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Smart Textiles: A New Era of Intelligent Fabrics

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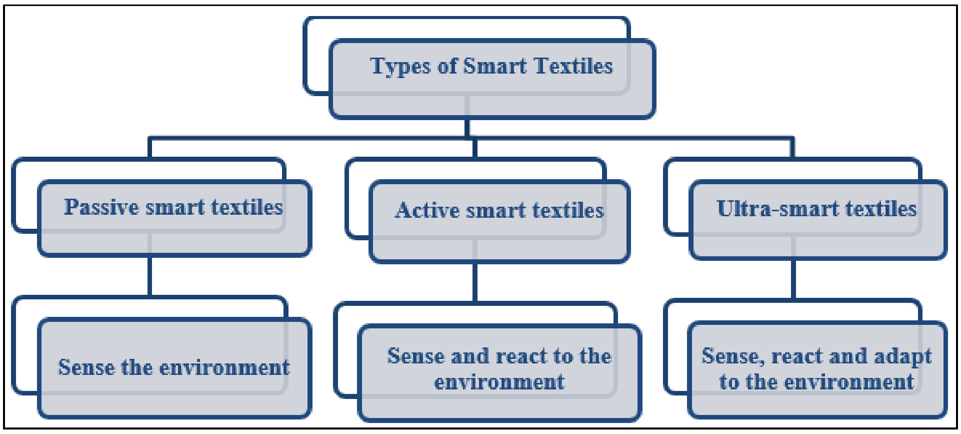
Abstract: ***Smart textiles, also known as intelligent or e-textiles, represent a transformative advancement in textile engineering, combining traditional fabrics with electronic, mechanical, thermal or chemical functionalities to create interactive and responsive systems. This review synthesizes extensive research on the materials, manufacturing techniques, properties and applications of smart textiles, highlighting their growing relevance across diverse sectors. Modern smart textiles employ conductive polymers, carbon-based nanomaterials, MXenes, metallic nanowires, piezoelectric polymers, hydrogels and phase-change materials, each selected for their conductivity, durability, flexibility or thermal properties. Advanced fabrication processes such as melt and solution spinning, coaxial spinning, yarn functionalization, printed electronics, CVD and PVD deposition, embroidery, weaving, knitting and encapsulation allow seamless integration of sensors, actuators and electronic circuits into fibers, yarns and fabrics without compromising comfort or wearability. Smart textiles exhibit essential properties such as electrical conductivity, flexibility, washability, responsiveness to environmental stimuli and energy-harvesting capabilities, enabling them to function as wearable monitoring and interactive platforms. Their applications span healthcare, where they support continuous physiological monitoring; sports and fitness, where they assist in performance optimization; and energy harvesting, where fabrics convert motion, heat or friction into usable power. Further uses include human machine interfaces, protective and military gear, adaptive fashion, environmental sensing and smart infrastructure. Recent advancements emphasize self-powered systems, AI-enabled analytics, thermoregulating fabrics, self-healing materials and textile-based displays, alongside emerging innovations in sustainable and biodegradable smart textiles. Overall, the evolution of smart textiles marks a significant shift toward intelligent wearable systems that enhance comfort, safety, performance and connectivity.***

Keywords: Smart textiles, e-textiles, Intelligent fabrics, Interactive textiles, Responsive materials

1. Introduction

Smart textiles, also known as intelligent or e-textiles; represent a ground-breaking advancement in the field of textile engineering and material science. Textiles that is capable of sensing and responding to mechanical, thermal, magnetic, chemical, electrical or other environmental conditions or stimuli are referred to as smart textiles. They have the capacity to see and react in a predefined manner to external stimuli.

Smart textiles are undoubtedly defined as textile items that have the ability to operate differently from a typical cloth and are primarily capable of carrying out a certain function. Further examples of smart textiles include materials that control body temperature, fabrics that may release moisturizer or medication into the skin and fabrics that assist in reducing muscle vibration during physical activity. In the textile industry, interactive textiles or smart textiles are a relatively new. They are active materials with actuation and sensing capabilities. They have a great deal of potential. One could consider of smart clothing that keeps us comfortable at all times, throughout any activity and in any environment; a suit that keeps a check on things, alerts us when something is dangerous and even aids in the treatment of illnesses and accidents (Syduzzaman, 2015). A smart textile is defined as "a textile product that can interact with its environment or the user by responding to external stimuli in a programmed way" (Stoppa and Chiolerio, 2014). These responses may include signal transmission, thermal regulation, shape change, moisture control or even light emission. They are typically composed of traditional fabric materials integrated with electronic components such as sensors, actuators, microcontrollers and conductive yarns or coatings. Depending on their complexity and functionality, smart textiles can be categorized into three types:



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Passive smart textiles: Can sense the environment (e.g., thermochromic shirts that change color with temperature). For instance, regardless of the outside temperature, a highly insulating coat would continue to be insulating to the same extent. Other examples include bulletproof, anti-microbial, anti-odor and anti-static properties.

