Advances in Sustainable Wearable Biosensors for Human Health Monitoring and Environmental Applications: A Comprehensive Review

Soosai Michael Sandy Subala[1], Sumathi K Sripathi[2]

[1]Department of Chemistry, St. Eugene University
[2]Department of Biology, St. Eugene University

Abstract

Biosensors have transformed the monitoring of human health and environmental conditions by allowing for real-time, non-invasive identification of markers and contaminants. This review consolidates perspectives from significant studies regarding wearable biosensors, their sustainable design, and their extensive effects on healthcare and public health. We examine advancements in materials science, the incorporation of AI, and techniques for single-molecule detection while discussing different types, manufacturing processes, applications in managing chronic diseases, fitness monitoring, environmental surveillance, and challenges such as durability and data privacy. Future developments highlight the importance of eco-friendly materials, hybrid systems, and personalized medicine to support the UN Sustainable Development Goals.

Keywords: Wearable biosensors, sustainable biosensing, human health monitoring, environmental detection, AI integration, single-molecule bioelectronics

1. Introduction

The advent of biosensors dates back to the 1960s with the development of the first glucose oxidase-based enzyme electrode by Clark and Lyons [1]. Since then, biosensors have evolved into sophisticated devices that detect biological analytes through bioreceptors such as enzymes, antibodies, nucleic acids coupled with transducers, electrochemical, optical, and mass-based to produce measurable signals. Their widespread impact on human health is profound, enabling early disease diagnosis, continuous monitoring, and personalized interventions, as highlighted in comprehensive overviews of biosensor technologies.

Wearable biosensors, integrated into devices like smartwatches, patches, or clothing, represent a paradigm shift in healthcare by facilitating real-time tracking of physiological parameters such as heart rate, glucose levels, and hydration [2]. A bibliometric analysis from 2007 to 2022 reveals exponential growth in research, with over 238 publications emphasizing sports science, physiology, and

cardiovascular applications. Concurrently, sustainable biosensing addresses environmental concerns exacerbated by climate change, such as pathogen spread and pollution monitoring, using eco-friendly materials to minimize waste [3,4].

Climate change intensifies public health threats, including vector-borne diseases like malaria and zoonotic outbreaks like COVID-19. Biosensors offer sustainable solutions for early detection, reducing mortality rates—for instance, improving pancreatic cancer survival through biomarker identification. [5, 6, 7].

2. Types of Biosensors and Key Technologies

Biosensors are classified by bioreceptor and transducer types. Electrochemical biosensors dominate due to their compatibility with electronics, low cost, and rapid readouts, ideal for point-of-care (POC) diagnostics like glucose meters. They function via enzyme-substrate reactions (e.g., glucose oxidase producing H_2O_2) or antigen-antibody interactions. Optical biosensors, such as those using surface plasmon resonance (SPR), excel in label-free detection for viruses or bacteria in turbid samples Mass-based sensors like quartz crystal microbalance (QCM) provide sensitivity for environmental pathogen detection [7, 8, 9].

Nanobiosensors enhance sensitivity using nanomaterials like graphene or carbon nanotubes, achieving attomolar limits [10]. Single-molecule bioelectronics, employing scanning tunneling microscopy break-junction (STM-BJ), detect RNA cancer biomarkers (e.g., KRAS G12C) at 0.1 aM without amplification, offering high specificity for single-base mismatches [11]. Wearable variants incorporate microfluidics for sweat or saliva analysis, flexible electronics for comfort, and wireless communication (Bluetooth, NFC) for data transfer [12].

Biosensor	Principle	Advantages	Limitations	Applications
Electrochemical	Redox reactions	Low cost, Portable	Fouling in complex media	Glucose monitoring, Cancer biomarkers
Optical	Light interaction	Laber free, suitable turbid samples,	Miniaturization challenges	Virus detection, Food safety
Mass based	Piezoelectric effect	High sensitivity	Coating uniformity	Environmental pathogens
Single Molecule	Conductance histograms	Attomolar LoD, no amplification	Integration complexity	RNA/DNA variants, COVID-19

Energy harvesting from body heat or motion extends battery life, crucial for long-term wearables.

