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REVIEW ARTICLE

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Recent Developments in Wearable Biosensors for Real-Time Health Monitoring: A Comprehensive Review

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Abstract

Instantaneous health monitoring through wearable biosensors has become an enhancement platform in healthcare management that provides a non-invasive individual continuous health monitoring solution making it compatible with the transformation towards proactive healthcare. With the incorporation of stretchable substrates, enhanced nanomaterials, miniaturized electronics, and wireless connectivity standards, the precise smart systems can measure an array of physiological and biochemical-related parameters such as heart rate, oxygen saturation, glucose levels, hydration, temperature, and metabolic biomarkers in mediums such as sweat, saliva, interstitial, and interdigital skin allergies. Innovation has in the recent past been laying stress on enhancing sensitivity, stretch capacity and long-run stability of these sensors and maintaining comfort and sturdiness in the end user. At the same time, the approach to energy harvesting, including triboelectric, thermoelectric, piezoelectric generators, has solved the issue of power autonomy, allowing to use battery-free, long-lasting power. At the same time, more and more frequently we are also to see AI-derived data processing methods that would allow us to increase signal accuracy, give out predictive information, and ensure smooth integration with mobile health (mHealth) technologies and Internet of Medical Things (IoMT), frameworks. Such innovations have enhanced the usage of wearable biosensors in various settings, such as chronic disease management (e.g., diabetes, cardiovascular diseases), sports activities, and fitness tracking, post-surgical care, aging, and pandemic surveillance. Nevertheless, the popularity of these systems is also associated with the issues of biocompatibility, skin irritability, and sensor wear, data protection, ethical standards, and regulatory licensing. Besides, the problem of artifacts or motion, calibration drift, and interoperability with some other devices are obstacles to stable clinical quality work. The broad review of wearable biosensor research gives a detailed overview of the latest innovation in wearable biosensor technology classified by sensor types, materials, fabrication processes, signal transmission pathways, power solutions and data acquisition methods. It also addresses real-life deployment, restrictions, and what trends and technologies have been introduced into the field including digital twins, self-healing smart sensors, and edge AI for decentralized healthcare. This review attempts to support future research and development by systematizing the existing efforts and establishing the remaining gaps in the goal of developing wearable healthcare systems that are scalable, secure, and smart.

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Introduction

In recent years, the healthcare landscape has witnessed a paradigm shift from reactive treatment to proactive and preventive care, driven largely by the integration of real-time health monitoring systems. Traditional clinical diagnostics, though highly accurate, are episodic in nature and often limited by accessibility, cost, and the inability to provide continuous physiological insights. In contrast, real-time health monitoring empowers individuals and healthcare providers with the ability to continuously track vital physiological and biochemical parameters, enabling timely detection of anomalies, early intervention, and personalized treatment strategies.

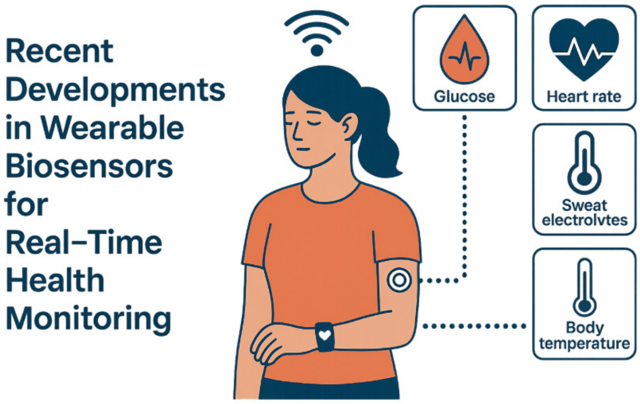

Fig. 1: Wearable biosensors for real-time health monitoring and key biomarker detection.

This shift is particularly vital in managing chronic conditions such as diabetes, cardiovascular diseases, and respiratory disorders, where real-time data can significantly reduce morbidity, mortality, and healthcare burden.