Active smart textiles: Can sense and react (e.g., shape memory garments that expand with heat). Shape memory, chameleonic, water-resistant, vapor-permeable (hydrophilic/nonporous), heat-storing, thermoregulated, vapor-absorbing, heat-evolving fabric and electrically heated suits are examples of active smart textiles.

Ultra-smart textiles: Can sense, react and adapt or make decisions based on feedback (e.g., garments that regulate temperature and track biometrics in real-time). In essence, a very smart or intelligent textile is made up of a unit with cognitive, reasoning and activating abilities that functions similarly to the brain. After a successful marriage of traditional textile and apparel technology with other scientific fields like material science, structural mechanics, sensor and actuator technology, advanced processing technology, communication, artificial intelligence, biology, etc., the production of extremely intelligent textiles is now a reality.

In order to produce truly useful smart clothing, smart textiles can be prepared using new fiber and textile materials as well as tiny electronic components. Wearable like regular clothing, these smart clothes offer assistance in a variety of circumstances based on their intended uses (Syduzzaman, 2015).

1.1 Examples of Smart Textiles

- **Health-monitoring shirts** with embedded ECG sensors that track heart activity and transmit the data to smartphones.
- **Heated gloves or jackets** using built-in carbon fiber heating elements to keep the wearer warm in cold environments.
- **Color-changing fashion garments** that alter appearance using thermochromic or photochromic inks.
- **Military uniforms** equipped with sensors that monitor hydration levels, detect chemicals or offer camouflage capabilities.
- **Athletic wear** integrated with sensors to monitor muscle activity, posture and exertion levels, helping athletes improve performance and reduce injury risk.

With growing advancements in electronics miniaturization, flexible materials and nanotechnology, smart textiles are poised to revolutionize a wide range of industries, including healthcare, sports, military, entertainment, space exploration and fashion. The integration of such intelligent functionalities within wearable textiles not only enhances user comfort and safety but also opens the door for seamless interaction between humans and their environment.

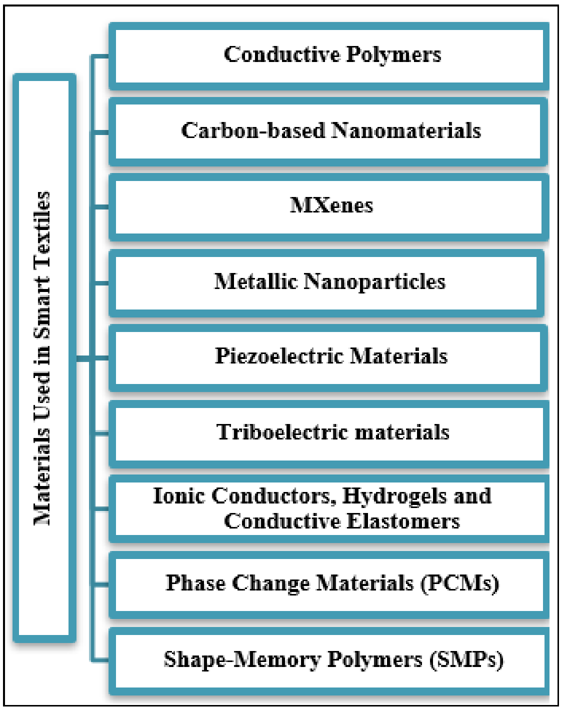
1.2 History of Smart Textiles

The fundamental components of conductive threads, fabrics and e-textiles have existed for more than a millennium. For ages, craftspeople have been encircling fabric threads with fine metal foils, primarily made of gold and silver (Gregory, 2001). For instance, gold-wrapped threads are used to embroider several of Queen Elizabeth I's garments. Designers and engineers started fusing electricity with apparel and jewellery toward the end of the 19th century as people became more acclimated to electric equipment. This led to the creation of a number of lit and motorized necklaces, hats, broaches and costumes (Post, 2000). For instance, in the late 1800s, one could engage young ladies from the Electric Girl Lighting Company to perform at cocktail parties while wearing evening gowns festooned with lights (Smith,1968).

