

Electronic Textiles and AI-Enabled Smart Apparel – A Comprehensive Review

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ABSTRACT

The convergence of textile engineering, flexible electronics, artificial intelligence, and communication technologies has accelerated the development of electronic textiles and AI-enabled smart apparel. Unlike conventional wearable devices, smart apparel integrates conductive materials, sensors, microprocessors, and wireless communication modules directly into textile structures, enabling continuous monitoring, real-time data processing, and intelligent user interaction. Recent developments in functional nanomaterials, including graphene, carbon nanotubes, MXenes, conductive polymers, and metallic nanowires, have enhanced the electrical and mechanical performance of textile-based electronic systems. Combining AI-driven analytics with IoT connectivity has transformed wearable garments from passive sensing platforms into intelligent decision-support systems. These systems support applications in healthcare monitoring, sports performance assessment, rehabilitation, industrial safety, and consumer electronics through vital-sign monitoring, activity recognition, predictive health assessment, and remote monitoring. Despite significant progress, challenges related to energy management, washability, durability, interoperability, data privacy, cyber security, and sustainable manufacturing continue to hinder large-scale commercialization. This review examines recent developments in electronic textiles and AI-enabled smart apparel, focusing on advanced materials, wearable sensing technologies, intelligent data analytics, and emerging applications. Future directions towards self-powered, sustainable, and autonomous wearable systems are also discussed.

Keywords: Electronic Textiles (E-Textiles); Smart Apparel; Artificial Intelligence (AI); Wearable Sensors; Internet of Things (IoT); Flexible Electronics; Machine Learning; Healthcare Monitoring

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1. INTRODUCTION

The emergence of intelligent garments represents the intersection of textile engineering, embedded electronics, advanced materials, and computational intelligence, enabling clothing to function as an active participant in data acquisition and decision support [1], [2]. Unlike conventional wearable devices, smart garments embed electronic functionalities directly into fabrics, enabling continuous monitoring of physiological, biomechanical, and environmental parameters while maintaining comfort and flexibility [2], [6]. Recent developments in nanomaterials such as graphene, carbon nanotubes, MXenes, and conductive polymers have significantly enhanced the performance, durability, and functionality of wearable textile systems [3], [4], [5]. The integration of artificial intelligence and Internet of Things technologies has further expanded the capabilities of smart apparel by enabling real-time data analysis, activity recognition, health monitoring, predictive analytics, and remote connectivity [8], [9]. These technologies have found applications in healthcare, sports, rehabilitation, defense, and occupational safety [7], [10].

2. EVOLUTION OF ELECTRONIC TEXTILES AND SMART APPAREL

The development of electronic textiles illustrates the progressive convergence of traditionally independent disciplines, including textile engineering, electronics, materials science, and computer intelligence. Each technological generation has addressed limitations of the previous one, moving from externally attached wearable devices toward fully integrated and intelligent textile systems. Early wearable systems consisted of bulky body-mounted devices used primarily in military, industrial, and research applications. The development of conductive fibres, flexible electronics, and textile-based sensors enabled the transition from conventional wearables to smart textiles capable of monitoring physiological and environmental parameters while maintaining comfort and flexibility.

Modern smart apparel integrates advanced sensors, wireless communication, artificial intelligence, and Internet of Things (IoT) technologies to create intelligent and connected wearable systems. These garments can collect, analyze, and transmit data in real time for applications in healthcare, sports, rehabilitation, defense, and occupational safety