Wearable biosensors are leading this evolution: they are miniature, skin-conformable devices that combine the latest materials, electronics, and wireless communications to measure a continuously expanding number of health parameters. These are non-invasive sensors that can easily be embedded into clothes, wristbands, patches, or even tattoos, so that biomarkers like glucose, lactate, sweat electrolytes, body temperature, heart rate, and oxygen saturation can be continuously determined. Wearable biosensors unlike traditional forms of diagnostic devices, can be used in real-time feedback and can be operated in an easy to operate manner thus they are best suited in clinical and home-based setting. The integration of flexible electronics, low power microcontrollers and miniaturized transducers also added to the ability of their functionality and wear capacity and has extended the limit of what can be done in mobile health (mHealth) or digital medicine.

This broad survey is necessitated by the fact that the field of research on wearable bio sensing technologies has experienced a massive explosion in interdisciplinary research. It will portray an exhaustive analogy of the latest advancement of sensor kinds, material development, processing procedure, power source, and data analytics structure. Not only that, it outlines the existing areas of application, presents technological and regulatory issues, talks about the upcoming trends, including those related to AI-driven analytics, energy harvesting, and using edge computing. This review aims to provide the roadmap to the researchers, developers, and clinicians in the sphere of intersection between healthcare, materials science, and embedded systems by critically examining the state of the art and outlining the directions of future research.

Literature Review

Wearable biosensors are one of the most essential elements of personalized and preventive healthcare advancement that allow constant and real-time monitoring of physiological and biochemical parameters in a non-invasive manner. The conventional biosensor systems used to appear very big as well as inflexible, making them uneasy to wear and not to be used over a long time. Initial investigation activities were mainly oriented to rigid designs that could be compatible in hospitals and other medical facilities; but these were not very ergonomic nor flexible to be applied smoothly with the human body.

Flexible, stretchable electronics have improved considerably so that sensors can now be placed on skin or textiles. Heikenfeld et al.[1] and Trung and Lee [2] have done background reviews on how using soft materials and miniaturization of systems have played a significant role in the accomplishment of skin-conformable biosensing device platforms. These systems provide a greater degree of comfort, mechanical durability, and signal acquisition over time, which establishes a foundation of their implementation in permanent health surveillance.

The use of the electrochemical biosensor was widely adopted in non-invasive detection of metabolites. As an example, the study of Lee et al.[3] presented an enzymatic based glucose sensor using functional electrodes, based on sweat, and the resulting sensitivity and response time were stable and satisfactory. Likewise, Gao et al.[4] presented a fully integrated epidermal patch that has the potential to monitor several of the biomarkers (lactate, sodium, potassium) in the sweat and exhibits multi-analyte sensing in a single wearable interface.

Commercially, optical biosensors (e.g. photoplethysmography (PPG) systems) are widely used in devices, such as Fitbit and Apple Watch. Even though they are widely used, they are affected by motion artifacts, skin pigmentation and interference of ambient light .[5] Graphene- and MXenes-based nanomaterials, such as, carbon nanotubes, have enhanced the sensitivity, stretchability, and signal-to-noise ratio of the sensors in a considerable manner.[6, 7]

To solve the problem of power limitations in long-term monitoring, Dagdeviren et al.[8] discussed energy harvesting approaches (sustainable energy) like piezoelectric and thermoelectric generator systems, which supply wearable systems with a constant source of power that does not need replacement batteries, thus ensuring its sustainability.

Irrespective of these progresses, there are challenges. As unresolved issues, the stability of calibration, biofouling, interdevice variation, and data security pop up on a regular basis and have to be solved in order to enable clinical translation. The market is also not ready due to regulatory barriers particularly in terms of FDA and CE compatibility. This is to fill these scattered gaps by synthesizing the trends within the realms of materials science, device engineering, signal processing and deployment at application level. It draws attention to a multi-disciplinary future towards fully autonomous, intelligent and scalable ecosystems of biosensing.

Methodology

This review was done using a systematic approach as presented in PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to warrant transparency and reproducibility.