Body Covering, a ground-breaking exhibition at the Museum of Contemporary Craft in New York City in 1968, examined the connection between clothing and technology. The show included space suits worn by astronauts as well as clothing that could light up, heat and cool itself and expand and contract. The work of Diana Dew, a designer who produced a line of electronic clothing that included belts that could emit alarm sirens and electroluminescent party skirts, was especially notable in this collection (Syduzzaman, 2015). A group of MIT researchers headed by Sandy Pentland, Thad Starner, and Steve Mann started creating what they called wearable computers in the middle of the 1990s. These gadgets were made up of conventional computer gear that was carried on and affixed to the body. Another group at MIT, which included Maggie Orth and Rehmi Post, started investigating how such devices might be more elegantly integrated into garments and other soft substrates in response to the technical, social, and design issues these researchers faced. This group created a technique for embroidering electrical circuits and investigated the integration of digital electronics with conductive textiles, among other innovations (Gere, 2010 and Marvin, 1990).

2. Materials Used in Smart Textiles

Smart textile functionality is created by combining (a) electrically conductive components for sensing, signal transmission and electrodes, (b) active materials that transduce energy (piezoelectrics, triboelectrics, electrochromics) and (c) functional additives for comfort, safety or user-feedback (PCMs, antimicrobial agents). Choice of material balances conductivity, stretchability, durability, biocompatibility and manufacturability (Sajovic, 2023).



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2.1 Conductive Polymers

Conductive polymers widely used in textiles include PEDOT: PSS, polyaniline (PANI) and polypyrrole (PPy). PEDOT: PSS stands out for solution processability, reasonable conductivity, mechanical flexibility and compatibility with printing/coating; it is used to make conductive yarns, coatings and ink formulations. PEDOT: PSS's water-dispersibility and film-forming behavior are why it's so popular for coating fabrics and creating stretchable conductive layers (Alamer, 2022).

2.2 Carbon-based Nanomaterials (CNTs, Graphene, GO, rGO)

Carbon nanotubes and graphene derivatives offer high electrical conductivity, excellent mechanical strength, large surface area and good chemical tenability, enabling sensing, electrodes for energy storage, EMI shielding and heating elements in textiles (Hughes, 2024).

Forms and integration

- **CNTs**: used as coatings, embedded in polymer matrix or aligned in fibers via spinning; enable strain/pressure sensing and conductive yarns.
- **Graphene/GO/rGO**: GO is dispersible and used for coating/printing; chemical or thermal reduction gives conductive rGO; functionalization improves adhesion to textiles.
- Integration methods: dip-coating, layer-by-layer assembly, vacuum filtration, electrophoretic deposition and composite fiber spinning are mainly used (Hughes, 2024).

2.3 MXenes (2D Transition Metal Carbides/Nitrides)

MXenes (e.g., $Ti_3C_2T\_x$) have emerged as highly conductive, hydrophilic 2D materials with tunable surface chemistries, high volumetric capacitance (good for textile supercapacitors) and strong electromagnetic shielding potential. MXenes integrate into fibers, yarns and fabrics via coating, printing or electrospinning; they enable energy storage, sensing and EMI shielding in textiles (Ahmed, 2020).

2.4 Metallic Nanoparticles and Nanowires

Silver (Ag) and copper (Cu) nanoparticles/nanowires

Silver nanoparticles and nanowires are widely used because of very high conductivity and antimicrobial properties (Ag). Silver nanowire networks enable transparent, conductive films for wearable electrodes and heaters. Copper is cheaper but more prone to oxidation; encapsulation strategies are used. Integration methods include electroless plating, sputter/vapor deposition, dip-coating with metal inks and embedding in polymer matrices (Zhu, 2025). Metal-based coatings provide excellent conductivity but face wash/wear durability problems (flaking, oxidation) and potential ionic release (biocompatibility concerns). Encapsulation, conductive polymer overcoats or alloying help mitigate these issues.

2.5 Piezoelectric Materials and Energy Harvesting Polymers

PVDF and copolymers

Poly (vinylidene fluoride) (PVDF) and its copolymers (P(VDF–TrFE)) are the dominant piezoelectric polymers for textiles due to flexibility, processability (electrospinning, coating, fiber drawing) and appreciable piezoelectric coefficients after β-phase formation. PVDF-based fibers and films are used as self-powered sensors, energy harvesters and wearable transducers (Wu, 2021).

2.6 Triboelectric materials

Triboelectric nanogenerators (TENGs) use combinations of polymers (e.g., PTFE, PDMS, nylon) and textile electrodes to harvest human motion. Their advantage is high output for low-frequency motion and simple structure; challenges include long-term mechanical stability and integration into breathable fabrics (Zhu, 2025).

