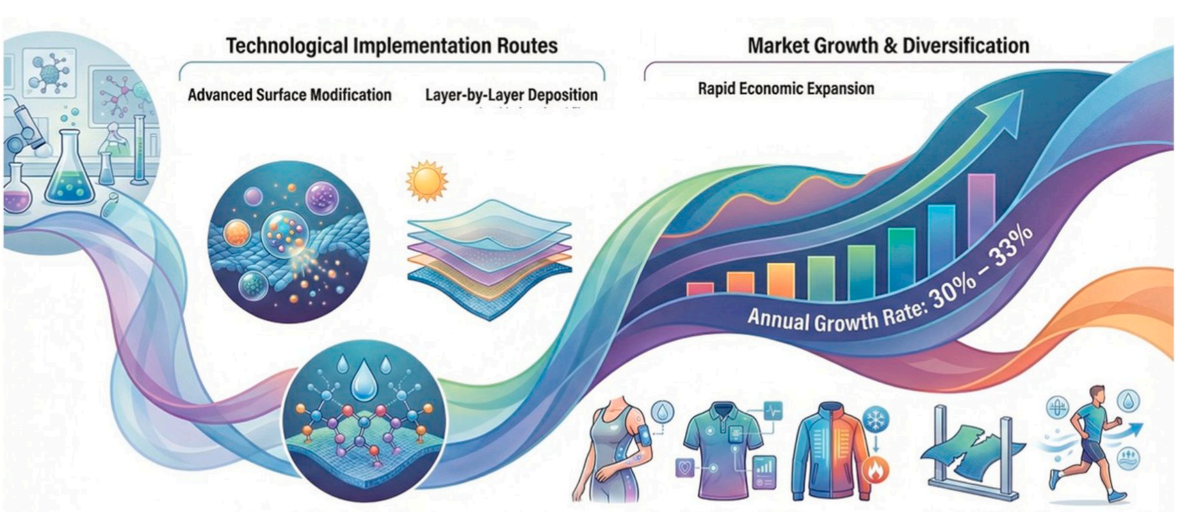

Fig. 5. Schematic of the future fabric showing a roadmap for sustainable functional textiles indicating the technological routes and market growth. (AI generated).

Table 3
The current challenges and the proposed roadmap for advanced textiles.

Pillar	Current Challenges	Strategic Goals	Implementation Strategy
Environmental Impact	High water/energy usage; reliance on non-renewable materials.	Transition to sustainable, bio-degradable, and resource-efficient materials.	Align textile innovation with broader renewable energy and e-mobility transitions.
Performance & Utility	Limited durability; functional and comfort constraints.	Enhance material longevity and meet specific performance requirements for healthcare and industry.	Mature early-stage prototypes into high-performance, market-ready products.
Economic Viability	Prohibitively high production and deployment costs.	Achieve cost-reduction through value-chain optimization and industrial scaling.	Move solutions along the value chain from the laboratory to the commercial market.

breathability and thermal resistance, and durability assessments that verify functional stability after repeated use and laundering. Together, these elements establish a robust and quantifiable roadmap for the industrial development of advanced and smart textile technologies.

CRediT authorship contribution statement

Urszula Stachewicz: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Visualization, Writing – original draft, Writing – review & editing. **Vaida Jonaitienė:** Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Jan K. Kazak:** Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Georgios Priniotakis:** Conceptualization, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Joanna Knapczyk-Korczak:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Writing – original draft, Writing – review & editing. **Enrico Venturini:** Conceptualization, Formal analysis, Investigation, Supervision, Writing – original draft, Writing – review & editing. **Leonarda Francesca Liotta:** Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Joost van Hoof:** Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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