Search strategy

To guarantee both comprehensiveness and currency of the synthesis of relevant literature on the use of wearable biosensors in real-time health monitoring, a rigorous search strategy was utilized in search of four major academic databases: Scopus, PubMed, IEEE Xplore, and ScienceDirect. Such databases were used because of their broad coverage of peer-reviewed journals and high-impact publications on engineering, biomedical sciences, and interdisciplinary research fields.

The search procedure has been carried out as a Boolean search by using well-designed search terms to find as relevant articles as possible with a balance between vague and detailed search. The Boolean search words with or without proper combination are as follows:

- **(“wearable biosensors” AND “real-time monitoring”)** - to retrieve articles that specifically target wearable sensor systems deployed in real-time physiological or biochemical body monitoring of humans.
- **(“flexible electronics” OR “nanomaterial sensors”)** - In order to find studies connected with the development of new materials and flexible form factors that will allow skin-conformal sensors or body-integrated system.
- **(“Energy harvesting” AND “health monitoring”)**- employed to retrieve literatures that discuss the topic of power autonomy, the one that relies on piezoelectric, triboelectric, or thermoelectric power harvesting methods incorporated into wearable systems.
- **(“AI in biosensors” OR machine learning in health wearables”)**- in order to consider the papers that address the application of artificial intelligence and machine learning algorithms to process data, detect anomalies, or make predictions with regard to wearable health devices.

Only articles published in January 2016- June 2025 were considered so that of recent technological advances could be captured. Only peer-reviewed journal articles, review papers and a few hand-picked high-quality conference proceedings are being used. There was removal of duplicate entries among databases, followed by relevance screening of titles and abstracts.

After the preliminary screening, the detailed contents of the selected articles were read to be sure of their consistency with the scope of the present paper. The studies basing only on non-wearable or implantable biosensors, modeling sensors theoretically without realizing them in practice, or the application areas that are not of any interest (e.g., industrial or animal biosensing) were not discussed and used in further analysis Table 1).

Table 1: Summary of Search Strategy for Literature Review

Component	Details
Databases Searched	Scopus, PubMed, IEEE Explore, ScienceDirect
Search Period	January 2016 – June 2025
Boolean Expressions	1. (“wearable biosensors” AND “real-time monitoring”) 2. (“flexible electronics” OR “nanomaterial sensors”) 3. (“Energy harvesting” AND “health monitoring”) 4. (“AI in biosensors” OR “machine learning in health wearables”)
Article Types	Peer-reviewed journals, review articles, selected conference proceedings
Inclusion Focus	Real-time wearable bio sensing, biomedical and healthcare applications
Exclusion Criteria	Non-wearable sensors, purely theoretical models, industrial/animal applications

This systematic strategy made the review rigorous, reproducible, and focused with emphasis on the literature, and this can be used on evaluation of the emerging trends, technologies, and gaps in the field of wearable biosensors used in real-time health monitoring).

Inclusion and Exclusion Criteria

In order to ensure the rigor and relevance of the review, a pre-determined criteria of inclusion and exclusion criteria was followed in the selection of the articles to review. These standards are put in place to indicate that the literature to be studied in this work is relevant to the research intent and also the state-of-the-art of wearable biosensors as a real-time health monitoring material.

Inclusion Criteria

To make the research relevant, of high quality, and centered on research objectives, a list of carefully determined inclusion criteria was used to guide selection of studies that constituted this review. It has only selected peer-reviewed articles published in 2016 through 2025, which offered an opportunity to include the recent progress made and new technologies in the sphere of wearable biosensing. To facilitate uniformity in study and interpretation publications were restricted to English language. Another criterion was focus of real-time or continuous biosensing, especially in mobile, dynamic or ambulatory environments because they are the main specifications of present-day healthcare monitoring systems. The review was particularly set to look at research findings that explained the idea of wearable sensor platforms including skin patches, smart textiles, wristbands, and epidermal electronics, which promise to be applied effectively and sensibly on the human body. Moreover, the articles that focused directly on biomedical applications (chronic disease management, fitness and wellness monitoring, post-operative monitoring, and remote diagnostics) were chosen as priorities. Such standards determined inclusive and specific evaluation of literature, which matched objectives of real-time health monitoring with wearable biosensors.