2.7 Ionic Conductors, Hydrogels and Conductive Elastomers

Ionic conductors (ionogels, polyelectrolyte hydrogels) and conductive elastomers (silicone or polyurethane matrices with ionic liquids or conductive fillers) are attractive for skin-contact sensors as they offer soft, conformal contact and stable ionic conduction under stretch. Conductive hydrogels are widely reviewed for wearable bioelectrodes and stretchable sensors; major concerns include dehydration and long-term stability, addressed via solvent-retaining matrices or encapsulation (Chen, 2023).

2.8 Phase Change Materials (PCMs) and Thermoregulating Additives

PCMs (microencapsulated paraffins, fatty acids) and endothermic/exothermic functional finishes are used to regulate skin temperature in garments. Microencapsulation allows incorporation into fibers or finishing baths; applications include thermoregulating underwear or outerwear for thermal comfort. Research highlights trade-offs: added mass, limited latent heat per unit mass, and wash durability of microcapsules; hence encapsulation and binder chemistry are critical (Sajovic, 2023).

2.9 Shape-Memory Polymers (SMPs) and Electroactive Polymers (EAPs)

SMPs and EAPs enable actuation (adaptive fit, variable porosity) in textiles. SMPs (e.g., crosslinked polyurethanes, PCL-based systems) change shape with temperature or stimuli; EAPs (ionic EAPs, dielectric elastomers) respond to electrical input. Research on textile-format SMPs/EAPs is more exploratory but shows potential for dynamic conformable garments and adjustable compression. Key challenges include integration into flexible textile systems and supply of safe, low-voltage actuation (Zhu, 2025).

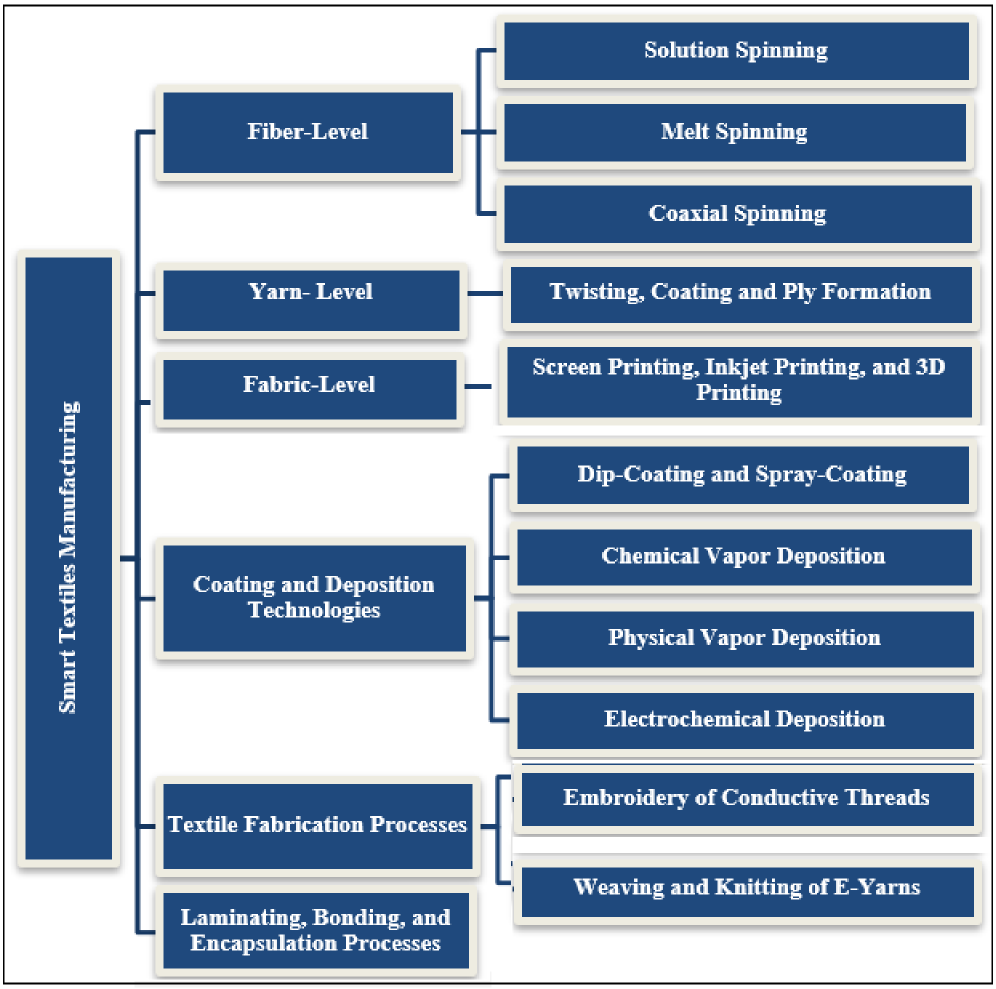
2.10 Conductive Inks, Printing and Coating Technologies