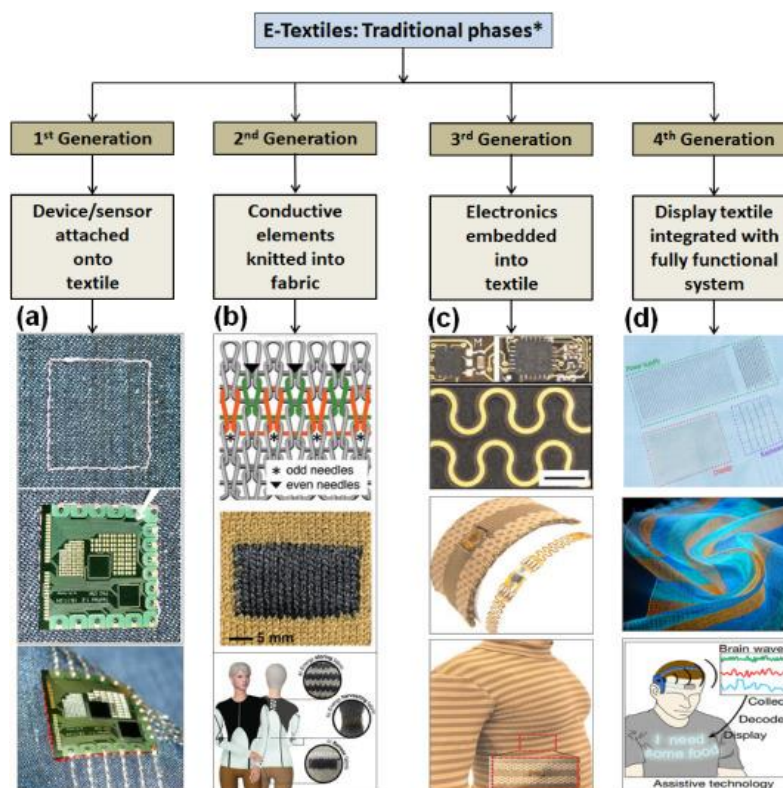


Fig 1: Evolution of Electronic Textiles

Recent innovations in nanomaterials, energy harvesting, and flexible electronics have further improved performance, durability, and wearability. Future developments are expected to focus on self-powered systems, sustainable manufacturing, self-healing materials, and AI-driven personalization, accelerating the adoption of next-generation smart clothing.

3. ADVANCED MATERIALS FOR ELECTRONIC TEXTILES

Advanced materials play a vital role in determining the performance, flexibility, and durability of electronic textiles [1], [4]. Conductive fibers and yarns form the foundation of smart textile systems by enabling electrical signal transmission and the integration of sensors, actuators, and communication components. Technological advancements in materials science have facilitated the development of lightweight, stretchable, and highly conductive materials that can be incorporated into fabrics without affecting wearer comfort. Nanomaterials such as graphene, carbon nanotubes (CNTs), and MXenes have significantly improved the functionality of wearable textiles due to their excellent electrical conductivity, mechanical strength, and sensing capabilities [3], [5]. Graphene-based textiles are widely used in sensing and energy-storage applications, while CNTs enhance strain sensing and motion-monitoring performance [3], [4]. MXenes offer additional

advantages including electromagnetic shielding and multifunctional sensing capabilities [5]. Conductive polymers such as polyaniline, polypyrrole, and PEDOT provide flexible and processable alternatives for wearable sensors and biosensing platforms [6]. Future research is expected to focus on enhancing biocompatibility, washability, sustainability, and multifunctionality [4], [5] to support the development of next-generation intelligent wearable systems.

Material	Key Properties	Applications
Graphene	High conductivity, flexibility, thermal stability	Sensors, smart fabrics, energy storage
Carbon Nanotubes (CNTs)	High strength, conductivity, flexibility	Motion monitoring, wearable sensors
MXenes	High conductivity, EMI shielding	Pressure sensors, energy storage
Conductive Polymers (PEDOT)	Lightweight, flexible, easy processing	Biosensors, conductive textiles
Metallic Nanowires	Excellent electrical conductivity	Flexible circuits, wearable antennas
Shape-Memory & Self-Healing Materials	Adaptive and repairable properties	Smart garments, durable wearables

Table 1. Key Materials for Electronic Textiles

Although graphene, CNTs, MXenes, and conductive polymers all exhibit desirable electrical characteristics, no single material currently satisfies all performance requirements simultaneously. Graphene offers excellent conductivity but remains expensive for large-scale textile integration. CNTs provide superior mechanical flexibility but often face challenges related to dispersion uniformity. MXenes demonstrate outstanding sensing performance but may suffer from oxidation-related stability issues. Conductive polymers provide cost-effective fabrication but generally exhibit lower conductivity than carbon-based nanomaterials. Consequently, hybrid material systems are increasingly being explored to balance conductivity, flexibility, durability, and manufacturing cost.

