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REVIEW

Materials in Technological-Wearable Devices for Health: Review and Perspectives

Materiales en Dispositivos Tecnológicos Portátiles para la Salud: Revisión y perspectivas

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ABSTRACT

The convergence between the textile industry and technology has revolutionized material design, enabling the development of smart textiles for wearable technological devices, especially in the healthcare sector. These devices, designed to continuously monitor physiological parameters and provide personalized support, have found in smart textiles an essential solution thanks to their properties of flexibility, comfort and adaptability, key to their prolonged use. This article examines the evolution of smart textiles from passive textiles, capable of responding to environmental stimuli, to ultra-smart textiles, which integrate sensors, actuators, microprocessors, and artificial intelligence algorithms to process information and offer adaptive solutions. The critical properties of smart textile materials are analyzed, such as their conductive, sensory, biocompatible, and energy-harvesting capabilities, as well as their application in areas such as health monitoring, treatment delivery, fall prevention, and rehabilitation. Advances in manufacturing methods are also explored, highlighting associated challenges such as technology integration and sustainability. This study presents a systematic review culminating in an integrative table of the main textile materials used in wearables for health, providing a clear view of their current potential and future areas of research. This approach not only highlights technological advancements, but also opportunities for innovation in smart textile design, positioning them as a key element in the transformation of personalized and technological health.

Keywords: Health Wearables; Integrated Technology; Biomedical Sensors; Materials; Industrial Design; Materials.

RESUMEN

La convergencia entre la industria textil y la tecnología ha revolucionado el diseño de materiales, permitiendo el desarrollo de textiles inteligentes para dispositivos tecnológicos wearables, especialmente en el sector sanitario. Estos dispositivos, diseñados para monitorizar continuamente parámetros fisiológicos y proporcionar un soporte personalizado, han encontrado en los textiles inteligentes una solución esencial gracias a sus propiedades de flexibilidad, comodidad y adaptabilidad, claves para su uso prolongado. Este artículo examina la evolución de los textiles inteligentes desde los textiles pasivos, capaces de responder a estímulos ambientales, hasta los textiles ultrainteligentes, que integran sensores, actuadores, microprocesadores y algoritmos de inteligencia artificial para procesar información y ofrecer soluciones adaptativas. Se analizan las propiedades críticas de los materiales textiles inteligentes, como sus capacidades conductoras, sensoriales, biocompatibles y de captación de energía, así como su aplicación en ámbitos como la vigilancia de la salud, la administración de tratamientos, la prevención de caídas y la rehabilitación. También se exploran los avances en los métodos de fabricación, destacando retos asociados como la integración tecnológica y la sostenibilidad. Este estudio presenta una revisión sistemática que culmina en una tabla integradora de los principales materiales textiles utilizados en wearables para la salud, proporcionando una visión clara de su potencial actual y de las futuras áreas de investigación. Este enfoque no sólo pone de manifiesto los avances tecnológicos, sino también las oportunidades de innovación en el diseño de textiles inteligentes, posicionándolos como un elemento clave en la transformación de la salud personalizada y tecnológica.

Palabras clave: Health Wearables; Tecnología Integrada; Sensores Biomédicos; Materiales; Diseño Industrial; Materiales.

INTRODUCTION

The textile industry, traditionally focused on the production of fabrics for clothing and protection, has currently undergone a radical transformation thanks to convergence with technology. This merger has led to the emergence of smart textiles, materials that are made up of electronic components and with advanced functionalities, expanding their field of application to sectors such as medicine, sports and consumer electronics.

