Multi-Partner Project: Sustainable Textile Electronics (STELEC)

Bo Zhou[*†], Mengxi Liu[*], Sizhen Bian[*], Daniel Geißler[*], Paul Lukowicz[*†],
Jose Miranda[‡], Jonathan Dan[‡], David Atienza[‡], Mohamed Amine Riahi[†], Nobert Wehn[†] ,
Russel Torah[§], Sheng Yong[§], Jidong Liu[§], Stephen Beeby[§], Magdalena Kohler[¶], Berit Greinke[¶],
Junchun Yu[‖], Vincent Nierstrasz[‖], Leila Sheldrick[**], Rebecca Stewart[**],
Tommaso Nieri[††], Matteo Maccanti[††] and Daniele Spinelli[††]
[*]German Research Center for Artificial Intelligence (DFKI), Kaiserslautern, Germany
[†]RPTU Kaiserslautern-Landau, Kaiserslautern, Germany
[‡]EPFL, Lausanne, Switzerland
[§]University of Southampton, Southampton, United Kingdom
[¶]Berlin University of the Arts, Berlin, Germany
[‖]University of Borås, Borås, Sweden
[**]Imperial College London, London, United Kingdom
[††]Next Technology Tecnotessile, Prato, Italy

***Abstract*—E-textiles are rapidly emerging as an important area of electronic circuit applications. It also facilitates many socially important applications such as personalized health, elderly care, and smart agriculture. However, the environmental impact and sustainability of e-textiles remain very problematic. STELEC, short for Sustainable Textile ELECtronics, is an interdisciplinary research project funded by the European Innovation Council (EIC) under the Pathfinder programme on the responsible electronics topic seeking cutting-edge innovation. STELEC started in September 2024 and is in its initial stage. The project is a multinational collaboration of research institutes, universities and companies across Europe. It aims at developing next-generation textile-based electronics in applications from sensing, processing to AI, with a commitment to full lifecycle sustainability.**

***Index Terms*—textile electronics, sustainability, materials, fabrication processes, life cycle analysis**

I. Introduction

E-textiles are rapidly emerging as an important area of electronic circuit applications. The European Apparel and Textile Confederation (Euratex) expects that the EU market for e-textiles and textile wearables reaches €1.5 billion in 2025 and will be a significant factor for an important European industry sector. It also facilitates many socially important applications such as personalized health, elderly care, and smart agriculture. Unfortunately, the environmental impact and sustainability of e-textiles remain very problematic: With e-textiles, electronic circuits are entering a new application domain increasing the number of devices that need to be produced and recycled. The vision behind e-textiles as part of Internet of Things is that intelligent components will increasingly diffuse into every-day objects, eventually leading to electronics being virtually everywhere in the environment, so that we are looking at a potentially huge environmental impact. E-textiles are particularly difficult to recycle and reuse. This is because, in general, they involve electronic components being deeply embedded in textile substrates. Before recycle/reuse the two need to be separated which is a non-trivial task that disrupts established recycle/reuse chains. Furthermore, the focus of research and development so far has been on overcoming the challenges involved in producing cost effective and robust conductive textile structures with little regard for environmental impact and sustainability. Therefore, the project STELEC [1] aims to address the sustainability issue of next generation textile electronics, specifically through the following objectives:

1) To develop sustainable, environmentally friendly materials for textile electronics that are recyclable and have advanced electrical properties. This involves improving conductive textiles and beyond, as well as creating models to predict their performance under various conditions.
2) To develop sustainable textile electronics devices using innovative materials and manufacturing processes, such as printing and embroidery, that reduce environmental impact. The project aims to create basic electronic components, circuits, sensing and communication functionality, and power sources all within textile technology, with the ability to simulate and analyze their properties in various settings.
3) To develop environmentally sustainable production and recycling processes for textile electronics, specifically focusing on fibers and textiles that incorporate certain materials. This includes designing processes for extracting reusable materials from old textiles to promote a circular economy.