Conductive inks (silver nanoparticle inks, carbon inks, graphene inks, PEDOT: PSS inks) facilitate patterning conductive traces by screen, inkjet or gravure printing. Printing enables localized functionalities (sensors, interconnects) on planar textile surfaces. Challenges during the process are ink–substrate wetting, penetration into porous textiles (which can blur patterns), adhesion and mechanical durability; research focuses on ink rheology, primers and post-curing methods compatible with textile substrates (Alamer, 2022).

3. Smart Textiles Manufacturing

Smart textiles manufacturing requires processes that embed sensing, actuation, communication or energy-harvesting functions into fibers, yarns or fabrics while maintaining comfort, flexibility and durability. Research articles emphasize that the manufacturing route depends heavily on the material system involved: conductive polymers, metal nanoparticles, graphene, MXene coatings, shape-memory polymers, piezoelectric nanofibers or printed conductive circuits (Ahmed *et al*., 2020; Kim and Lee, 2022).

This review synthesizes research-article-based findings on the primary manufacturing processes, including fiber spinning, yarn functionalization, surface coating, printed electronics, embroidering and weaving electronic circuits, laminating and chemical finishing.



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3.1 Fiber-Level Manufacturing Techniques

3.1.1 Melt Spinning and Solution Spinning of Conductive Fibers

Several research studies demonstrate that melt spinning is widely used to manufacture conductive smart fibers by incorporating carbon nanotubes (CNTs), graphene, stainless steel fibers or metallic powders within polymer melts (Hughes *et al*., 2024). Melt spinning offers scalability, high orientation and mechanical strength. However, dispersion of nanomaterials in the polymer matrix remains a major challenge because agglomeration reduces conductivity and fiber tensile properties.

Solution spinning especially wet spinning and electrospinning enables better dispersion of conductive materials. For example, CNT/PU and graphene/PVA fibers produced by wet spinning show high conductivity and stretchability suitable for wearable sensors (Zhang *et al.,* 2022). Electrospinning is particularly advantageous for fabricating piezoelectric PVDF and PVDF-TrFE nanofibers, which exhibit β-phase crystallinity required for energy harvesting (Wu *et al*., 2021). These nanofibrous mats are being explored for wearable nanogenerators, respiratory sensors and motion-sensing patches.

3.1.2 Coaxial Spinning for Core–Sheath Smart Fibers

Coaxial spinning allows the creation of core–sheath structures embedding conductive or optoelectronic materials inside protective polymer layers. Research shows this technique improves durability during washing and mechanical abrasion (Chen *et al*., 2023). For example, a liquid metal core injected inside an elastomeric sheath gives stretchable, self-healing, high-performance smart fibers suitable for electronic interconnects.

3.2 Yarn Functionalization Processes

3.2.1 Twisting, Coating and Ply Formation

Functional smart yarns can be manufactured by twisting conductive filaments with natural or synthetic fibers to achieve a hybrid structure. Research demonstrates that twisting CNT-coated fibers or stainless steel microfilaments with cotton improves comfort while maintaining conductivity (Kim and Lee, 2022).

The dip-coating method is extensively used to deposit silver nanoparticles (AgNPs), graphene oxide, PEDOT: PSS, or MXene dispersions onto yarns. Studies indicate that MXene-coated yarns exhibit excellent surface conductivity and are widely used for strain-sensing applications (Rahman and Bhat, 2023). However, MXene oxidation remains a major barrier for commercial viability. Ply formation combining multiple treated yarns enhances robustness of electronic pathways and increases the textile's tolerance to bending and cyclic loading.

3.3 Fabric-Level Manufacturing Processes

3.3.1 Screen Printing, Inkjet Printing, and 3D Printing

Printed electronics are one of the most researched methods for manufacturing smart textiles. Conductive inks often containing silver nanowires, carbon nanotubes, graphene, PEDOT: PSS or MXene flakes are printed on woven, knitted, or nonwoven substrates (Liu *et al.*, 2022).

Screen printing is preferred for high-viscosity inks and large-area circuit patterns. Studies indicate that screen-printed silver inks maintain conductivity even after multiple laundry cycles when binder polymers remain intact (Kim and Lee, 2022).

Inkjet printing allows high precision and is suitable for low-viscosity nanoparticle inks used in temperature sensors, RFID antennas and bio-monitoring electrodes (Liu *et al.,* 2022). However, ink spreading and poor wash durability remain limitations.