The field of health is undergoing a revolution thanks to the integration of wearable technological devices, which allow continuous and personalized monitoring of various physiological parameters. Smart textile materials play a crucial role in this transformation, providing flexibility, comfort, and adaptability to the skin, essential for the long-term acceptance and use of these devices.(1)

Research into smart textiles has advanced significantly, exploring materials with conductive, sensory, biocompatible, and energy-harvesting properties. These advances open up new possibilities for the creation of wearables that not only monitor health, but also deliver treatments, prevent falls, and improve rehabilitation.(2)

It is important to highlight the evolution that textiles have had; in the first generation known as passive textiles, it can be said that they have emerged in the twenty-first century, these have been characterized by their ability to respond to environmental stimuli, such as temperature or humidity, a classic example is waterproof textiles, these textiles were modified through the properties of the fabrics to provide specific functionalities; In the second generation known as active textiles or "smart textiles" it represented a significant leap by incorporating sensors and actuators that allow dynamic interaction with the user and the environment , It is no longer just a matter of reacting to a stimulus but of detecting it and adapting accordingly, as an example we have thermoregulating textiles, photochromic materials that change color with light and sportswear that monitors physical performance.(3,4)

In the third generation, textiles are known as ultra-intelligent because they are capable of processing information, learning and adapting to the needs of users. These textiles integrate microprocessors, wireless communication systems, and artificial intelligence algorithms to offer a personalized and highly sophisticated experience. The evolution of textiles has gone beyond simply modifying the properties of the fabric. They incorporate sensors, actuators and microprocessors that allow dynamic interaction with the user and the environment.(5)

This systematic review aims to analyze the current state of textile materials in wearable devices for health, examining their properties, manufacturing methods, applications, and challenges. The product of this analysis is a table that comprehensively summarizes the textile materials used in wearables for health, facilitating the understanding of their potential and future areas of research.(6)

METHOD

The process included inclusion criteria that included peer-reviewed academic publications, with a time range between 2012 and 2023 to ensure the relevance of the data. Studies addressing textile materials used in wearable devices were prioritized, with a focus on properties such as conductivity, biocompatibility, sustainability, and flexibility. Conversely, we excluded articles that did not specifically deal with smart textiles in the field of health, duplicate publications or publications with low academic rigor, and studies that lacked significant empirical data Literature searches were conducted in high-impact databases such as PubMed, Scopus, and Web of Science. The keywords used included "smart textiles", "e-textiles", "wearable devices", "health" and "monitoring", which allowed for a thorough and systematic review of the existing literature.(6)

For data extraction, the information was structured according to key categories that included the main materials and components, the technical properties (such as conductivity, flexibility and sustainability), the manufacturing technologies used, the identified limitations and the main applications in monitoring and health care. In addition, a specific weighting was assigned to each material based on its cost, technical feasibility and adaptability to the user. The analysis of the collected data allowed the synthesis of the findings in a comprehensive table that summarizes the materials evaluated, their most relevant characteristics and their applications in wearable devices for health. The results were discussed in detail, highlighting key patterns and relationships between the properties of the materials and their feasibility for different applications. The discussion included a comparison between the most promising materials and the areas that require further research, addressing both current opportunities and limitations. This approach provides a solid basis for future research into the design and optimization of smart textiles in the field of health.[7,8]

To ensure a rigorous and systematic analysis of textile materials used in wearable devices for health, a set of inclusion, exclusion criteria and categories of analysis were established. The following table summarizes the most relevant aspects of the method used, including the time range, databases consulted, keywords used and the analysis approach. This methodological framework provides a structured framework that ensures the validity and relevance of the data collected in the review.

Table 1. Methodological summary of the criteria and results in the review of smart textiles

Category	Detail
Temporal Range	2012 - 2023
Databases used	PubMed, Scopus, Web of Science
Keywords	Smart textiles, e-textiles, wearable devices, health, monitoring
Inclusion criteria	Peer-reviewed publications; studies with a focus on conductivity, biocompatibility, sustainability and flexibility.
Exclusion Criteria	Articles that do not treat smart textiles in the field of health; duplicate publications or of low academic rigor.
Analysis Categories	Main materials and components, technical properties, manufacturing technologies, constraints, main applications.
Method of analysis	Weighting of materials according to cost, technical feasibility and adaptability to the user.
Synthesized results	Comprehensive table of textile materials: relevant properties, applications and recommendations for use.
Key References	Li et al., 2023; Bhushan, 2009; Kamps et al., 2017

