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Current Status and Prospects of Smart Textile Technologies

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Abstract

Smart textiles represent an innovative multidisciplinary field emerging from the integration of modern technologies with the traditional textile industry. This paper provides a systematic analysis of the current state, developmental trajectories, and future opportunities of smart textile technologies. The research involves the evaluation of over 75 scientific sources published between 2015 and 2025. Findings indicate that the smart textile sector is growing at an annual rate of 22–24%, with the global market projected to reach USD 15.9 billion by 2028. The article covers the applications of smart textiles in medicine, sports, defense, and consumer sectors.

Keywords: smart textiles, intelligent fabrics, e-textiles, wearable technologies, biosensors, medical monitoring.

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1. Introduction

Smart textiles represent a multidisciplinary domain formed by the convergence of textiles with microelectronics, nanotechnology, and computer science [1]. This technology endows traditional textile materials with "intelligent" functions, such as active interaction with the environment, data sensing, processing, and transmission.

The concept was first defined by Takagi in 1990 as "materials that respond optimally to environmental changes and adapt to those changes" [2]. According to the ISO/TR 23383 technical report adopted by the International Organization for Standardization in 2020, smart textiles are materials that interact reversibly with their environment and adapt to external stimuli [3].

The evolution of smart textile technology has occurred in three primary stages:

1. **First Generation (Passive Smart Textiles):** Possess only sensing functions to perceive external influences [4].
2. **Second Generation (Active Smart Textiles):** Capable of both sensing and responding to stimuli [5].
3. **Third Generation (Ultra-Smart Textiles):** Integrate sensing, response, and adaptation functions [6].

Currently, these technologies are utilized in healthcare for monitoring vital parameters and early disease detection [7,8]; in sports for tracking physiological status and injury prevention [9,10]; and in defense for monitoring soldiers' vitals and detecting hazardous environments [11,12].

Table 1: Generations of Smart Textiles and Their Characteristics

Generation	Type	Features	Examples
1st Gen	Passive	Sensing	Fabrics with temperature sensors
2nd Gen	Active	Sensing + Response	Shape-memory fibers
3rd Gen	Ultra-smart	Sensing + Response + Adaptation	AI-integrated smart garments

Economically, the sector exhibits high growth rates. According to Grand View Research, the global market was valued at USD 3.8 billion in 2022 and is expected to reach USD 26.1 billion by 2030, representing a Compound Annual Growth Rate (CAGR) of 24.6% [13].

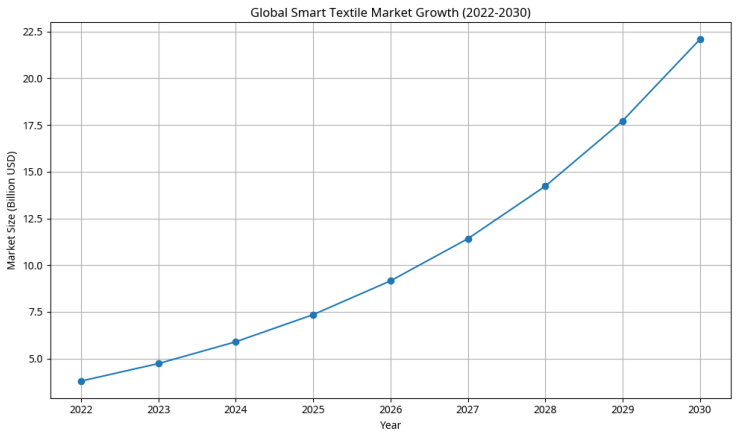

Figure 1. Forecasted Growth of the Smart Textile Market (www.grandviewresearch.com)

2. Methodology

This study was conducted using the Systematic Literature Review (SLR) methodology. Data were gathered from leading scientific databases, including Scopus, Web of Science, Google Scholar, IEEE Xplore, and PubMed. The search strategy utilized keywords such as "smart textile," "intelligent fabric," "e-textile," and "wearable technology" in combination with sectors like "healthcare," "sports," and "military."

Criteria for selection included peer-reviewed articles published in English between 2015 and 2025. From an initial pool of 1,247 articles, 312 were shortlisted after title and abstract screening. Finally, 75 articles were selected for full-text analysis based on quality and relevance.