Exclusion Criteria

In order to meet the relevance and scientific discipline of this review, certain exclusion criteria were implemented to discount the study that did not suit the primary review objectives. The articles that would have concentrated on non-wearable sensors, which could include implantable systems, ingestible systems and bench top systems were not included except when the article had direct connection to integration of wearable systems. Further, models that are purely hypothetical, (such as those that remain only in simulation, or as an algorithm suggestion, or as a model proposal, but none experimentally actualized) were excluded out of the lack of any verification of practicality. The case studies without experimental verification that is studies beyond laboratory, prototype development, and in vivo /in vitro experiments were also excluded because it was important that the review be representative of real applicability. Besides, those papers that focused on irrelevant areas of application such as industrial monitoring, veterinary uses and environmental/structural sensing, were weeded out to maintain the biomedical and healthcare focus. Through such consistent use of these exclusion parameters or inclusion criteria, the review provides quality, domain-specific evidence-based synthesis of literature that will reflect the most influential trend with regard to wearable biosensors to monitor real-time health.

Table 2: Inclusion and Exclusion Criteria for Literature Selection

Category	Criteria Description
Inclusion	• Peer-reviewed journal and conference articles (2016–2025) • English-language publications • Focus on real-time or continuous biosensing • Research on wearable systems (e.g., patches, textiles, wristbands) • Biomedical applications (e.g., disease management, fitness, remote monitoring)
Exclusion	• Non-wearable sensors (e.g., implantable, benchtop systems) • Theoretical-only studies without experimental validation • Lack of prototype or lab testing • Irrelevant domains (e.g., industrial, veterinary, environmental sensing)

Data Extraction and Synthesis

After identifying relevant studies, a synthesis and data extraction procedure was systematically done in order to make an analysis of the entire literature to be able to provide a comparative study of literature. As part of the extraction process, relevant technical and application specific parameters that would help draw meaningful conclusions concerning the evolution and the contemporary picture as regards wearable biosensors that can be used to monitor health in real-time were sought.

The main data points that were obtained in every study were as follows:

- Kinds of sensors and biomarkers of interest, e.g. electrochemical sensors on glucose and lactate, optical sensors on oxygen saturation and heart rate, and pressure sensors on breaths or heartbeat.
- The materials, techniques of fabrication and information about nanomaterials (e.g., graphene, MXenes), flexible substrates (e.g., PDMS, PET), and ways of integration, such as inkjet printing, 3D printing, and microfabrication processes.
- Areas of use and deployment: This is a wide array of application areas including the management of chronic diseases, monitoring athletic performance, remote monitoring of patients, and tracking the recovery process after operations.
- Ways of acquiring and processing signals, as well as communication codes, such as noise reduction strategies, machine-learning-based signal analysis, and wireless communication technologies, such as Bluetooth Low Energy (BLE), NFC, and Wi-Fi.

In a bid to draw meaningful interpretation of the extracted data, the studies were constructed within thematic clustering along major technological and functional dimensions. Those clusters were sensor technology, energy and power management, material science, data analytics, and clinical or real-world deployment. It was with the help of this thematic synthesis that interdisciplinary trends could be identified, performance tradeoffs, innovations in design, and repeated challenges in various areas of research.

By means of this systematic process, the review does not merely reflect and compare significant developments, but also traces the progress of the field and highlights gaps in the research, as well as shapes further works in design and implementation of wearable biosensors.