The table summarizes the criteria and approaches employed in the systematic review, showing how each aspect contributed to the structuring and extraction of relevant data. This methodological framework allowed for a precise classification of textile materials, highlighting both their technical properties and their limitations in practical applications. Likewise, the use of high-impact databases and specific keywords guaranteed exhaustiveness in the literature search. This approach not only consolidated the results obtained, but also establishes a solid methodological basis for future research on smart textiles applied to wearable devices in the field of health.

DEVELOPMENT

Smart textiles, also known as e-textiles, have emerged as a revolutionary technology with a profound impact on the healthcare sector. These materials, which integrate electronic functionalities into textile fibers, are transforming the way we monitor health, deliver treatments, and promote wellness. The evolution of smart textiles has gone through three generations of passive textiles, active textiles, and ultra-smart textiles.

The choice of textile materials is crucial for the development of effective and health-safe wearable devices. Different types of fibers, both natural and synthetic, offer specific properties that allow the integration of sensors, actuators, and other electronic components.

Among the textiles that stand out the most is this:

Natural Fibers: Cotton, wool, silk and bamboo that offer biocompatibility and comfort, making them ideal for applications in contact with the skin. However, its low electrical conductivity limits its use in signal transmission.[9]

Synthetic Fibers: Polyester, nylon, elastane and acrylic, versatile materials that allow the creation of fabrics with specific properties, such as waterproofness, breathability or elasticity. However, some synthetic materials may present long-term biocompatibility issues.[10]

Conductive Fibers: Carbon fibers, metallic threads, conductive polymers (PPy, PANI), essential for the transmission of electrical signals, allowing the integration of sensors and actuators into the fabric. Conductive polymers, such as polypyrrole (PPy) or polyaniline (PANI), stand out for their flexibility and ease of processing, opening up new possibilities in the design of wearable devices. Nanomaterials: Graphene, carbon nanotubes, nanofibers, offer high conductivity, flexibility, and potential for new functionalities, such as biomarker detection or drug delivery at the cellular level. However, their cost, long-term safety, and complex manufacturing processes are still challenges to overcome.(2,10,11)

It is important to note that there are certain manufacturing techniques of smart textiles for wearable devices and the integration of electronic components in fabrics and that these allow maintaining the flexibility and comfort of the textile material depends on the Integration of Conductive Wires, Printing of Flexible Circuits, Conductive Coatings, Microencapsulation with the incorporation of active substances in microcapsules that are released in a controlled way. It allows the creation of textiles with therapeutic properties, such as the release of drugs or the hydration of the skin, nanotechnology that allows the manipulation of materials at the nanometric scale, such as the incorporation of conductive nanoparticles in textile fibers, allows the creation of new materials with improved properties, such as electrical conductivity, mechanical resistance or biocompatibility.(1,10,12,13,14,15)

The applications of Smart Textiles in wearable devices for Health have been focused on different areas, transforming the way we monitor health and administer treatments.(16)

Table 2. Classification of Textile Materials and Manufacturing Techniques for Health Wearables