3D printing of conductive filaments (e.g., TPU/CNT composites) onto textiles has been explored for stretchable circuits and wearable antennas. While promising, adhesion between the printed circuit and textile substrate depends heavily on surface pre-treatment (Arumugam and Nagarajan, 2023).

3.4 Coating and Deposition Technologies

3.4.1 Dip-Coating and Spray-Coating: Dip-coating is the most common method for applying conductive polymers and nanomaterials to fabrics. Spray-coating provides more uniform deposition, especially for graphene and MXene sheets (Ahmed *et al*., 2020). These methods are low-cost and compatible with existing finishing lines.

3.4.2 Chemical Vapor Deposition (CVD): CVD-grown graphene and CNT networks are used for sensors, heaters and EMI-shielding fabrics. Research shows that graphene grown via CVD on copper foil can be transferred onto fabrics, offering high transparency and conductivity (Zhang *et al.,* 2022). However, scale-up is challenging due to high temperatures and transfer defects.

3.4.3 Physical Vapor Deposition (PVD): Magnetron sputtering deposits thin layers of Ag, Cu, Au or ZnO onto textile surfaces. Fang and Yu (2021) showed that sputtered silver on cotton provided superior antibacterial and sensing performance.

The major limitation is reduced flexibility over time due to metal cracking.

3.4.4 Electrochemical Deposition: Electroplating and electroless plating deposit metals uniformly. Electroless nickel–phosphorus coatings have shown excellent wash durability and electrical stability in smart textiles (Kim and Lee, 2022).

3.5 Textile Fabrication Processes for Integrating Electronics

3.5.1 Embroidery of Conductive Threads

Embroidery machines can stitch conductive yarn into fabrics forming circuits, interconnects and sensor patterns. Studies show embroidered electrodes provide high comfort for ECG or EMG monitoring (Singh *et al*., 2022). The technique is scalable and compatible with apparel manufacturing.

3.5.2 Weaving and Knitting of E-Yarns

Weaving and knitting allow electronic elements to be structurally integrated during fabric construction. Research indicates:

- **Jacquard weaving** can create pressure-sensing matrix fabrics by controlling conductive yarn placement (Shao and Zhang, 2022).
- **Circular knitting** of conductive yarns yields stretchable strain sensors ideal for athletic wear and medical monitoring (Hughes *et al.,* 2024).

E-yarns containing micro-LEDs, sensors or microcontrollers encapsulated inside protective polymer coatings have been successfully woven into complex structures without losing flexibility (Ahmed *et al.,* 2020).

3.6 Laminating, Bonding, and Encapsulation Processes

Smart textiles often require protective layers to withstand washing, sweat and abrasion.

Research highlights the use of:

- **Thermoplastic polyurethane (TPU) laminates** for waterproof yet breathable encapsulation.
- **Silicone elastomer coatings** to enhance mechanical durability (Chen *et al*., 2023).
- **Hot-press bonding** for integrating flexible printed circuits.

Encapsulation is essential for wearable electrodes and heating elements, as it prevents oxidation of conductive components and maintains stable performance over long-term use.