[1]https://stelec.eu ; https://cordis.europa.eu/project/id/101162257

978-3-9826741-0-0/DATE25/

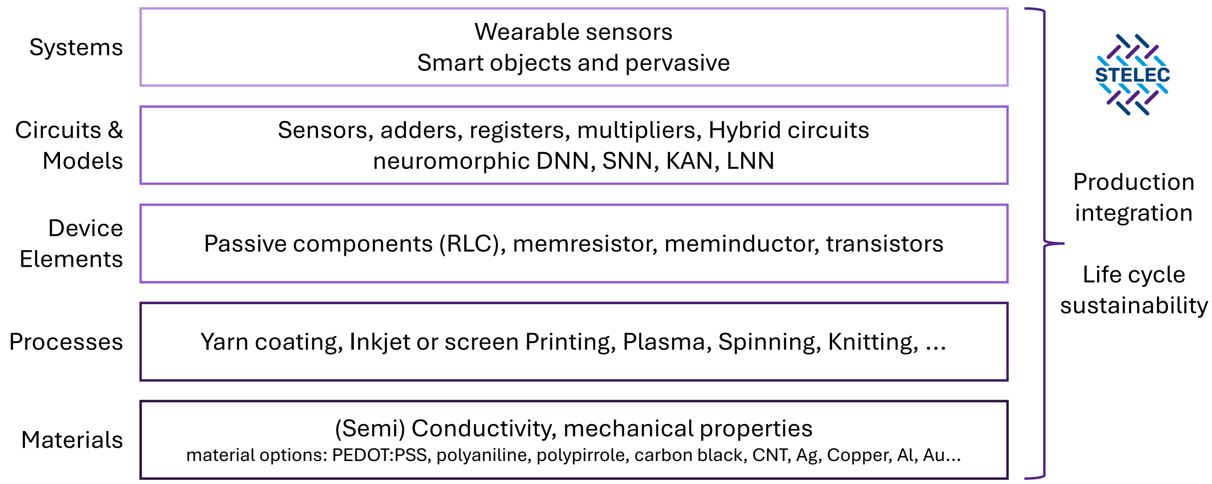

Fig. 1. The full e-Textile technology stack of STELEC

4) To validate proof-of-concept by implementing and evaluating individual devices and sensors in various textiles, and developing relevant use cases for simple circuits. This involves creating simplified versions of specific circuits and testing them in textile applications.
5) To develop life cycle sustainability models and assessments for textile electronics, comparing different technologies and creating a decision support tool to aid in designing environmentally friendly e-textiles.

To achieve the above objectives, the STELEC project will develop a full e-Textile technology stack (Fig. 1) from the fiber level to the application level, which is comprehensively devoted to sustainability from the materials and components to full life cycle and circular economy.

II. From E-Textiles to Computational Textile

E-textiles integrate electronics into textiles at various levels, like garment, fabric, and fiber, forming the foundation of the burgeoning smart wearable market [2]. At the garment level, electronics and textiles are processed independently and merged later. At the fabric level, circuits are partially attached to the fabric's surface, with conductive fiber interconnections sewn in. In these integration levels, the textile itself lacks computational abilities; rigid electronic components remain crucial for data acquisition and processing tasks in E-textiles. However, advancements in manufacturing technologies like ink-jet printing and plasma processing enable fiber-level integration, significantly reducing reliance on silicon-based electronics. By embedding basic electronic elements such as transistors inside the fiber core, functionalized fibers replace rigid parts, leading to seamless integration where electronics are merged within the fiber itself.

3D printing shows great potential for manufacturing yarn- and fiber-based electronic elements due to its high productivity, flexibility, and customization capabilities. This technology can produce filaments and intricate textile structures. Yarns exhibiting various electrical properties, including conductivity, semi-conductivity, supercapacitance, solar energy harvesting, piezoelectricity, and piezoresistivity, have been demonstrated in the literature. While many of these yarns have been woven or knitted into basic textile structures, few have been used to create complex networks of functional devices or circuits combining multiple device types. None have achieved high fabric densities, complementary multifunctional devices, or exploited custom textile structures capable of forming complex, high-density circuits. Early examples include organic field-effect transistors on flexible films woven into textiles [3] and wire electrochemical transistors consisting of textile monofilaments coated with conducting PEDOT polymer [4]–[6]. Although these approaches have shown potential, they suffered from low interconnection density and poor transistor performance.