Category	Types of Materials/Components	Features and Advantages	Limitations
Natural Fibers	Cotton, wool, silk, bamboo	Biocompatibility, comfort, suitable for skin contact	Low electrical conductivity, limited utility in signal transmission (Sundriyal & Bhattacharya, 2020).
Synthetic Fibers	Polyester, Nylon, Elastane, Acrylic	Versatility, elasticity, waterproofness, breathability	Long-term biocompatibility issues (Shak Sadi & Kumpikaitė, 2022).
Conductive Fibers	Carbon fibers, metal wires, conductive polymers (PPy, PANI)	High electrical conductivity, integration of sensors and actuators, flexibility (Shak Sadi & Kumpikaitė, 2022; Khoso et al., 2024).	Prone to corrosion, limited durability in some cases.
Nanomaterials	Grafeno, nanotubos de carbono, nanofibras	Superior conductivity, flexibility, capacity for new functionalities such as biomarker detection (Wu, 2022).	High cost, complex manufacturing processes, long-term safety challenges (Shak Sadi & Kumpikaitė, 2022).
Manufacturing Techniques	Integration of conductive wires, flexible circuit printing, conductive coatings, microencapsulation, nanotechnology	Maintenance of flexibility and comfort, advanced functionality such as controlled drug release or hydration (Wei et al., 2023; Júnior et al., 2022).	Complexity in processes, need to ensure the stability of properties in real conditions (Meena et al., 2023).

RESULTS

The following table classifies and evaluates 20 types of textile materials and their derivatives for wearables in the field of health, evaluating them in five key criteria: conductivity, biocompatibility, sustainability, flexibility and cost. Each criterion was weighted on a scale of 1 to 5, with 5 representing outstanding performance and 1 indicating poor performance. The selected materials reflect a combination of technical and economic properties that make them suitable for different applications.

Conductive hydrogels, silk-based textiles, and bio-inspired hybrid materials stand out as the top three materials in the field of smart textiles for biomedical applications. Conductive hydrogels, with a score of 4,2, are especially effective for biomedical sensors due to their ability to adapt to biological environments and transmit electrical signals. Silk-based textiles, with a score of 4,4, are ideal for sutures and biological regeneration thanks to their biocompatibility and mechanical properties. Finally, bio-inspired hybrid materials, also with a score of 4,4, offer innovative solutions for advanced regenerative systems by combining mechanical, electrical and biological properties efficiently. The choice and balanced use of these materials depend on the specific applications, whether in biomedical, sports or regenerative contexts, highlighting their adaptability and relevance in different fields of health and well-being.

For example, conductive hydrogels obtained a final weighting of 4,2, standing out as a priority choice for biomedical sensors thanks to their excellent biocompatibility (5), flexibility (5) and conductivity (4). This material is key for interfaces that require direct contact with the skin. Biodegradable textiles, with a score of 3,6, stand out for their high sustainability (5), which makes them ideal for disposable wearables, although their low conductivity (2) limits their use in electronic applications. On the other hand, materials such as graphene and conductive polymers, which have a weighting of 4,0 and 3,8 respectively, balance conductivity, flexibility and cost, being recommended for multifunctional applications and portable devices.

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Table 3. Comprehensive Analysis of Textile Materials in Wearables for Health