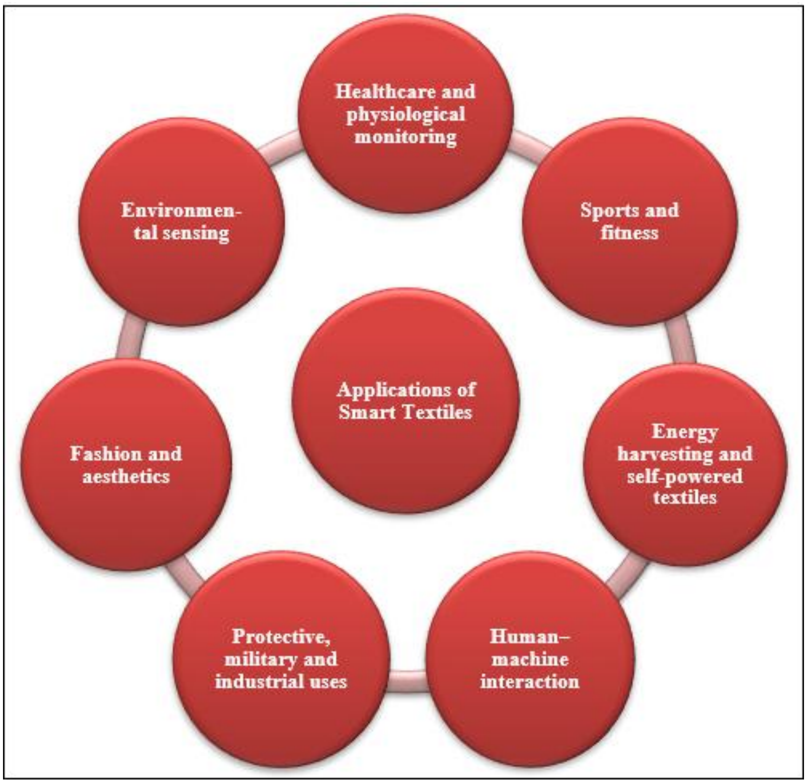
4. Properties of Smart Textiles

Smart textiles possess a unique combination of advanced properties that set them apart from traditional fabrics, enabling them to function as interactive and intelligent materials. One of the most significant features is electrical conductivity, which allows these textiles to transmit signals, power embedded components and support functions such as sensing, monitoring, or communication. This conductivity is often achieved through the integration of conductive fibers, coatings or nanomaterials. Alongside functionality, flexibility and stretchability remain essential characteristics, ensuring that the textile adapts comfortably to the wearer's body movements without compromising performance. This makes smart textiles suitable for applications in sportswear, medical monitoring and daily-use garments where comfort is paramount.

Another crucial property is washability and durability, which ensures that the electronic or functional components embedded within the textile can withstand routine wear, mechanical stress and exposure to water or detergents. The long-term practicality of smart textiles largely depends on their ability to remain functional after repeated use and washing cycles. Additionally, smart textiles exhibit responsiveness, meaning they can sense and react to environmental stimuli such as temperature, light, pressure, humidity or chemical changes. This responsiveness enables functionalities like thermal regulation, color change, pressure sensing or real-time physiological monitoring. Furthermore, many smart textiles are designed for energy harvesting, allowing them to generate power from ambient sources such as body heat, mechanical movement or solar energy. This capability supports self-powered systems, reducing the need for external batteries and enhancing the autonomy of wearable devices. Together, these properties make smart textiles an innovative class of materials with vast potential across healthcare, fashion, defense, sports and environmental applications

5. Applications of Smart Textiles

Smart textiles fabrics with embedded sensing, actuation, communication or energy-management functionality have moved rapidly from laboratory curiosity to demonstrator systems with real application potential across healthcare, sports, fashion, defense, environment and industrial.



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5.1 Healthcare and continuous physiological monitoring

One of the most mature and intensively investigated application areas for smart textiles is medical and health monitoring. Textile-integrated sensors (electrodes, chemical sensors, strain sensors and acoustic/pressure transducers) permit continuous, non-invasive monitoring of cardiac activity, respiration, sweat composition, body motion and even biochemical markers in sweat or interstitial fluid. Recent systematic reviews emphasize textile-based sweat sensors as a promising route to monitor electrolytes, metabolites and stress markers (e.g., cortisol) in real time, enabling personalized and remote disease management and athletic recovery strategies (Akter *et al*., 2024). Textile form-factors dramatically improve wearer comfort and adherence compared to patch or rigid wearable devices, which fosters long-term monitoring in chronic disease or post-operative care. At the same time, researchers are advancing textile acoustic waveguides and piezoelectric fibres to capture physiological sounds or mechanical strains for heart and lung monitoring (Wang *et al*., 2025). These developments point to a near-term ecosystem of shirts, bandages and bedsheets that carry clinically useful continuous signals.

5.2 Sports, fitness and performance optimization

Smart textiles are strongly positioned in sports and fitness because they combine comfort with rich biomechanical data capture. Textile-embedded inertial sensors, piezoresistive strain sensors and EMG electrodes can measure joint angles, muscle activation and impact forces directly from clothing, enabling technique coaching, injury risk reduction and load monitoring for training periodization (Yang, 2024). Reviews of e-textiles for sports highlight integration strategies (knitting, embroidery, printing) and note that garment-level systems (e.g., compression garments with distributed sensors) can deliver higher-fidelity movement and physiological monitoring than wrist-worn devices alone (Yang, 2024). Work is also demonstrating closed-loop garments that provide haptic or thermal feedback to modify athlete behavior in real time.

5.3 Energy harvesting and self-powered textiles

A major enabling trend is integrating energy harvesting directly into textiles so garments can power their sensors and radios without bulky batteries. Researchers have demonstrated triboelectric and piezoelectric textile generators that harvest motion energy, thermoelectric modules that exploit body–environment temperature gradients and textile-compatible photovoltaic fibres for ambient light harvesting. Reviews of 2D materials and nanostructured coatings for textile energy harvesters show improved power densities and flexible integration methods that are compatible with mass fabrication approaches (Ali, 2024; Collado, 2024). Self-powered sensing, sensors that generate their own interrogation signal or harvest enough energy for low-duty communications is an active research frontier and a necessary step toward fully autonomous wearable networks.

