Review

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Recent Advancement of Innovative Approaches to Sustainable Smart Textiles: A Systematic Review

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Abstract

Smart textiles are fabrics with integrated advanced functionality. They are materials that combine electronics and sustainable features to create fabrics that are capable of sensing, responding, and adapting to environmental stimuli. This systematic review analyzed the advancements in sustainable smart textile technologies and gathered the most relevant published literature between 2018 and 2024. In accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, 78 papers were selected and analyzed. Major breakthroughs include eco-friendly electronic fibers, textiles that can generate solar energy, thermoelectric wearable devices, polymers that repair themselves, and natural conductive inks. The paper reveals a major shift in the textile industry towards adopting circular economy models as a result of stricter regulations and consumers' preference for environmentally responsible products. The study shows that smart textiles made from sustainable materials not only match the performance of their traditional counterparts but at the same time also reduce the environmental impact by up to 60%. The paper finishes with specific suggestions for researchers and other stakeholders in textile technology who want to speed up the responsible commercial use of sustainable smart textile technologies.

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1. Introduction

The textile industry across the world is in a seminal crisis where it is faced by two imperatives of technology and eco-friendly approaches. The industry is producing more than 92 million tonnes of waste every year and contributing about 10 percent of the carbon emissions in the world at large. The need to adopt sustainable change has never been greater. At the same time, the development of nanotechnology, flexible electronics, and bioengineering has opened up new vistas of possibilities of textile beyond their traditional passive functions [1]. The advent of smart textiles- fabrics with sensing, actuating, computing, and communicating functions provides an interesting avenue of meeting both industrial competitiveness and sustainability objectives.

Smart textile, also known as the electronic textile (e-textiles), or intelligent garment, is an interdisciplinary field at the interface of materials sciences, electrical engineering, fashion design, and environmental science [2]. The initial prototypes that were created in the late 1990s mainly aimed at incorporating hard electronic devices in clothes. The last ten years have, however, seen an absolute change to the formulation of intrinsically working fibers and yarns, which may either be woven, knitted or embroidered like other standard textile machines. This development has enhanced the wearability of the smart textile systems, their washability, and scalability tremendously.

The eco-friendliness aspect of intelligent fabrics is becoming a prominent feature of future generation developments. Traditional smart fabrics tend to be based on non-biodegradable synthetic fibers, rare earth and unsafe chemical technologies that erode their environmental claims. Researchers, in turn, are leading the way towards bio-based conductive technology, natural fibre materials, biodegradable encapsulants, and fabrication with low energy usage. Moreover, the cradle-

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to-cradle design, modular electronics and end-of-life recyclability are being incorporated in product development models, and these are indicative of a systemic approach to sustainability [3].

Sustainable application of smart textiles has a truly remarkable range of applications through healthcare monitoring, optimizing athletic performance, military and first-responder missions, environmental sensing, integration with architecture, and fashion-tech interfaces. The number of performance requirements and sustainability trade-offs in each of the domains is different, and therefore, a division of material and design approaches is required. Combining Internet of Things (IoT) connectivity, artificial intelligence, and enhanced textile engineering is further increasing the pace of innovation, and now, the garments that not only trace physiological measurements but also send or receive data, adjust to the environment or condition, and have a self-healing method are attainable.

This fast development notwithstanding, the staff encounters dire issues such as reliability following repeated laundry, electronic component biocompatibility, comparability of performance indices, scalable environmentally-green production, and compliance over borders [4]. The aim of the review is to systematize the current developments in the area of sustainable smart textiles, outline the current trends in research, represent the interdisciplinary relationships, and critically assess the accomplishments and shortcomings. In such a manner, it also seeks to provide a resource base to the researchers, engineers, and policymakers striving to propel this paradigmatic discipline in a responsible manner.

2. Materials and Methods

2.1. Study Design

The methodology applied in this review was a systematic literature review to deliver a transparent, reproducible, and rigorous evidence synthesis with respect to evidence-based practices and pinpointing the key issues in various contexts using PRISMA (Preferred Reporting Items to Systematic Reviews and Meta-Analyses), 2020 guidance. The PRISMA methodology entailed four consecutive stages, i.e., Identification, Screening, Eligibility Assessment and Inclusion, made sure that only high-quality and relevant literature was used to derive the conclusions made [5].

2.2. Search Strategy

There was a database search in the Web of Science, Scopus, PubMed, IEEE Xplore, and Google Scholar. The Boolean query used was as follows: (smart textiles or e-textiles or electronic textiles) and (sustainable or biodegradable or green or eco-friendly) and (innovation or advancement or development) [6]. Only the peer-reviewed articles published in English since January 2018 were searched.

2.3. Inclusion and Exclusion Criteria

The papers were incorporated where they dealt with innovative materials, processes of fabrication, or uses of sustainable smart textiles; experimental or review-based findings were reported, and they were published in indexed journals. Articles that were not peer reviewed entirely and were not in English, as well as articles that addressed any type of sustainable textile other than smart, were filtered out. The first search produced 412 records, and after elimination of 134 duplicates, 278 articles were screened on title and abstract [7]. After full text review, 78 studies were found to fit all inclusion criteria and were included in the final synthesis.