#No.	Category	Materials/ Components	Conductivity	Biocompatibility	Sustainability	Flexibility	Cost	Manufacturing Technologies	Limitations	Main Applications	Final Weighting	Recommendation
1	Electronic Textiles	Graphene, Conductive Polymers	5	4	3	5	3	3D printing, embroidery, coatings	Low sustainability High costs	Wearable Sensors, Smart Sportswear	4,0	Ideal for advanced wearables with high sensitivity.
2	Conductive Materials	Silver, Carbon Nanotubes	5	4	2	4	2	Coating with inks, deposition	High costs (Silver and CNT) Possible toxicity	Flexible circuits, embedded IoT systems	3,4	Useful for high conductivity.
3	Flexible Materials	PDMS, Carbon-Based Textiles	4	4	3	5	3	Laminate, hybrid manufacturing	Low conductivity Requires integration with other materials	Ergonomic garments, continuous monitoring	3,8	Suitable for comfort and adaptability.
4	Biodegradable Textiles	PLA, Chitin	2	4	5	3	4	Extrusion, chemical processing	Low durability Limited mechanical properties	Disposable wearables, biodegradable packaging	3,6	Excellent for sustainable and temporary solutions.
5	Conductive Hydrogels	CNT in Hydrogels, Nanowires	4	5	4	5	3	Photolithography, encapsulation in elastomers	Low mechanical stability Requires additional encapsulation	Biomedical electrodes, skin-device sensors	4,2	Priority for biomedical interfaces.
6	Metal-Based Materials	Air, Plata, Gallo-Indio	5	3	2	4	2	Chemical Reservoir, Direct Printing	Very high costs Low sustainability	Implantable sensors, precision electrodes	3,2	Limited to high technology.
7	Piezoelectric Materials	PVDF, Collagen	4	5	3	4	3	Electrospinning, polarization	Requires manufacturing specialization Limited direct integration	Power generation, pressure sensors	3,8	Ideal for stand-alone systems.
8	Smart Textiles	Cotton, Polyester, Wool	3	4	5	3	5	NFC technology, smart embroidery	Low conductivity Limited durability vs. advanced textiles	Sweat analysis patches, cardiac monitoring clothing	4,0	Recommended for accessible applications.
9	Carbon Composites	CNT, Graphene	5	4	3	5	3	Functional coatings, hybrid integration	High cost of production Difficulties in material uniformity	Multifunctional wearables, advanced devices	4,0	Great for next-generation technology.
10	Conductive Polymers	PEDOT:PSS, Polipirrol	4	4	3	4	4	Printing, chemical deposition	Sensitivity to degradation Moderate conductivity	ECG/EEG sensors, portable systems	3,8	Versatile and balanced.

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11	Thermochromic Materials	Copper Oxides, Vanadium	3	4	3	5	3	Chemical Reservoir, Coating	Poor durability in extreme conditions Limited optical properties	Thermal Monitoring T-Shirts	3,6	Useful in temperature monitoring.
12	Elastomeric Polymers	Ecoflex, Sylgard	4	5	4	5	4	Molding, Encapsulation	Intermediate costs Reliance on additional substrates	Pressure sensors, touch surfaces	4,2	Recommended for adaptive wearables.
13	Conductive Nanostructures	Silver Nanowires, Aluminum	5	4	3	4	3	Electrospinning, Injection	Scale costs Variable uniformity	Advanced circuitry, motion sensors	3,8	Ideal for advanced technologies.
14	Photo-resistant materials	Acrylates, Photopolymers	4	4	2	4	3	Photolithography	Low chemical stability Limited biocompatibility properties	Integration into optical and electronic devices	3,4	Recommended for optical integration.
15	Bio-Inspired Hybrid Materials	Quitosan with Graphene	4	5	5	4	4	Chemical synthesis, advanced coatings	Complex production High cost	Bioactive sensors, regenerative systems	4,4	Excellent for regenerative applications.
16	Flexible photovoltaic materials	Organic cells, Perovskites	5	3	3	4	4	Roll Tank	Low thermal stability Moisture sensitivity	Power generation for wearables	3,8	Ideal for autonomous power generation.
17	Silk-Based Textiles	Silk Fiber, Recombinant Silk	4	5	4	5	4	Biotech Processing	Expensive production Limited to specific applications	Smart sutures, biocompatible textile	4,4	Highly recommended in biomedical applications.
18	Magnetoresistive Materials	Ni-Fe, Ti-Co alloys	5	3	3	4	3	Laminated, deposition	Low flexibility Dependence on external magnetic fields	Posture monitoring, guidance devices	3,6	Useful in posture and navigation devices.
19	Conductive Transparent Materials	ITO, Transparent Nanotubes	5	4	2	4	3	Thin Layer Deposit	High cost Scratch sensitivity	Flexible touch screens, optical interfaces	3,6	Recommended on advanced screens.
20	Antimicrobial Textiles	Plata, Poliquaternarios	4	5	4	4	4	Impregnation, coatings	Potential toxicity at high concentrations Variable efficiency	Medical garments, hospital textiles	4,2	Excellent for healthcare applications.