Recent developments include fiber electrochemical transistors based on PEDOT combined with multi-walled carbon nanotubes used as potassium ion sensors [7], though device density remains low and concerns exist over material safety [8]. Multilayer fiber organic electrochemical transistors in coaxial configurations have achieved higher transconductance using gold electrodes [9]. Other devices like yarn supercapacitors for energy storage and textile memristors have been realized, but challenges persist, such as high electrode resistance leading to power losses [10], [11]. Current woven electronic textiles with functional yarns have reached densities of around 1,000 threads across 60 cm, significantly below standard textile densities [12]. Integration of elementary switching elements and logic circuits into textiles has been explored [4], [13], granting potential data processing capabilities. However, these works are limited to basic logic circuitry and quasi-static applications [2]. Developing complex circuits built as integral textile structures remains an area requiring further research.

To develop e-textile devices and circuits, the STELEC project takes a comprehensive approach that leverages knowledge from conventional silicon-based CMOS technology and printed electronics, while also investigating the unique characteristics of e-textile technology. From basic e-Textile electronic

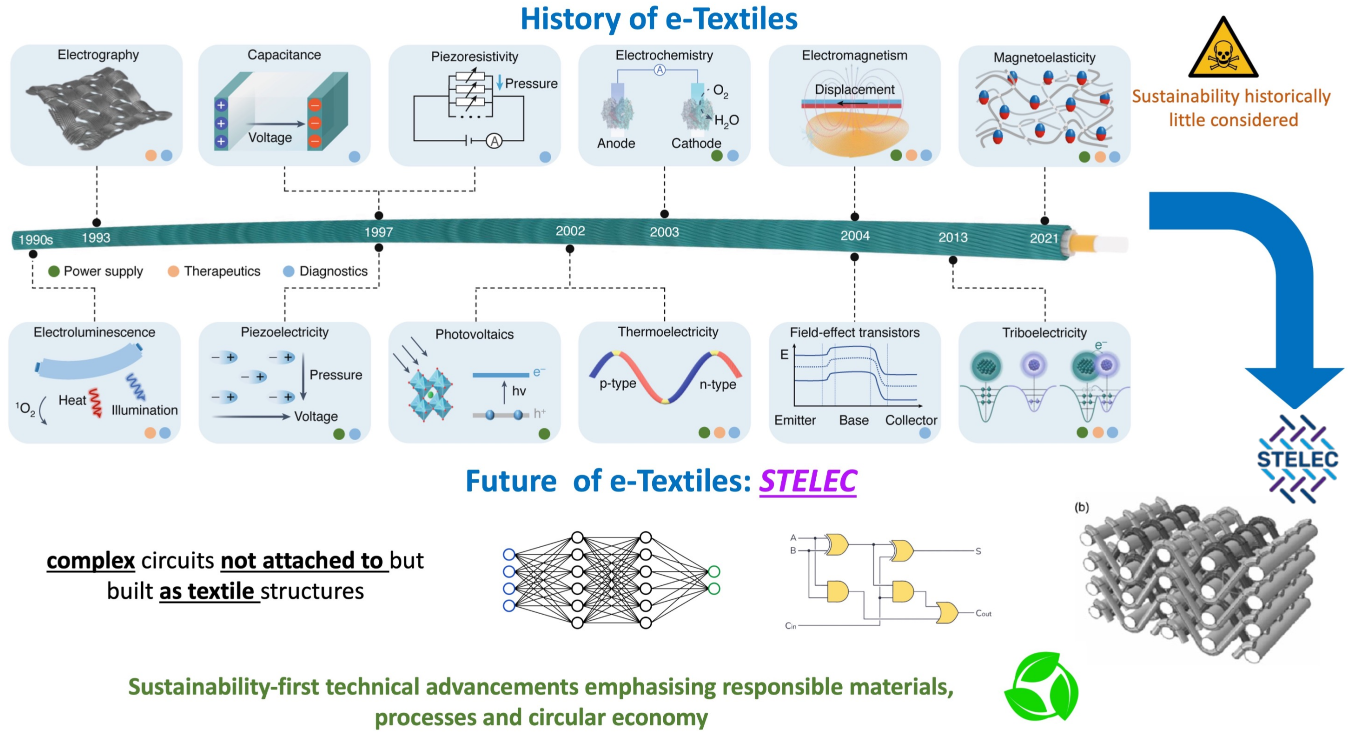

Fig. 2. History of e-Textiles [1] and STELEC vision

components, STELEC explores various circuit techniques, including digital logic and PTL-based circuits, to overcome challenges such as device parameter variability and robustness of interconnect fabrics in textiles. We will also investigate neuralmorphic implementations of next generation AI architectures like spike neural networks [14], liquid time-constant neural networks [15], Kolmogorov-Arnold Networks [16], etc. The project will develop design tools that can convert circuit schematics into layouts compatible with fibers and e-Textiles. The approach also considers the end-use requirements, evaluating performance under conditions like washability, UV exposure, and sweat/body oil exposure, a step often overlooked in low technology readiness level (TRL) development. Furthermore, the project aims to replace non-biodegradable materials with state-of-the-art biodegradable alternatives, such as Carboxymethyl cellulose, and design components for ease of disassembly, recycling, or reuse, prioritizing repairability to extend the lifespan of e-textile devices.