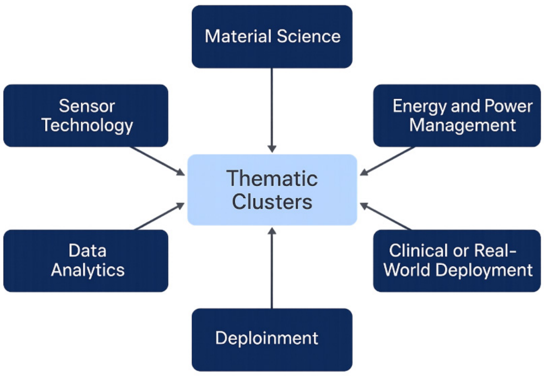

Fig. 2: Thematic clustering of extracted data categories in wearable biosensor literature synthesis.

Energy Sources and Power Management

Effective and Eco-Friendly Power management: A wearable biosensor system, its usability, reliability, and long-term operational life are directly related to power management. Originally, wearable technology has been dominated by battery-powered systems, the most widely used (Lithium-ion, and zinc-air batteries) are favoured because of their high energy density, compact size, and availability as commercial products. These traditional energy sources, however, generate restrictions considering the need to replenish power regularly, limited working life, and additional weight of the device, which may negatively affect the comfort level of the user and the ability to continually work. To cope with these drawbacks energy harvesting technology was becoming more developed as a method of converting some of the surrounding energy into electricity to make devices more independent. The most famous are the piezoelectric gas generators that can obtain mechanical energy during body movement; thermoelectric gas generators capable of transforming body heat into usable current and third there are triboelectric gas generators that can take advantage of friction-based energy between skin or fabric. The self-sustaining systems cause a decrease in the need to charge one externally and increase the amount of time that devices spend operational thus they are suitable especially in applications that involve long term physiological recording. To supplement these, wireless charging technologies, and especially those using Near-Field Communication (NFC), allow transferring power without any contacts being made, thereby enhancing the usability of devices in such a way that it does not break the wear. Also, ultra-low-power integrated circuits (ICs) have become critical towards reducing power usage of signal acquisition, processing, and wireless transmission to keep the wearable biosensors working in the limited power environment. Collectively, they amount to a multisided power management that increases the wear ability, durability, and usability of biosensor platforms to move them toward the point of entirely self-contained and friendly healthcare products (Figure 3).

Application Domains

Wearable biosensors have shown life changing potential in a broad range of healthcare and wellness applications through real time continuous monitoring of physiological parameters. Chronic disease management is one of the most influential spheres since these devices help to track various biomarkers that are of essential importance to such conditions as diabetes, by monitoring levels of glucose via sweat; cardiovascular diseases, by monitoring the heart rate and electrocardiogram (ECG); and epilepsy

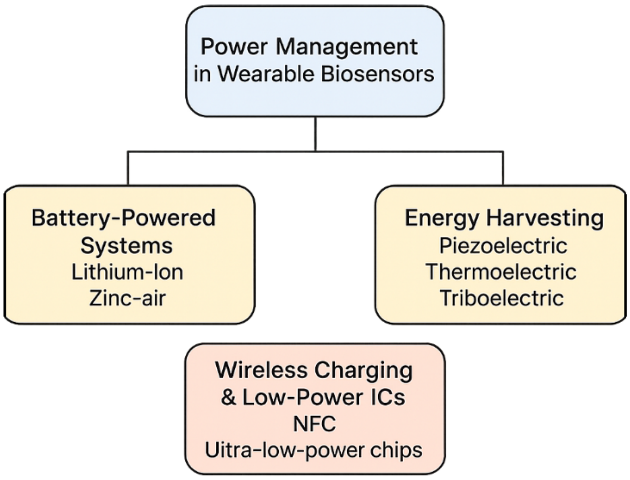

Fig. 3: Power management strategies in wearable biosensors, including battery systems, energy harvesting techniques, and wireless charging with low-power IC integration.