Piezoelectric materials (3,8) and flexible photovoltaic cells (3,8) demonstrate great potential for autonomous devices that require power generation. Their combination of flexibility (4) and conductivity (4-5) makes them suitable for wearables designed to operate without external sources of power. In contrast, metal-based materials such as gold or gallium-indium, with a score of 3,2, are limited by their high cost, although they are critical in high-precision applications, such as implantable sensors.

Analysis of manufacturing technologies reveals that materials such as smart textiles and bio-inspired hybrid materials (4,4) stand out for their versatility and emerging applications in health and tissue regeneration. These materials not only meet technical requirements, but also promote advances in the design of wearables aimed at biological regeneration and direct interaction with the human body.

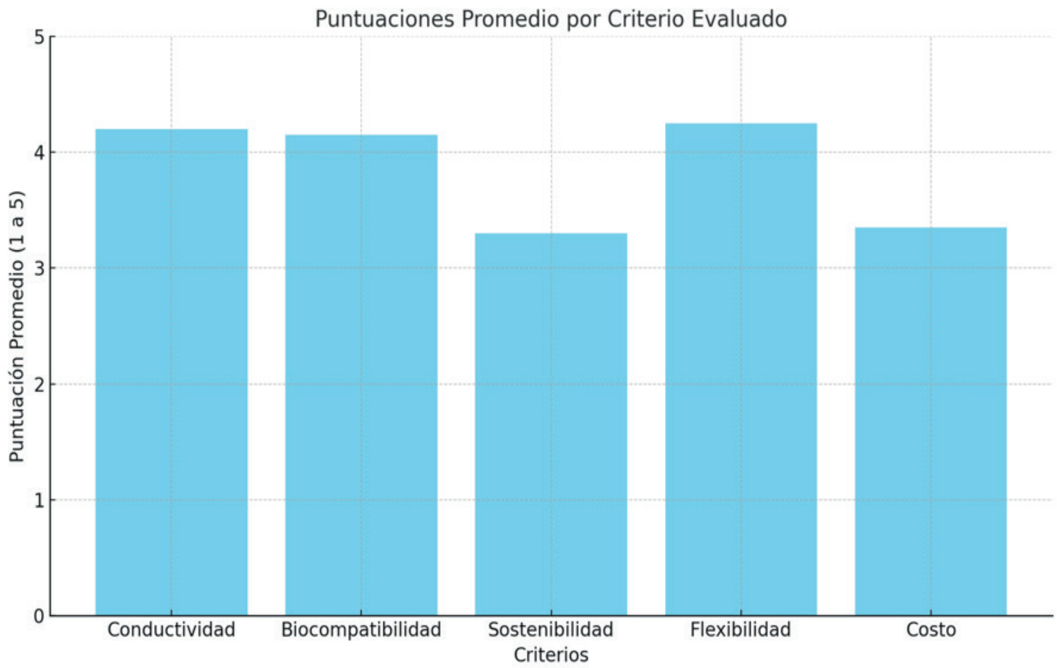

Figure 1. Analysis of Weights by Criterion

The graph presents the average scores of the criteria evaluated for all materials. The results show the following:

1. Conductivity and Flexibility: They stand out with scores close to 4.5 on average, reflecting their importance in the selection of wearable materials that must be sensitive and adaptive to the human body.
2. Biocompatibility: It also maintains a high score, reinforcing the need for skin-compatible materials and biological tissues, especially for medical applications.
3. Sustainability: Although important, it is underperforming, reflecting that many advanced materials (such as metals and conductive composites) are not yet ecologically optimal.
4. Cost: This criterion has the lowest score, indicating that many high-tech materials have significant economic barriers to mass adoption.