III. Sustainable Textile Electronics

Electronic textiles, inherited with the wearability of conventional clothes, are deemed fundamental for emerging wearable electronics, particularly in the Internet of Things era. However, the electronic waste produced by electronic textiles will further exacerbate the severe pollution in traditional textiles. To realize the transformational impact of wearable e-textiles, materials innovations can pave the way for effective user adoption and the creation of a sustainable circular economy. The future research directions for wearable e-textiles will include an integrated product design approach based on the use of eco-friendly materials, the development of sustainable manufacturing processes, and an effective end-of-the-life strategy to manufacture next generation smart and sustainable wearable e-textiles that can be either recycled to value-added products or decomposed in the landfill without any negative environmental impacts. The research and innovation opportunities of environmentally friendly materials in e-Textiles include:

1) Green Nanomaterials: These are increasingly being integrated into smart textiles for environmental and biomedical applications. They can enhance functionality while promoting sustainability. Examples include nanoparticles for pollution monitoring and air and water filtration [17].
2) Conductive Yarns and Threads: These can be made from eco-friendly materials like organic cotton or recycled fibers, combined with conductive elements like silver or carbon nanotubes. This approach maintains the textile's flexibility and breathability [18].
3) Biodegradable Polymers: Polymers such as polylactic acid (PLA) are used in e-textiles for their biodegradability. These materials break down more easily in the environment compared to traditional synthetic fibers [19].
4) Natural Fibers: Materials like silk, wool, and bamboo are gaining traction in e-textile design. They offer unique properties such as luxurious texture, warmth, and eco-

friendliness [18].

These advancements not only make e-textiles more sustainable but also open-up new possibilities for their use in various fields, from healthcare to environmental monitoring.

IV. Life Cycle Sustainability and Circular Economy

Responsible e-textile production requires a comprehensive and integrated approach that considers the entire life cycle of a product. This involves merging expertise from various fields, including textile design, engineering, electronics, and end-of-life management to ensure sustainable practices are implemented at every stage. A continuous integration model, where technical and design professionals collaborate from the outset, enables the development of e-textiles that not only retain their electronic and mechanical functionality but also have minimal environmental impact. By addressing challenges such as conformability, durability, and sustainability, manufacturers can create products that meet user needs while minimizing waste and reducing environmental harm. This approach can be achieved through iterative cycles of design, testing, and evaluation, complemented by workshops with experts to ensure that all aspects of e-textile production are considered, from fiber to end product manufacturing processes.

Achieving lifecycle sustainability and embracing a circular economy are crucial aspects of responsible e-textile production. To address this, a design science approach is employed to embed life cycle thinking throughout the project. By integrating expertise from various fields and adopting a collaborative mindset, the development of sustainable e-textiles can be informed by a deep understanding of their environmental impact across all stages of their lifecycle. Through iterative cycles of descriptive and prescriptive studies, a comprehensive life cycle model and design guidelines are developed to support the creation of e-textiles that not only minimize waste but also promote recyclability and reuse. This approach enables the identification of potential trade-offs and preferable solutions early in the project, ultimately leading to the development of sharable resources that can be used by the wider material development community to foster a more circular economy. By prioritizing lifecycle sustainability, the e-textile industry can move towards a more regenerative model that reduces environmental harm while promoting innovation and economic growth.

V. The Consortium

STELEC brings together a highly interdisciplinary consortium from across Europe to implement the hitherto vision.

