Electrochemical Biosensors for Allergen Detection in Atmosphere: An SDG-3 Driven Approach for Asthma Monitoring and Allergy Pattern Tracing

Ananya Julka
[1]Shishukunj International School Indore, Madhya Pradesh. India
Mail Id: ananyajulka2008@gmail.com

***Abstract*- Airborne allergens such as pollen proteins and dust-mite particles are major triggers of asthma and allergic reactions, yet conventional detection techniques are typically laboratory-based, time-consuming, and unsuitable for continuous monitoring. This review discusses recent developments in electrochemical biosensing technologies and their potential for real-time environmental allergen detection. It further proposes a compact wearable sensing platform designed to monitor allergen exposure directly in a user's surroundings.**

The suggested device utilizes functionalized electrodes coupled with allergen-specific biorecognition probes that produce measurable electrochemical variations when target particles bind to the sensing interface. The resulting electrical signal is conditioned, digitized, and transmitted wirelessly to a smartphone for visualization and exposure tracking. Emphasis is placed on high sensitivity, selectivity, rapid response, and multiplex capability for detecting multiple allergens simultaneously while maintaining portability and user comfort.

By integrating advanced materials, miniaturized electronics, and wireless communication, wearable electrochemical biosensors provide a practical approach for personalized environmental health monitoring. Continuous exposure information may help individuals and clinicians recognize allergen patterns, anticipate symptom aggravation, and implement preventive strategies, thereby improving management of asthma and related allergic disorders.

Keywords: Electrochemical biosensor; Airborne allergens; Asthma monitoring; Wearable sensing; Real-time detection; Personalized healthcare; SDG 3: Good Health and Well-Being.

I. INTRODUCTION

Recent advances in sensing technologies have transformed healthcare by enabling continuous monitoring of physiological and environmental conditions. Biosensors, which integrate a biological recognition element with a signal-transduction system, are capable of converting biochemical interactions into measurable electrical or optical signals [1]. Owing to their high sensitivity, fast response, and adaptability, biosensors are increasingly applied in clinical diagnostics, environmental monitoring, and public health applications [2]. The development of wearable biosensors has further expanded their relevance by allowing non-invasive and real-time monitoring, supporting the shift toward preventive and personalized healthcare.

Airborne allergens constitute a significant environmental risk factor. Particles such as pollen, fungal spores, and dust-mite proteins can trigger immune reactions in susceptible individuals through immunoglobulin-E-mediated mechanisms, resulting in inflammation and respiratory complications [3]. One of the most common

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consequences of repeated exposure is asthma, a chronic respiratory condition characterized by wheezing, coughing, and shortness of breath. The increasing prevalence of allergic diseases worldwide emphasizes the importance of monitoring environmental allergen exposure [4]. Early detection of allergen presence may allow patients to adopt protective measures, initiate timely treatment, and prevent severe attacks.

Conventional allergen detection methods, including enzyme-linked immunosorbent assay (ELISA), provide reliable quantification but are typically confined to laboratory settings and require specialized personnel and lengthy processing times [5]. Similarly, advanced analytical approaches such as chromatography and mass spectrometry offer high specificity but rely on complex instrumentation and extensive sample preparation, limiting their suitability for field-based monitoring [6]. Consequently, there is a strong need for portable systems capable of providing immediate information regarding airborne allergen concentrations.

Electrochemical biosensors have emerged as promising alternatives for this purpose. These devices detect target analytes by converting biochemical reactions at an electrode surface into measurable electrical parameters such as current, voltage, or impedance [7], [8]. Their advantages include low cost, simple instrumentation, and easy miniaturization, making them compatible with portable electronics and point-of-care applications [9], [10]. In particular, label-free impedimetric sensing techniques allow rapid biomolecule detection without complicated sample preparation [11].

Recent improvements in biorecognition elements, including antibody-based immunosensors and aptamer-based detection systems, have enhanced selectivity, stability, and reproducibility in allergen sensing [12], [13]. Integration of such sensing approaches with wearable electronics and wireless communication technologies offers continuous environmental exposure tracking and personalized disease management. These platforms have the potential to identify allergen patterns, assist clinical decision-making, and improve preventive care strategies for individuals suffering from asthma and related allergic conditions.

Therefore, this work reviews electrochemical biosensing strategies for atmospheric allergen detection and discusses a wearable sensing platform designed for real-time monitoring. The objective is to highlight the role of portable electrochemical biosensors in bridging environmental exposure assessment and personalized healthcare management.