as well, by detecting the neurological patterns that might indicate a premature seizure. Wearable biosensors aid in early diagnosis, treat a patient individually, and minimize the reliance on hospital visits by providing appropriate data in real-time. These sensors provide accurate real-time information on fitness and sport activities such as physical activity measurements, hydration rates, and muscle fatigue and in general fitness rates. This form of feedback that benefits athletes and other fitness enthusiasts is applicable in the real-time condition that enables them to optimize training programs and avoid injury as well as to determine recovery status. In addition to fitness and chronic health, wearable biosensors are crucial to remote patient monitoring and telehealth, particularly in situations in which incessant surveillance is required. One application is to track post-surgical recovery, in real-time monitor elderly patients in home care, and pandemic surveillance, or temperature, oxygen saturation and respiratory rate monitoring in case of an infectious outbreak such as the current COVID-19 situation. Besides alleviating the load on clinical facilities, these applications enable the patient to manage his or her health actively. As a whole, wearable biosensors embody a combination of biomedical engineering, digital health, and personalized care that have various potential applications to a variety of healthcare issues in scalable dimensions (Figure 4).

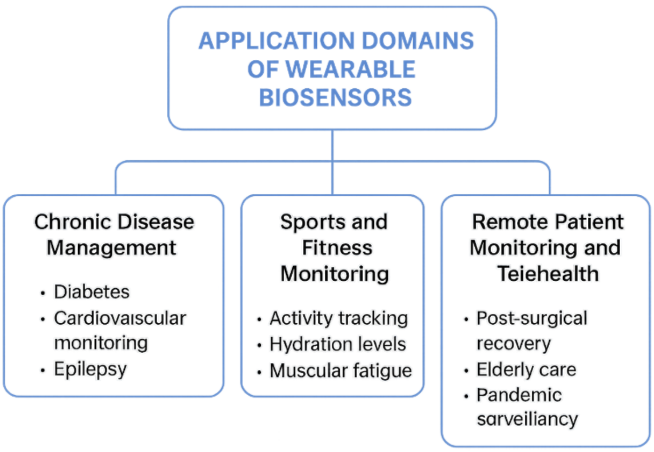

Fig. 4: Application domains of wearable biosensors across chronic disease management, sports monitoring, and remote patient care.

Results and Discussion

Newer developments in wearable biosensors technology have improved its functionality, form factor and flexibility to a large extent and this has made it more applicable in terms of use in real time health feedback in various applications. Regarding sensor activity, electrochemical biosensors have been identified to be the major alternative sensor to detect biomarkers such as glucose and lactate, as adequate sensitivity can be achieved and it is convenient to be integrated with flexible materials. Such sensors usually make use of high tech nanomaterials like graphene and carbon nanotubes (CNTs) to enhance electrochemical transduction and signal fidelity. Optical sensors, more specifically on the basis of Photoplethysmography (PPG system) or Photospectrography, perform very well to measure physiological parameters like heart rate and blood oxygen saturation (SpO 2), and many commercial fitness devices include it. Pulse and respiration tracking is possible in real-time using pressure and strain sensors constructed of materials, such as PDMS and gold nanowires, which allows effective monitoring of respiratory health. Thermal sensors manufactures using flexible thermistors have been developed to continuously measure the skin and core temperatures assisting in early onset of infection or fever. The advancements do

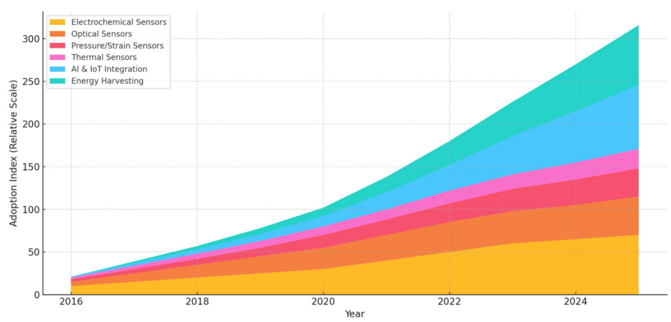

Fig. 5: Adoption trends of wearable biosensor technologies (2016-2025) across sensor types and intelligent features.

not only increase the range of physiological parameters that can be measured, but also ensure increased user comfort and sensor lifespan due to the miniaturization and flexible integration.