4. FABRICATION AND MANUFACTURING TECHNOLOGIES

The fabrication of electronic textiles relies on manufacturing techniques that enable the integration of electronic functionalities while preserving textile comfort, flexibility, and durability. Conventional textile processes such as weaving and knitting are widely employed to incorporate conductive yarns into fabric structures, producing wearable systems capable of sensing, communication, and physiological monitoring [1]. Embroidery techniques further allow conductive threads to be stitched directly onto garments, enabling the creation of sensors, antennas, and interconnections with high design flexibility [1], [10]. Advanced fabrication approaches, including printing technologies, 3D printing, and fiber spinning, have significantly expanded the capabilities of smart textiles [4], [6].

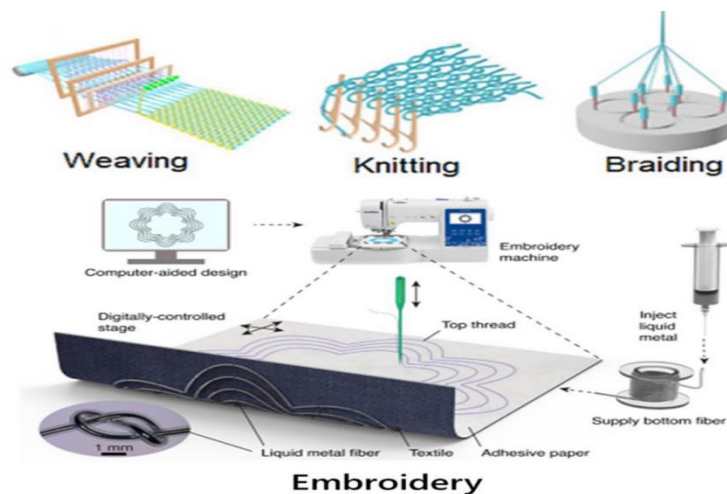


Fig 2: Manufacturing of Electronic Textiles

Screen and inkjet printing facilitate the deposition of conductive materials onto fabrics for the development of flexible circuits and sensors, while 3D printing enables customized wearable structures and electronic components [6]. Fiber spinning techniques, including electro-spinning and wet spinning, allow conductive materials to be integrated directly into fibers, producing highly flexible and durable smart textiles.

Despite these advances, challenges related to washability, mechanical durability, large-scale manufacturing, and sustainability remain significant barriers to commercialization [7], [10]. Future research is expected to focus on scalable production methods, multifunctional textile architectures, and environmentally sustainable manufacturing processes for next-generation smart apparel.

Commercialization challenges extend beyond technical fabrication processes. Although laboratory-scale manufacturing methods have demonstrated excellent functionality, industrial implementation remains constrained by production cost, process repeatability, quality control, and compatibility with existing textile manufacturing infrastructure. Conductive coatings frequently suffer from performance degradation after repeated washing cycles, while printed electronic components may experience cracking under mechanical strain. Furthermore, the integration of multiple functional components, including sensors, communication modules, power sources, and processing units, often increases garment complexity and manufacturing expenses. Future commercialization therefore requires scalable fabrication strategies that simultaneously optimize performance, durability, sustainability, and economic feasibility.

5. WEARABLE SENSORS AND TEXTILE-BASED ELECTRONICS

Wearable sensors constitute the fundamental building blocks of electronic textile systems [6], [9]. These devices enable continuous monitoring of physiological, biomechanical, and environmental parameters while maintaining the comfort and flexibility expected from everyday clothing. The integration of sensors directly into textile structures has transformed garments into intelligent platforms capable of real-time data acquisition and analysis.

5.1. Physiological Sensors

Physiological monitoring is one of the most important applications of wearable sensors. Textile-based physiological sensors are designed to measure vital signs such as heart rate, respiration rate, body temperature, blood oxygen saturation, and muscle activity [9], [11]. These sensors provide continuous monitoring capabilities without requiring cumbersome medical equipment. Electrocardiogram (ECG) sensors integrated into smart garments enable real-time monitoring of cardiac activity. Textile electrodes fabricated using conductive fibers and conductive coatings offer improved comfort compared to traditional gel-based electrodes [6], [11]. Similarly, electromyography (EMG) sensors embedded within garments can monitor muscle activity and support rehabilitation and sports performance analysis.

5.2. Motion and Strain Sensors

Motion and strain sensors play a critical role in activity recognition and biomechanical monitoring. These sensors detect body movements, joint angles, posture changes, and gait patterns by measuring mechanical deformation within textile structures [4], [6]. Conductive fabrics incorporating graphene, carbon nanotubes, or MXene materials exhibit high sensitivity to strain and pressure changes [3], [5]. Such sensors are widely used in sportswear, rehabilitation garments, and human-machine interaction systems. Their ability to provide continuous motion tracking enables precise analysis of physical activities and movement disorders.