3. Findings

3.1. Biodegradable and Bio-Based Conductive Materials

A common finding in the reviewed literature is that the biodegradable conductive materials are rapidly maturing into potential alternatives to the traditional metallic and synthetic polymer conductors. During a controlled environment, carbon nanotube-functionalized carbon nanotube-aerogels based on the principle of using cellulose have exhibited electrical conductivities of up to 140 S/m, and full compostability in 12 weeks. The protein polymer based on Bombyx mori silkworms, which is known as silk fibroin, was not left behind, as it is a material with a lot of potential in terms of serving as a flexible biosensor because of its natural biocompatibility with tissue, mechanical strength, and biodegradability [8]. Research has been published on 12 pressure sensors of silk with signal-to-noise ratios of 1.8 kPa-1 and reaction times less than 20 microseconds, and they are comparable commercially with synthetic probes.

Another huge movement in innovation is bio-based conductive inks. Inks made by means of plant-based carbon materials, such as lignin and graphene fabricated through biomass pyrolysis, can be screen-printed or inkjet deposited onto natural fabric substrates [9]. These inks have sheet resistances as low as 2 O/sq after sintering at 120degC- a temperature which can be used with most natural fibers. The use of these inks will remove the need to use toxic silver nanoparticles and allow full-garment assembly composting at the end of the production process.

3.2. Energy Harvesting Technologies

Energy harvesting has become a dominant topic in smart textile sustainability research because it is required to operate wearable sensors without using disposable batteries. Power outputs have also been demonstrated to up to 1.2 mW/cm2 through triboelectric nanogenerators (TENGs) integrated into textile architecture using human movement, which is enough to continuously drive Bluetooth Low Energy microcontrollers [10]. These devices use contact-electrification and electrostatic induction between non-similar layers of textile, and do not require any external power source or any rare-earth material. Self-powered bumper matrices based on parallelograms of force have been released through piezoelectric textile fibers, especially those with polyvinylidene fluoride (PVDF) mixed in with barium titanate nanoparticles, and these materials have been woven such that they can measure joint kinematics at resolutions of less than Newtons.

Integration Photovoltaic integration Photovoltaic integration has come a long way, and flexible organic solar cells (OSCs) have been developed with power conversion efficiencies approaching 14.2% when deposited on a polyester woven substrate. Importantly, scientists have now shown that OSC-knitted fabrics can maintain more than 85 percent of their original efficiency even after 50 normal wash cycles, a historical obstacle to the commercial process [11]. The thermoelectric textile generators based on the temperature gradient between the body and the environment generated stable powers of 30-40 mW/cm2, which are enough to build the ultra-low-power IoT sensor nodes. It has been reported that hybrid multi-modal energy harvesters commercializing thermal, kinetic and solar energy sources in one textile fabric have been developed, with continuous power densities approaching 2 mW/cm2 in normal outdoor environments.

3.3. Self-Healing and Adaptive Material Systems

The addition of self-healing polymers to smart textile matrices is a major step towards increasing the product's lifespan and minimizing electronic waste. Stretchable conductive composites based on poly siloxane networks with dynamic disulfide bonds have been designed and can independently repair mechanical and electrical damage at room temperature within 24 hours and recover 94% of the initial conductivity. The healing agent can also be applied to the fracture site via microvascular networks woven into woven spacer fabrics and is estimated threefold more effective in extending functional lifespan in comparison to non-healing counterparts [12]. Forms of polymer fibers with memory. Shape-memory polymer fibers that contain resistive heating elements allow garments to be restored to a desired geometry following deformation, hence avoiding the formation of ironing and mechanical care cycles that cause fiber degradation.

3.4. Functional Finishing and Nanotechnology

Multiple simultaneous responses to different environmental factors have been facilitated by nanostructured surface functionalizations that allow smart textiles to perform. Focusing on zinc oxide nanowire arrays grown directly on cotton fibers, fabrics exhibiting a combination of UV-blocking (UPF > 50), antibacterial (>99% inhibition of S. aureus and E. coli), and piezoelectric sensing applications have been demonstrated, and all were made using a single earth-abundant material deposited by a low-temperature hydrothermal reaction. Microacrete materials Phase change materials (PCM) encamped inside bio-based poly(lactic acid) shells have been embedded into knitted designs to have passive thermoregulation within the temperature range of 6 deg C to eliminate the need for active heating and cooling systems in protective clothing [13]. Beeswax nanoparticle hydrophobic coating has been shown to have a water contact angle that is above 155 °, with a 30-wash-cycle life, and can be used instead of beeswax fluorocarbon-based treatments, which are associated with a heavy environmental and human health risk.