It has even changed the power of wearable biosensors with the introduction of artificial intelligence (AI) and Internet of Things (IoT) technologies integration. The use of machine learning algorithms in embedded systems is becoming an increasingly trendy development in biosensing where they can be used to offer intelligent interpretation of data, anomaly detection, and health trends forecasting. It allows personalized healthcare to conform to user behaviours and profiles. Also, it is possible to deploy edge computing infrastructure, which may process information on the device and minimize the need to use cloud infrastructure to achieve responses in real-time, e.g., due to low latency. This is particularly important in such scenarios as resource-constrained scenario, e.g., hospitals or senior care or epilepsy monitoring, where anomaly detection speed may mean the difference between life and death. With the perspective of power management, over 70 per cent of new-record wearable biosensors have already integrated energy harvesting systems, such as triboelectric Nano generators (TENGs) and thermoelectric generators (TEGs). Such technologies produce electricity by utilising biomechanical movement, body heat, or natural light and thus reduce the dependency use on normal batteries and allow them an increased power source, which is important characteristic of long term monitoring applications (Table 2).

All of the pilot implementations of wearable biosensing, whether in diabetes management, post-operative recovery, or monitoring of athletic performance, show high accuracy and compliance with the device. As an example, the electrolyte sensors in sweat have been tested out with more than 90 % correlation to conventional blood diagnostics, proving it as a potentially viable alternative to invasive methods. All these successes notwithstanding, there are still a number of challenges. Biocompatibility: Long-term wear of biosensors, both skin irritation and machine deterioration, as well as signal drift are of concern. Furthermore, data security and privacy is still a major concern and requires secure protocols of transferring information, end-to-end encryption, and possibly blockchain-based data management system to make healthcare information trustworthy and held intact. Legal compliance is another huge stumbling block, because reaching such approval as FDA or CE requires a massive clinical testing and multi-step confirmation, which in turn can slow down deployment. In the future, the next and new technologies should include multimodal sensing systems, self-healing and biodegradable materials, cloud and edge hybrid analytics framework, which will increase scalability, sustainability, as well as the intelligence of wearable bio sensing solutions, leading to the frontier of personalized healthcare and connected healthcare.

Conclusion

The application of wearable biosensors has evolved to one of the most sought-after innovations in contemporary healthcare, where it can continuously and non-invasively monitor and analyze physiological and biochemical parameters that provide much importance to personalized and preventive medicine as well as track and manage the individuals in real-time. Armed with filed advancements in flexible electronics, nanomaterials, energy harvesting, and artificial intelligence, these systems have considerably expanded the area of remote health diagnostics and patient management.

Table 3: Trends in Wearable Biosensor Technology Adoption (2016-2025) across Sensor Types and Intelligent Features

Year	Electrochemical Sensors	Optical Sensors	Pressure/Strain Sensors	Thermal Sensors	AI & IoT Integration	Energy Harvesting
2016	10	5	3	2	1	0
2017	15	10	5	4	3	2
2018	20	15	7	6	5	4
2019	25	20	10	8	8	7
2020	30	25	15	10	12	10
2021	40	30	18	12	20	18
2022	50	35	22	15	30	28
2023	60	38	26	17	45	40
2024	65	40	30	20	60	55
2025	70	45	33	23	75	70

Their incorporation into systems like chronic condition management, fitness management and telehealth have exhibited significant promise towards enhancing patient activities and clinical outcomes. To achieve the full potential of their transformative abilities, however, many challenges that persist to be encountered need to be solved- especially with regard to long-lasting biocompatibility, data security, equipment calibration, and standardization of regulations. The next steps will involve the multidisciplinary approach to communication across the borders of the discipline of materials science, biomedical engineering, data science, and regulatory policy. It has been projected that the intersection of the technologies of the next generation of sensors and the edge computing, secure wireless communication, and adaptive AI algorithms would form autonomous wearable systems, intelligent and scalable. Not only will these developments propel their integration into mainstream healthcare and general wellness to greater growth speeds but will set a new course of how health is being monitored, managed and individualized in the next decade.

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