3. Results and Discussion

This study systematically analyzes the current state of smart textile technologies, including development trends, Technology Readiness Levels (TRL), global market dynamics, application areas, and patenting activity. The 14-fold increase in the number of scientific publications on smart textiles between 2015 and 2025 clearly demonstrates the growing relevance of this field in both academic and industrial circles. Notably, China (28%), the United States (22%), and nations such as Germany, Japan, and the United Kingdom have emerged as leading global research hubs. The annual distribution of publications based on bibliometric analysis is detailed in the figure below:

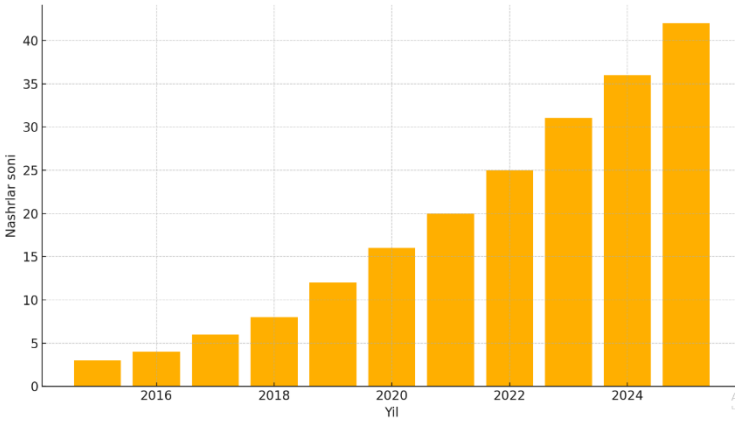

Figure 2. Annual number of scientific publications on smart textiles from 2015 to 2025

Technological analysis allows for the classification of smart textiles into four primary domains: sensor technologies, conductive materials, energy harvesting systems, and data processing algorithms.

Sensor Technologies (32%) form the foundation of the field. Utilizing strain sensors, biosensors, and temperature/humidity sensors, these systems enable the real-time transmission and analysis of physiological signals from the human body.

Conductive Materials (28%) include high-conductivity nanocomposites such as silver nanoparticles (Ag NPs), graphene, MXenes, and PEDOT:PSS. These materials facilitate the development of flexible, washable, and elastic textiles.

Energy Harvesting (24%) focuses on autonomous power generation within smart garments using triboelectric, piezoelectric, and thermoelectric generators. Furthermore, independent energy systems are emerging through the combination of wearable supercapacitors based on stitchable gel-polymer electrolytes and photovoltaic fibers that generate energy from sunlight [14,15].

Data Processing (16%) encompasses AI algorithms, IoT integration, cloud computing, edge computing, and even blockchain technology. These advancements transition smart textiles from passive sensing units into intelligent, autonomous decision-making systems.

The distribution of these domains according to their Technology Readiness Levels (TRL) is categorized as follows:

Table 2. Technological Domains of Smart Textiles and Their Technology Readiness Levels (TRL)

Domain	Share of Research	Core Technologies	TRL
Sensor Technologies	32%	Biosensors, Strain sensors	7–8
Conductive Materials	28%	Ag NPs, Graphene, MXenes	6–7
Energy Harvesting	24%	TENG, Piezo, Thermo, Supercapacitors	5–6
Data Processing	16%	AI, IoT, Cloud, Blockchain	8–9

When analyzed by application sector, healthcare (42%) emerges as the dominant field. Research in this area focuses on smart garments designed to monitor heart rate, blood glucose levels, ECG, EEG, and neurological signals, as well as the development of bioactive bandages capable of assessing wound conditions. In the sports and fitness sector (28%), smart textiles are utilized to evaluate physical exertion, muscle fatigue, core body temperature, and the biomechanical movements of athletes. Within the defense sector (18%), smart apparel enables continuous physiological monitoring of personnel, detection of hazardous or toxic environments, and enhanced ballistic safety. In the fashion industry (12%), key innovations involve chromic (color-changing) materials, interactive lighting, and thermoadaptive garments.

According to global market analysis, the smart textiles sector was valued at USD 3.8 billion in 2022 and

is projected to reach USD 26.1 billion by 2030. While active smart textiles currently constitute the primary market segment, it is anticipated that ultra-smart textiles—featuring integrated AI, IoT, and adaptive structures—will account for 75% of the total market share by 2030.

Another indicator of innovative momentum is the rate of patenting activity. Between 2020 and 2024, more than 1,900 patents were registered across the US, European, and WIPO systems. This trend underscores the industry's readiness for commercialization and the concerted effort to secure intellectual property rights within the smart textile domain (Figure 3).