Asthma is a long-term inflammatory disorder of the airways that commonly presents with episodes of breathlessness, coughing, and wheezing. Because these symptoms overlap with those of several other respiratory conditions, accurate differentiation can be difficult in clinical practice. Diagnosis generally requires a history of recurrent respiratory complaints together with objective evidence of variable expiratory airflow limitation confirmed through spirometry testing. In this context, localized surface plasmon resonance (LSPR) biosensors can be particularly valuable, as they enable detection of otherwise unrecognized allergen exposure and may assist in identifying triggers in affected individuals.

II. Objectives and Scope of the Review

The objective of this review is to examine current developments in biosensing technologies for detecting airborne allergens and to evaluate their relevance in monitoring asthma and allergic conditions. It aims to analyze different sensing principles, biorecognition elements, and transduction

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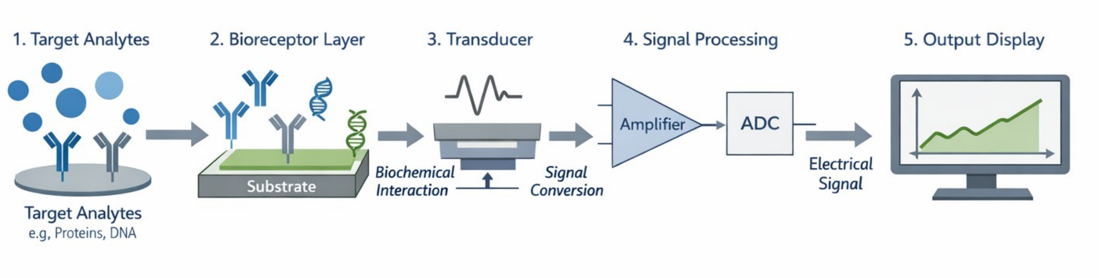
mechanisms, with particular attention to electrochemical approaches suitable for portable and wearable applications. The review also outlines the conceptual framework of a compact sensing platform designed for continuous environmental monitoring and real-time data acquisition. By discussing performance requirements such as sensitivity, selectivity, response time, and user adaptability, the study seeks to highlight how advanced biosensors can support exposure assessment and personalized health management. Overall, the scope includes both existing detection strategies and future prospects, emphasizing the potential role of wearable biosensing systems in improving preventive care and environmental health awareness.

III. Overview of Biosensors

Fundamental Operating Principle

A biosensor is an analytical device that detects a specific chemical or biological species by integrating a biological recognition mechanism with a physical signal conversion process. In these systems, a selective bioreceptor—such as an antibody, enzyme, nucleic acid sequence, or synthetic ligand, is immobilized on a sensing interface and interacts with the target analyte. This interaction produces measurable physicochemical changes at the surface, including variations in mass loading, electrical properties, or refractive index, which are converted into a quantifiable signal by a transducer [1]. Optical sensing platforms commonly utilize surface plasmon resonance, where molecular adsorption modifies the local refractive index at a metallic interface and shifts the resonance condition of propagating plasmons [1]. Figure 1 illustrates the general working principle of a biosensor. The target analyte interacts with an immobilized biorecognition element on the sensing surface, producing a physicochemical change. The transducer converts this change into an electrical signal, which is then processed and displayed as measurable output.



General Architecture of a Biosensor

Types of Biosensors

Wearable and portable biosensors are generally classified according to the method of signal transduction. Electrochemical biosensors determine analyte concentration through redox reactions occurring at an electrode surface, generating measurable electrical parameters such as current, voltage, or impedance [7]. Devices such as glucose monitoring systems represent practical

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implementations of this approach.

Optical biosensors rely on light–matter interaction to detect biomolecules by measuring changes in absorption, fluorescence, scattering, or refractive index. Piezoelectric biosensors operate on the piezoelectric effect, where mechanical disturbances such as mass loading or pressure alter the vibration characteristics of a crystal, producing an electrical response. Together, these sensing approaches support non-invasive and real-time monitoring for medical and wellness applications [2].

Key Components and Functional Roles

A biosensor typically consists of three major units: a biorecognition element, a transducer, and a signal processing system. The recognition element selectively binds the target analyte, while the transducer converts this binding event into a measurable signal. The electronic processing stage amplifies and interprets the signal so that the output correlates with analyte concentration [1].