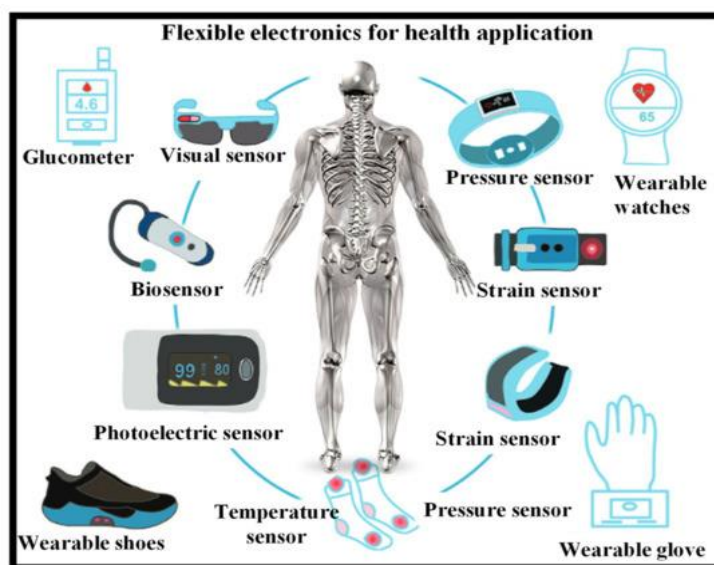


Fig 3: Wearable Sensors

5.3. Temperature Sensors

Temperature monitoring is essential for healthcare, industrial safety, and environmental sensing applications. Textile-based temperature sensors utilize thermoresistive, thermoelectric, or fibre-optic sensing mechanisms to detect changes in body and ambient temperatures [6], [9]. Smart garments equipped with temperature sensors can assist in monitoring fever, thermal stress, and environmental conditions. Recent advances in flexible temperature sensing materials have improved sensor sensitivity, response time, and long-term stability.

5.4. Pressure Sensors

Pressure sensors integrated into textiles enable monitoring of contact forces, body posture, and movement dynamics. These sensors are commonly used in rehabilitation systems, smart footwear,

and seating applications. Capacitive, piezoresistive, and piezoelectric pressure sensors have been successfully incorporated into textile structures [10]. Their ability to detect subtle pressure variations makes them valuable tools for gait analysis, posture assessment, and pressure ulcer prevention.

5.5. Biochemical Sensors

The emergence of wearable biochemical sensors has expanded the capabilities of smart textiles beyond physical monitoring. These sensors can analyse biomarkers present in sweat, saliva, tears, and interstitial fluids [11]. Textile-based biochemical sensors enable non-invasive monitoring of glucose levels, electrolyte concentrations, hydration status, and metabolic activity [7], [10]. Such systems have significant potential for personalized healthcare, sports science, and chronic disease management.

5.6. Environmental Sensors

Environmental sensing represents another important function of smart apparel. Wearable environmental sensors monitor humidity, air quality, ultraviolet radiation, toxic gases, and particulate matter. These capabilities are particularly valuable in industrial safety, military operations, and outdoor activities. Smart garments equipped with environmental sensors provide real-time alerts regarding hazardous conditions, thereby improving worker safety and environmental awareness.

5.7. Future Trends in Wearable Sensing

Future wearable sensing systems are expected to become increasingly multifunctional, self-powered, and AI-enabled. Advances in nanomaterial, flexible electronics, and energy harvesting technologies will further enhance sensor performance while reducing power consumption. The integration of multiple sensing modalities within a single garment will enable comprehensive monitoring of human health, behaviour, and environmental conditions.

6. ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING IN SMART APPAREL

Artificial intelligence has emerged as a transformative technology in the field of wearable systems, enabling smart apparel to evolve from simple monitoring devices into intelligent platforms capable of decision-making, prediction, and adaptive interaction [8], [12]. The combination of AI with wearable sensing technologies allows smart garments to process complex datasets and provide meaningful insights regarding user health, activity, and behaviour.