5.4 Human–machine interaction, assistive tech and soft robotics

Textiles are proving a comfortable and scalable medium for human–machine interfaces (HMI). Conductive yarns, pressure-sensitive fabrics and touch-sensing weaves enable gesture control, textile keyboards and capacitive or resistive touch panels embedded in garments or furniture. Recent work on body-coupled electronic fibres that can emit signals or light when touched and that can be read remotely has enabled fabric user-interfaces and assistive devices for

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people with disabilities (The Guardian reporting on fibre electronics, 2024). In soft robotics and prosthetics, sensorized textiles provide distributed tactile and pressure sensing to improve control and feedback. These textile HMIs integrate naturally with clothing and seats, opening intuitive interaction for domestic, clinical and entertainment applications (Medeiros, 2021).

5.5 Protective, military and industrial uses

Smart textiles in defense and industry include garments that change thermal properties, detect chemical or biological agents and provide distributed situational awareness. Integration of flexible antennas and textile electronics means soldiers can carry communications and sensing in clothing with reduced system bulk. Protective clothing (flame retardant, ballistic overlays) now can incorporate sensors to monitor fabric integrity, temperature and wearer vitals, enabling earlier hazard detection and automated responses. While many prototypes exist, scaling to reliable, durable field systems remains an engineering challenge because of mechanical stress and harsh environmental exposure (Younes, 2023).

5.6 Fashion, aesthetics and adaptive garments

Fashion applications leverage electrically conductive inks, thermochromic/photonic coatings and light-emitting fibres to create garments that change color, pattern or luminosity in response to environmental cues or user commands. Designers are experimenting with responsive garments that adapt insulation and breathability based on activity or that display personal messages and data. These aesthetic applications often act as rapid-prototyping platforms for functional features (e.g., integrating sensors with pleasing aesthetics) and accelerate consumer acceptance (Medeiros, 2021).

5.7 Environmental sensing, occupational safety and smart textiles for infrastructure

Beyond personal wearables, textile sensors in workwear can detect toxic gases, UV exposure, temperature extremes and mechanical impacts, offering a low-cost, wearable early warning system in hazardous workplaces. Textile sensors woven into building materials or furniture can monitor occupancy, moisture and structural strain for smart buildings and asset management. The low cost and conformability of textiles make them attractive for distributed environmental sensing where rigid sensors are impractical (Sadi, 2022).

6. Conclusion

Smart textiles represent an evolutionary leap in the traditional textile sector, bringing together advanced materials science, flexible electronics, wearable engineering and intelligent systems to create fabrics that do far more than cover or protect the body. They have matured from early prototypes using conductive threads and decorative electronics into multifunctional, durable and responsive systems capable of sensing, monitoring, actuating, storing energy and even making autonomous decisions. This review highlights that the progress in smart textiles has been largely driven by innovations in functional materials such as conductive polymers, carbon nanomaterials, MXenes, metallic nanowires, piezoelectric fibers, hydrogels and phase-change materials each offering unique electrical, mechanical, thermal or sensing advantages. Their integration into fibers, yarns and fabrics through advanced techniques like fiber spinning, printed electronics, coating, embroidery, weaving, knitting and encapsulation has enabled the creation of textiles that retain flexibility, breathability, softness and comfort while providing electronic or multifunctional capabilities.

The applications of smart textiles have expanded widely across disciplines. In healthcare, these textiles support long-term physiological monitoring, detect biochemical markers and assist in rehabilitation making them valuable tools for preventive medicine and patient-centric care. In sports and fitness, they optimize performance through real-time biomechanical and physiological data tracking. Smart military and industrial textiles enhance safety by detecting hazards, monitoring environmental conditions and supporting communication systems. Fashion and entertainment industries benefit from adaptive aesthetic elements such as color-changing surfaces, illumination and interactive features. Meanwhile, environmental and infrastructure applications demonstrate the potential of textile-based sensors for smart buildings, pollution monitoring and occupational safety.

In conclusion, smart textiles stand at the forefront of a technological revolution in wearable systems. As interdisciplinary research continues to strengthen, the future promises intelligent garments and textiles that seamlessly integrate into daily life enabling continuous health monitoring, energy generation, enhanced safety, personalized comfort and interactive experiences. Smart textiles are no longer a futuristic concept, but an emerging reality with transformative potential across industries and society.

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