- The Embedded Intelligence team from the German Research Center for Artificial Intelligence (DFKI) is the coordinator of the project while contributing to the research activity by developing next-generation neural network circuits composed of novel textile materials developed from the project. The DFKI ethics team will guide project activities to follow relevant EU ethics standards.
- The research group Textile Materials Technology at the University of Borås (HB) is STELEC's key research partner for resource effective processes for functional e-textiles, such as wearable textile sensors, multilayer conductive textiles, dynamic patterns - coating of textiles, surface treatments, quality assessment of (smart) textiles, supercritical CO2 dyeing, UV-sensing and anti-bacterial textiles, as well as development of chemical formulations for functional e-textiles.
- Next Technology Tecnotessile (NTT) is a private non-profit research company representing a reference point for research and technological innovation in the textile sector in Italy. It provides services on prototyping and product innovation regarding smart and intelligent textiles and their innovative function.
- The Research Chair of Microelectronic System Design (EMS) from the University of Kaiserslautern-Landau (RPTU) provides expertise in analogue design, transistor and circuit modeling, conventional and unconventional design methodology with an emphasis on circuit reliability.
- The Wearable Computing lab from the Berlin University of the Arts (UDK) contributes to STELEC with expertise in e-textile prototyping and sustainable production with an interdisciplinary technical design research approach.
- The Embedded Systems Laboratory (ESL) from the Swiss Federal Institute of Technology Lausanne (EPFL) focuses on delineating systematic, multi-objective design techniques, optimization methodologies, and hardware and software tools tailored to the development of high-performance embedded systems and nano-scale Multi-Processor System-on-Chip (MPSoC) architectures. These endeavours are specifically oriented towards addressing the requirements of a more sustainable Internet-of-Things (IoT) and edge-to-cloud sustainable Era.
- The School of Electronics and Computer Science (ECS) from University of Southampton (UOS) has world-leading expertiese on e-textiles materials, devices and manufacturing methods and the team are currently exploring the use of sustainable materials across a spectrum of applications.
- Imperial College London (ICL) joins the project with two teams from the Dyson School of Design Engineering. The research team includes the e-Body Lab who focus on body-centric technologies and interfaces utilising e-textiles, and the Design Futures lab, which contains expertise in product development and manufacturing, having brought several products to market and worked extensively with companies to support them in embedding sustainability into their activities and strategies.
- Tech2Market (T2M) is a strategic consulting company specializing in technological innovations. T2M handles the communication, dissemination, exploitation including IPR management of the project.

VI. Conclusion

The STELEC project is poised to have a transformative impact on sustainable electronics, materials science, and e-textiles. By developing biodegradable, environmentally friendly materials for creating electrically active structures using efficient techniques such as digital and 3D printing and plasma treatment, the project will make a significant contribution to sustainable electronics in general, not just e-textiles. Furthermore, STELEC will establish general principles for building soft electronic components that can be bent, squeezed, and stretched, including design guidelines and simulation models, thereby enabling the transition from flexible electronics to soft and stretchable systems. This will unlock new applications in areas where electronics need to be incorporated into mechanically deformable structures, such as foldable phones and soft on-body sensors. Ultimately, STELEC technology will fundamentally change the way e-textiles and wearable systems are designed and built, facilitating whole new application domains like e-skin and neuralmorphic processing in textile, by enabling electronic components to be part of the textile structure itself, thereby overcoming limitations in design space and functionality. To reach the project objectives, an integrated approach across disciplines is required. STELEC has therefore assembled an interdisciplinary consortium to address this goal, joining expertise from e-textile materials, electronics, and sustainability. STELEC is funded by the European Union under the European Innovation Council's Pathfinder programme, with the project duration from 2024 to 2028.

Acknowledgment

This project is funded by the European Union under the EIC Pathfinder programme, with the project 101162257 STELEC.

References

[1] A. Libanori, G. Chen, X. Zhao, Y. Zhou, and J. Chen, "Smart textiles for personalized healthcare," *Nature Electronics*, vol. 5, no. 3, pp. 142–156, 2022.

[2] S. de Mulatier, M. Nasreldin, R. Delattre, M. Ramuz, and T. Djenizian, "Electronic circuits integration in textiles for data processing in wearable technologies," *Advanced Materials Technologies*, vol. 3, no. 10, p. 1700320, 2018.

[3] A. Bonfiglio, D. De Rossi, T. Kirstein, I. R. Locher, F. Mameli, R. Paradiso, and G. Vozzi, "Organic field effect transistors for textile applications," *IEEE Transactions on Information Technology in biomedicine*, vol. 9, no. 3, pp. 319–324, 2005.