6.1. Role of Artificial Intelligence in Smart Apparel

Modern smart garments generate large volumes of data through embedded sensors that continuously monitor physiological and environmental parameters. Artificial intelligence algorithms facilitate the interpretation of these data streams by identifying patterns, extracting relevant features, and generating predictive models. Unlike conventional monitoring systems that merely collect data, AI-enabled smart apparel can analyze information in real time and provide personalized recommendations. This capability significantly enhances the value of wearable systems across healthcare, sports, industrial safety, and consumer applications.

6.2. Machine Learning for Activity Recognition

Activity recognition represents one of the most widely studied applications of machine learning in wearable technology. Smart garments equipped with motion sensors, strain sensors, and inertial measurement units can capture movement-related information during daily activities. Machine learning algorithms such as Support Vector Machines (SVM), Random Forests, Decision Trees, and k-Nearest Neighbors (k-NN) are commonly employed to classify activities such as walking, running, sitting, standing, and exercising [8]. Accurate activity recognition enables personalized fitness tracking, rehabilitation monitoring, and workplace safety assessment.

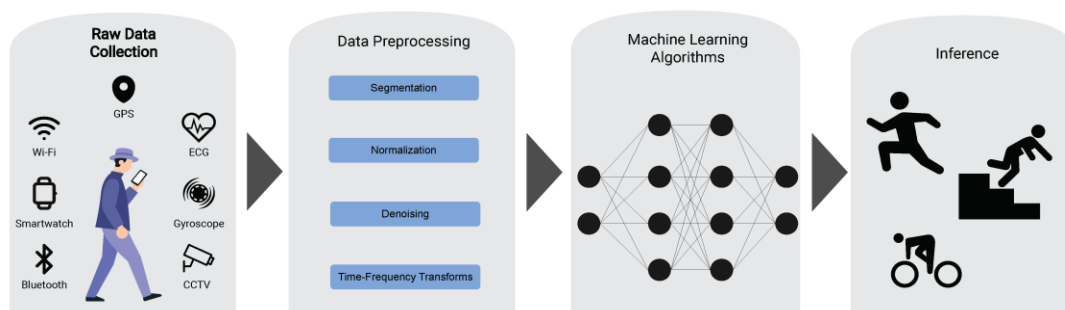


Fig 4: Machine Learning for Human Activity Recognition

6.3. Deep Learning in Wearable Systems

Deep learning techniques have further improved the analytical capabilities of smart apparel. Convolutional Neural Networks (CNNs), Recurrent Neural Networks (RNNs), and Long Short-Term Memory (LSTM) networks can automatically extract meaningful features from complex sensor data without extensive manual pre-processing. Deep learning models have demonstrated exceptional performance in physiological signal analysis, emotion recognition, gesture detection, and health prediction [9], [11]. Their ability to process multimodal data from multiple sensors enables more accurate and robust wearable intelligence systems.

6.4. Predictive Healthcare and Personalized Monitoring

AI-driven smart garments are increasingly employed in predictive healthcare applications. Machine learning algorithms can identify subtle physiological changes associated with cardiovascular diseases, respiratory disorders, fatigue, stress, and other health conditions. Continuous monitoring combined with predictive analytics enables early detection of abnormalities and supports preventive healthcare strategies. Personalized health recommendations generated by AI systems improve patient engagement and facilitate proactive disease management.



Fig 5: Applications of Artificial Intelligence in Healthcare

6.5. Edge AI and Real-Time Decision Making

Traditional wearable systems often rely on cloud-based processing, which can introduce latency and raise privacy concerns. Edge AI addresses these limitations by enabling data processing directly within wearable devices or local computing nodes. Edge computing reduces communication requirements, enhances response times, and improves data security. AI-enabled

smart garments equipped with edge processors can perform real-time analysis and provide immediate feedback without relying on external cloud infrastructure [8], [12].

6.6. Adaptive and Context-Aware Smart Apparel

Future wearable systems are expected to become increasingly adaptive and context-aware. AI algorithms will enable garments to learn user preferences, recognize environmental conditions, and modify their behaviour accordingly. Examples include smart clothing that adjusts thermal properties based on ambient temperature, rehabilitation garments that adapt exercise programs according to patient progress, and sportswear that provides individualized coaching recommendations during training sessions.