Table 4. Impact of Textiles on Wearable Devices

Aspect	**Impact on Wearables**
Comfort and Adaptability	- Provide softness and flexibility for a comfortable fit. - Optimize weight, reducing the burden on the user.
Electronics Integration	- Conductive textiles allow circuits and sensors to be integrated directly into fabrics. - They house sensors to monitor parameters such as heart rate and temperature.
Improved Functionality	- Moisture management (sweat absorption and water repellency). - Thermal regulation using thermochromic or phase-change materials.
Biocompatibility	- Skin-friendly materials, such as organic cotton or silk. - Antimicrobial properties that reduce the risk of infections.
Aesthetics and Fashion	- Design flexibility in colors, patterns and textures. - Technology integrated in a discreet way, resembling ordinary clothing.

Sustainability	- Use of biodegradable textiles such as PLA and silk.- Recyclable components that promote a circular economy.
Applications	- Health: Monitoring of vital signs and rehabilitation support.- Sport: Monitoring of performance, hydration and recovery.- Daily use: Thermal, luminous and self-cleaning clothing.
Challenges	- Durability: Resistance to washing, stretching and prolonged use.- Costs: Advanced materials such as graphene are expensive.- Complexity: Specialized processes make production more expensive.

DISCUSSION

From the analysis presented it is important to highlight that wearable textiles have several factors for which they can be selected for comfort and adaptability considering weight, on the other hand, there is electronic integration based on the ability to integrate circuits and sensors directly into the fabrics is a distinctive feature of smart textiles.[10] On the other hand, there are conductive textiles that act as platforms for electronics, allowing the creation of wearables with advanced functionalities. Another factor that is considered is moisture management through sweat absorption and water repellency is crucial for comfort in sportswear and in everyday applications.[2,4,17] Thermal regulation using thermochromic or phase-change materials allows the creation of garments that adapt to different temperatures, improving comfort and safety in various weather conditions.[18]

It is also important to consider biocompatibility and that it is skin-friendly and has antimicrobial properties reducing the risk of infections, relevant in wound care and sportswear, it is important to also consider sustainability in relation to biodegradable textiles such as PLA (polylactic acid) and silk, along with recyclable components, contributes to a circular economy and reduces environmental impact.[17,19] Despite their advantages, smart textiles still face challenges that limit their large-scale adoption. Durability, i.e., resistance to washing, stretching, and prolonged use, is a critical factor for commercial viability. Research into analyzing materials and manufacturing techniques that ensure the durability of wearables, especially in applications that require frequent washing, such as sportswear.[2,4]

The cost of advanced materials, such as graphene, can be an obstacle to mass production. The search for cheaper alternative materials and the optimization of manufacturing processes are essential for the democratization of technology, the complexity of manufacturing processes requires specialized personnel and expensive equipment, which makes production more expensive. Innovation in simpler and more scalable manufacturing techniques is critical for the mass production of smart textiles at an affordable cost.[10,17,20]

CONCLUSIONS

Smart textiles represent a revolution in the development of wearable devices, especially in the field of health and wellness, thanks to their ability to integrate advanced functionalities such as monitoring, thermal regulation, and biocompatibility. This article highlights that the selection of materials depends on key factors such as comfort, adaptability, electronic integration capability and specific functional properties. The ability to integrate sensors and circuitry directly into fabrics, as seen in conductive textiles, enables the creation of wearables with advanced functionalities, while moisture wicking and thermal regulation properties ensure comfort and performance in sports and everyday applications.

Despite their advances, smart textiles face significant challenges, including durability and cost. Resistance to washing and prolonged use remains a critical challenge, especially in applications that demand high maintenance frequency, such as sportswear. The high cost of advanced materials, such as graphene, and the complexity of manufacturing processes limit the mass production and accessibility of these textiles. Therefore, research should focus on the development of cheaper and more sustainable alternative materials, as well as more scalable and accessible manufacturing techniques. Finally, sustainability emerges as a central axis, with biodegradable and recyclable materials such as PLA and silk, which promote the circular economy and reduce environmental impact. Smart textiles offer a promising future, but they require continuous innovation in materials, manufacturing techniques, and sustainability to democratize their large-scale adoption and maximize their impact in various applications.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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