3.5. Digital Manufacturing and Circular Economy Integration

Digital fabrication technologies are modelling the sustainable smart textile manufacturing environment [14]. Three-dimensional knitting, printing of functional inks using inkjets with direct-to-garment printing, and laser-patterned conductive traces have all decreased waste in materials by 25-40 percent over cut-and-sew processes. Online twin platforms with the capability to perform a virtual prototyping of smart textile systems have reduced the development time by more than 18 months to less than 6 months. According to the sources reviewed in this corpus, the concept of incorporating circular economy design principles such as modular detachable electronics, mono-material production, and take-back plans into the design of smart garments can decrease the carbon footprint of the latter by 55-60 percent in comparison with the traditional production-and-disposal framework [15]. Supply chain traceability systems based on blockchain have been tested to check the provenance of sustainable raw materials, which would give the consumers and regulators verified sustainability credentials.

4. Discussion

The synthesis of 78 new papers from 2018 to 2024 on the subject illustrates that it is an active research area subject to stunning material advances and long-term systemic issues. The intersectionality of digital manufacturing, renewable energy harvesting and biodegradable electronics is establishing a rallied technological division which relates smart textile performance to planetary boundaries. Especially remarkable is the trend of helping towards any mono-material and bio-derived systems that make end-of-life processing much easier and reduce the number of toxic substances in the supply chain in general [16].

Nevertheless, some crucial gaps exist. The vast majority of laboratory demonstrations are performed on small-scale pieces of fabric under controlled conditions, and neither evidence of scaling up to industrial production volumes has been given. Washability, the most important real-life performance measure of garments, is also reported inconsistently, with test procedures differing widely between studies, so cross-study comparisons are unreliable. The long-term biocompatibility of new nanostructured materials in close-contact with the skin should be thoroughly investigated with toxicological investigations, which are mostly lacking in the literature [17]. Also, the economic viability of sustainable smart textiles at affordable consumer scales is an unexploited aspect, with most cost studies focused on how components cost, rather than the system life cycle costs.

Another issue identified in the findings is the lack of an interdisciplinary divide to facilitate progress. Material scientists often innovate but do not collaborate well with textile engineers on processability, and electrical engineers come up with wearable systems but lack consultations with sustainability experts on material choice. Sealing these gaps with explicitly transdisciplinary research consortia, including even the social scientists, life cycle analysts, and regulatory experts, is known as an essential ability requirement to isolate laboratory successes into marketable, responsible products [18]. Not only does the development and realisation of sustainable smart textiles have an ethical foundation, but also a strategic base to secure the interest of multi-stakeholder investment because of the alignment of sustainable smart textile development with international frameworks such as the United Nations Sustainable Development Goals, especially SDG 9 (Industry, Innovation and Infrastructure) and SDG 12 (Responsible Consumption and Production).

5. Conclusions

This literature review shows that sustainable smart textiles have evolved a long way since their theoretical backgrounds up to technology-driven realities. An increase in biodegradable conductive materials, ambient energy sources, self-healing polymer manufacturing, and digital circular manufacturing all speak of an emerging field that will be able to offer workable clothing, reducing its environmental footprint across the entire lifecycle. Triboelectric energy harvesters, silk-based biosensors, bio-based conductive inks, modular electronic architectures and bio-derived conductive inks are all examples of ingenuity behind this transformation [19].

However, the way to translate the laboratory breakthrough into broad-based sustainable commercialization requires persistent interdisciplinary work, uniform assessment procedures, and facilitating political settings. The analysed literature has provided strong evidence that sustainable smart textile is indeed a viable typology for next-generation textile innovation. Real-world validation, scale-up engineering, toxicological safety profiling, and inclusive design strategies need to become the priorities of future research that can bring the advantages of smart textile technology to the global markets equally. It will be the addition of sustainability as a first principles design criterion and not as an afterthought that will define the smart textiles in the future that will fascinate the manner in which people interact with clothing.

6. Recommendations

Based on the results of this systematic review, the specific recommendations are forwarded to the stakeholders in the field of research, industry and policy:

Standard wash-durability tests (at least 50 cycles according to ISO 6330) should be implemented, such as complete life cycle analysis, and performance of materials and devices should be reported. The use of transdisciplinary research teams that include sustainability scientists, toxicologists, social researchers, materials and electronic engineers must not be an exception but a rule [20].

Manufacturers are motivated to implement the modular electronic architectures that enable individual recovery and recycling of the electronic and textile parts that can be used at the end of life, to support the circular economy business models. The development of biodegradable encapsulation materials and bio-based conductive inks would need to be expedited, with pilot manufacturing levels recorded and uploaded into an open-access platform to reduce entry barriers for smaller entities. For Policymakers: Regulatory frameworks should mandate sustainability labeling covering the material composition, energy consumption, and end-of-life instructions of smart textile products [21]. Funding bodies for research should give top priority to grants requiring that the proposed projects be aligned with the principles of the circular economy and also have scale-up pathways as deliverable milestones. An international harmonization of smart textile safety and sustainability standards, including those related to the use of nanomaterials and the classification of electronic waste, is very much required in order to promote responsible global trade and equitable access to innovation.

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