6.7. Challenges and Future Opportunities

Despite significant advancements, challenges remain regarding computational efficiency, model interpretability, energy consumption, and data privacy. Developing lightweight AI algorithms suitable for resource-constrained wearable platforms remains a major research priority. Future research will likely focus on explainable AI, federated learning, digital twin integration, and autonomous wearable intelligence. The convergence of artificial intelligence, advanced materials, and connected wearable systems is expected to create a new generation of smart apparel capable of supporting personalized healthcare, intelligent assistance, and seamless human–technology interaction.

7. EMERGING AI PARADIGMS FOR NEXT-GENERATION SMART APPAREL

7.1. TinyML for Wearable Intelligence

Tiny Machine Learning (TinyML) represents an emerging paradigm that enables machine learning algorithms to operate directly on low-power microcontrollers embedded within wearable garments [13]. Unlike cloud-based processing, TinyML performs inference locally, significantly reducing communication overhead, latency, and energy consumption. This approach is particularly beneficial for continuous physiological monitoring applications where real-time decision-making is essential. Recent studies have demonstrated the feasibility of deploying lightweight neural networks for activity recognition, health monitoring, and anomaly detection on resource-constrained wearable platforms [8], [12].

7.2. Federated Learning for Privacy-Preserving Analytics

Federated Learning (FL) has emerged as a promising solution to address privacy concerns associated with wearable healthcare systems. In federated learning, model training occurs locally on user devices, while only model parameters are shared with a central server [14]. This decentralized approach minimizes exposure of sensitive physiological data and complies with emerging data protection regulations. Integration of federated learning into AI-enabled smart apparel can facilitate large-scale healthcare analytics without compromising user privacy [9], [11].

7.3. Explainable Artificial Intelligence (XAI)

Although deep learning models provide high prediction accuracy, their decision-making processes are often difficult to interpret. Explainable Artificial Intelligence (XAI) aims to improve transparency by providing understandable explanations for model predictions [15]. In healthcare-oriented smart apparel systems, XAI can enhance clinical trust and facilitate regulatory acceptance by allowing healthcare professionals to understand how specific physiological indicators contribute to diagnostic outcomes. The adoption of XAI is expected to become increasingly important as wearable technologies move toward medical-grade applications [11].

7.4. Digital Twins for Personalized Healthcare

Digital Twin technology involves the creation of virtual replicas of physical systems using real-time sensor data [16]. In smart apparel applications, digital twins can continuously model an individual's physiological state and predict potential health risks. Integration of wearable sensors, AI algorithms, and digital twin frameworks can support personalized healthcare, rehabilitation planning, and preventive medicine. Future smart apparel systems may utilize digital twins to provide predictive assessments and adaptive interventions tailored to individual users [10], [12].

8. CONCLUSION

Electronic textiles and AI-enabled smart apparel have progressed from experimental research concepts to highly promising intelligent wearable platforms capable of supporting healthcare, sports analytics, rehabilitation, industrial safety, and human-machine interaction. The integration of advanced materials, textile-based electronics, wireless communication technologies, and artificial intelligence has significantly expanded the functional capabilities of modern garments.

However, the future success of smart apparel should not be evaluated solely in terms of sensing accuracy or computational performance. Practical deployment requires addressing several interconnected challenges, including durability, washability, power management, cybersecurity, data privacy, manufacturing scalability, and user acceptance. Many existing systems continue to demonstrate strong laboratory performance while facing difficulties in long-term real-world operation. Consequently, commercialization depends on achieving a balance between technological sophistication and practical usability.

From an artificial intelligence perspective, emerging approaches such as TinyML, federated learning, explainable AI, and digital twins offer promising solutions to challenges involving energy efficiency, privacy preservation, transparency, and personalized healthcare. These technologies are expected to reduce reliance on cloud-based infrastructures while enabling intelligent decision-making directly at the edge.

Future research should prioritize interdisciplinary collaboration among textile engineers, material scientists, electronics specialists, AI researchers, healthcare professionals, and industrial manufacturers. Particular attention should be directed toward sustainable materials, self-powered energy systems, standardized communication protocols, and trustworthy AI frameworks. The convergence of these developments is expected to accelerate the transition from prototype demonstrations to commercially viable smart apparel ecosystems.

Ultimately, electronic textiles are evolving from passive wearable products into intelligent cyber-physical systems capable of continuous adaptation, predictive analysis, and personalized interaction. Their successful implementation may fundamentally redefine the relationship between clothing, healthcare, and digital technology in the coming decade.

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