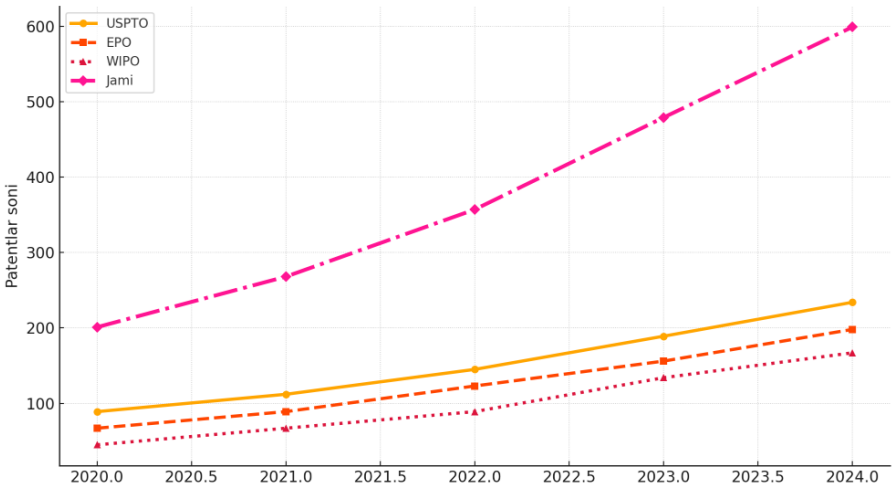

Figure 3. Patenting Activity in the Field of Smart Textiles, 2020–2024 (USPTO, EPO, WIPO)

3.4 Challenges and Future Perspectives

Despite the rapid growth, several limiting factors remain critical for the sector's long-term viability. Key technical challenges include washability and durability of integrated electronics, mechanical degradation during repeated stretching, and the consistency of power supply. Furthermore, the reliability of AI algorithms and environmental safety are paramount concerns. Specifically, non-biodegradable nanoparticles, heavy metals, and chemical stabilizers pose significant risks to ecosystem health.

In response, there is a growing global trend toward "Green Smart Textiles," utilizing biodegradable polymers, non-ecotoxic electrolytes, and recyclable materials. Future innovations must align with ESG (Environmental, Social, and Governance) and SDG (Sustainable Development Goals) standards. The next phase of development will see the seamless integration of smart textiles with 5G networks, Edge Computing, and IoT ecosystems, enabling real-time predictive analytics and cloud-secured "smart environments" within everyday apparel.

3.5 The Uzbekistan Context: Local Implementation

The application of smart textile technologies is actively emerging within the Republic of Uzbekistan. Currently, medical institutions and sports academies in Tashkent are collaborating on prototypes of biosensor-equipped shirts designed to track cardiac activity, perspiration, and movement.

Healthcare Integration: The Tashkent Medical Academy, in partnership with the Center for Innovative Healthcare Technologies, is developing biosensor shirts for cardiovascular monitoring. These systems enable real-time ECG signal transmission via Bluetooth, allowing for the remote monitoring of patients with diabetes and hypertension in local clinics.

Sports Performance: In the Namangan and Andijon regions, smart apparel featuring movement analyzers is being developed for youth sports schools. These garments integrate Inertial Measurement Units (IMU), sweat rate sensors, and heart rate modules to optimize training efficiency.

Industrial Innovation: Within the "O’zto’qimachiliksanoat" association's innovative clusters—specifically in the Sirdaryo and Bukhara Textile Technoparks—prototypes of garments utilizing solar-harvesting

fabrics are under development. These projects utilize Gel Polymer Electrolyte (GPE) supercapacitors to create integrated systems for energy storage and discharge.

4. Conclusion

This systematic literature review explicitly confirms that smart textile technologies have evolved into a rapidly advancing, multidimensional field of strategic importance. The 14-fold increase in scientific publications between 2015 and 2025—with over 60% of research produced in the last five years—signifies a global "scientific-innovation explosion" in this sector. While sensor technologies and data processing systems (including AI, IoT, and cloud platforms) have achieved high Technology Readiness Levels (TRL 7–9), energy harvesting modules (such as triboelectric, piezoelectric, and photovoltaic systems) remain in the developmental and experimental phases (TRL 5–6).

The analysis indicates that smart textiles find their most significant applications in medicine (42%) and sports (28%). The necessity for remote monitoring technologies during the pandemic era particularly catalyzed the importance of these fields. Market forecasts suggest the global smart textile market will reach USD 26.1 billion by 2030, maintaining a compound annual growth rate of at least 24.6%. Emerging technologies like MXenes, triboelectric nanogenerators (TENGs), and AI integration are defining future innovative trajectories.

However, critical challenges—including washability and durability, power continuity, data security, and the lack of standardization mechanisms—remain significant hurdles that require resolution. In summary, smart textile technology is not only redefining the concept of apparel but is also moving toward establishing a new lifestyle integrated with user-centric intelligent systems for healthcare and security. Furthermore, the testing of initial prototypes within the healthcare, sports, and textile clusters of Uzbekistan highlights the potential for integrating these advanced technologies into the national economy.

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