[4] M. Hamedi, R. Forchheimer, and O. Inganäs, "Towards woven logic from organic electronic fibres," *Nature materials*, vol. 6, no. 5, pp. 357–362, 2007.

[5] M. Asplund, "Conjugated polymers for neural interfaces: Prospects, possibilities and future challenges," Ph.D. dissertation, KTH, 2009.

[6] A. Schwarz, J. Cardoen, P. Westbroek, L. Van Langenhove, E. Bruneel, I. Van Driessche, and J. Hakuzimana, "Steps towards a textile-based transistor: development of the gate and insulating layer," *Textile Research Journal*, vol. 80, no. 16, pp. 1738–1746, 2010.

[7] Y. Wang, Y. Wang, R. Zhu, Y. Tao, Y. Chen, Q. Liu, X. Liu, and D. Wang, "Woven fiber organic electrochemical transistors based on multiwalled carbon nanotube functionalized pedot nanowires for nondestructive detection of potassium ions," *Materials Science and Engineering: B*, vol. 278, p. 115657, 2022.

[8] S. F. Hansen and A. Lennquist, "Carbon nanotubes added to the sin list as a nanomaterial of very high concern," *Nature Nanotechnology*, vol. 15, no. 1, pp. 3–4, 2020.

[9] Y. Fang, J. Feng, X. Shi, Y. Yang, J. Wang, X. Sun, W. Li, X. Sun, and H. Peng, "Coaxial fiber organic electrochemical transistor with high transconductance," *Nano Research*, vol. 16, no. 9, pp. 11 885–11 892, 2023.

[10] J. T. Carvalho, I. Cunha, J. Coelho, E. Fortunato, R. Martins, and L. Pereira, "Carbon-yarn-based supercapacitors with in situ regenerated cellulose hydrogel for sustainable wearable electronics," *ACS Applied Energy Materials*, vol. 5, no. 10, pp. 11 987–11 996, 2022.

[11] X. Xu, X. Zhou, T. Wang, X. Shi, Y. Liu, Y. Zuo, L. Xu, M. Wang, X. Hu, X. Yang *et al.*, "Robust dna-bridged memristor for textile chips," *Angewandte Chemie International Edition*, vol. 59, no. 31, pp. 12 762–12 768, 2020.

[12] H. W. Choi, D.-W. Shin, J. Yang, S. Lee, C. Figueiredo, S. Sinopoli, K. Ullrich, P. Jovančić, A. Marrani, R. Momentè *et al.*, "Smart textile lighting/display system with multifunctional fibre devices for large scale smart home and iot applications," *Nature communications*, vol. 13, no. 1, p. 814, 2022.

[13] C. Müller, M. Hamedi, R. Karlsson, R. Jansson, R. Marcilla, M. Hedhammar, and O. Inganäs, "Woven electrochemical transistors on silk fibers," *Advanced Materials*, vol. 23, no. 7, pp. 898–901, 2011.

[14] S. Ghosh-Dastidar and H. Adeli, "Spiking neural networks," *International journal of neural systems*, vol. 19, no. 04, pp. 295–308, 2009.

[15] R. Hasani, M. Lechner, A. Amini, D. Rus, and R. Grosu, "Liquid time-constant networks," in *Proceedings of the AAAI Conference on Artificial Intelligence*, vol. 35, no. 9, 2021, pp. 7657–7666.

[16] Z. Liu, Y. Wang, S. Vaidya, F. Ruehle, J. Halverson, M. Soljačić, T. Y. Hou, and M. Tegmark, "Kan: Kolmogorov-arnold networks," *arXiv preprint arXiv:2404.19756*, 2024.

[17] M. Popescu and C. Ungureanu, "Green nanomaterials for smart textiles dedicated to environmental and biomedical applications," *Materials*, vol. 16, no. 11, p. 4075, 2023.

[18] M.-R. Azani and A. Hassanpour, "Electronic textiles (e-textiles): types, fabrication methods, and recent strategies to overcome durability challenges (washability & flexibility)," *Journal of Materials Science: Materials in Electronics*, vol. 35, no. 29, p. 1897, 2024.

[19] S. Guridi, M. Iannacchero, and E. Pouta, "Towards more sustainable interactive textiles: A literature review on the use of biomaterials for etextiles." in *Proceedings of the CHI Conference on Human Factors in Computing Systems*, 2024, pp. 1–19.