3. Materials and Design for Sustainability

Sustainable design is imperative to mitigate biosensor waste, which contributes to environmental degradation amid climate crises [3,6,17]. Life-cycle analysis (LCA) evaluates impacts from production to disposal, promoting circular economy principles [3]. Eco-friendly materials include biodegradable polymers such as PDMS, polyethylene, cellulose, paper, bioplastics, and green nanomaterials like graphene [2,3,11,19]. Hydrogels ensure biocompatibility for skin contact, while conductive inks facilitate flexible printing [2,19].

Design focuses on miniaturization, flexibility, and integration with smart devices [2,13,18]. Challenges include energy efficiency, data security, and durability against motion artifacts [2,20]. Referenced works emphasize nanomaterials for enhanced specificity, such as noble metal nanoparticles for biosensing [21]. For wearables, textiles embed sensors for seamless monitoring [2,22].

4. Applications in Healthcare

Wearable biosensors transform healthcare through real-time monitoring. For chronic diseases, continuous glucose monitors (CGMs) manage diabetes by tracking interstitial fluid levels [2,23,30,32]. Cardiovascular applications include photoplethysmography (PPG) for heart rate and ECG for arrhythmias [2,24,35,36]. Non-invasive sensing analyzes sweat for electrolytes, glucose, or hormones, aiding hydration and stress tracking [2,25,41].

In diagnostics, biosensors detect cancer biomarkers early, improving survival rates [1,3]. AI integration analyzes data for predictive insights, such as cardiac event forecasting [2]. Remote patient monitoring (RPM) reduces hospital visits, especially for elderly or remote populations [2,28]. Bibliometric trends show growing focus on sports and fitness, where sensors track performance, recovery, and injury prevention via heart rate variability and biomechanics [4,27,33].

Wellness applications monitor sleep stages, cortisol levels, and lifestyle metrics for personalized feedback [2,41]. In military and industrial settings, they detect fatigue, hazards, or toxins [2].

5. Applications in Environmental and Public Health Monitoring

Biosensors address climate-induced health risks by detecting pathogens in water, soil, or air [3,13]. Single-molecule platforms identify E. coli toxins or SARS-CoV-2 variants rapidly [3]. Sustainable designs use paper-based sensors for recyclable POC testing in resource-limited areas [3].

Referenced studies highlight impacts on vector-borne diseases, with biosensors enabling early outbreak detection [3,10,11]. Integration with IoT and AI facilitates global surveillance, aligning with SDGs for health and environment [3,29].

6. AI and Machine Learning Integration

Artificial intelligence (AI) significantly enhances biosensor data analysis by enabling advanced pattern recognition, anomaly detection, and personalized predictions. Machine learning algorithms efficiently process large volumes of data generated by wearables and other biosensors, allowing them to forecast events such as glucose fluctuations in diabetes management or potential cardiac risks through continuous monitoring of vital signs.

Deep learning techniques further improve accuracy, particularly in portable and real-time devices, by handling complex, high-dimensional biological signals with greater precision and speed. However, key challenges remain, including data privacy concerns related to sensitive health information, as well as interoperability issues that hinder seamless integration of data across different devices, platforms, and electronic health records. Addressing these will be essential for broader adoption and realizing the full potential of AI-powered biosensing in personalized healthcare [2,23].

7. Challenges and Limitations

Achieving consistent accuracy in complex biological media is a major challenge, as interference from proteins, cells, and other biomolecules frequently distorts biosensor signals. Sensor fouling, resulting from biofouling and surface accumulation, causes progressive signal drift, diminished sensitivity, and reduced device lifespan. The ongoing need for frequent calibration to counteract drift and environmental variations makes long-term and continuous monitoring particularly difficult in practice. User compliance represents a significant barrier, especially for wearable and implantable devices, where factors such as comfort, ergonomics, and ease of use directly affect consistent adherence. Finally, varying regulatory frameworks across regions hinder commercialization, while the reliance on single-use plastic components generates substantial environmental waste, and continuous wireless data transmission raises serious privacy concerns due to risks of breaches and unauthorized access.

Conclusion

Biosensors, particularly wearable and sustainable variants, are pivotal in advancing human health and environmental monitoring. By leveraging insights from the reviewed articles, this synthesis underscores their transformative potential in early detection, personalized care, and climate resilience. Addressing challenges through innovation will ensure equitable access and sustainability.

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