In respiratory healthcare applications, biosensors can detect biomarkers such as nitric oxide in exhaled breath, which reflects airway inflammation, and can also identify environmental allergens responsible for asthma exacerbations [3].

Localized Surface Plasmon Resonance (LSPR) Biosensors

Surface plasmon resonance sensors operate through collective oscillations of free electrons at a metal–dielectric interface. When incident light satisfies the resonance condition, energy coupling occurs and a characteristic reduction in reflected intensity is observed. Binding of biomolecules at the surface alters the refractive index and shifts the resonance parameter, enabling detection of target substances. Although optical SPR methods can detect allergen-specific immunoglobulin E, their sensitivity to very small airborne allergen particles is limited, and relatively slow detection response restricts their suitability for continuous atmospheric monitoring [5].

Electrochemical Biosensors

Electrochemical biosensors translate biochemical interactions into electrical signals produced at an electrode interface. A biological recognition element immobilized on the electrode reacts with the target substance, resulting in measurable changes in current, potential, or impedance through redox or enzymatic processes [7], [8].

These sensors provide rapid response, high sensitivity, and relatively low fabrication cost, making them appropriate for point-of-care diagnostics and environmental sensing [9]. Their compatibility with miniaturized electronics also enables integration into portable and wearable monitoring devices [10].

Among them, impedimetric biosensors measure variations in electrical impedance caused by biomolecular binding and allow label-free detection in complex environmental samples such as airborne particulate matter [11]. Figure 2 shows the electrochemical sensing mechanism at the

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electrode interface. Binding of biomolecules at the functionalized electrode causes electron transfer or impedance variation, which is measured using a potentiostat and converted into a quantifiable electrical response.

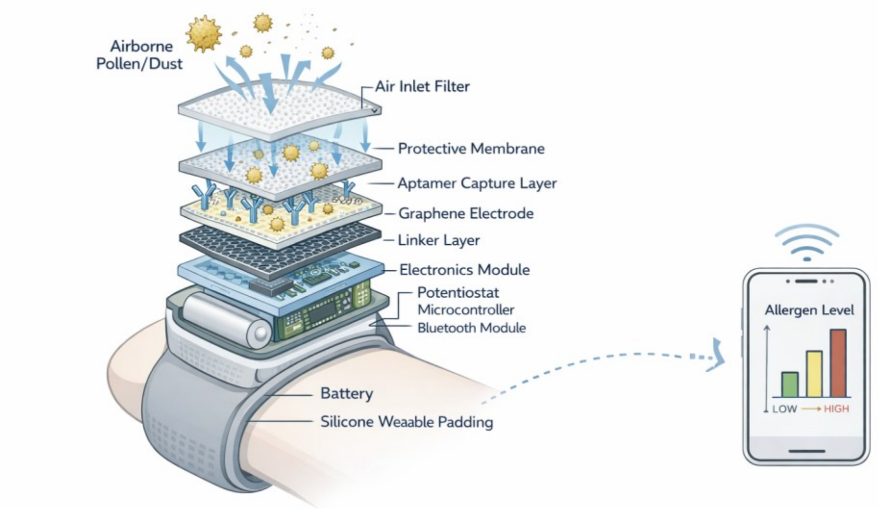

Figure 2. Electrochemical Biosensor Electrode Mechanism

IV. ALLERGEN DETECTION APPROACHES

Immunosensors

Immunosensors utilize highly specific antigen–antibody interactions to detect allergenic proteins. The binding event can be measured using electrochemical or optical readout techniques. Conventional immunological assays, including ELISA, provide accurate allergen quantification but require controlled laboratory conditions and are sensitive to environmental degradation, limiting their use for real-time atmospheric monitoring [12].

Aptamer-Based Sensors (Aptasensors)

Aptasensors employ short nucleic acid sequences that fold into three-dimensional structures capable of selectively binding target molecules. Compared with antibodies, aptamers exhibit higher chemical stability, reproducibility, and easier synthesis. When combined with nanomaterials, they enable enhanced signal amplification and sensitive detection of allergens, supporting portable and wearable monitoring systems [13].

Enzyme-Based Biosensors

Enzyme-based biosensors detect analytes through catalytic biochemical reactions that generate measurable electrochemical or optical changes, such as variations in pH or oxygen concentration. Integration with microfluidic platforms enables simultaneous detection of multiple allergens and supports continuous environmental monitoring outside laboratory settings. Figure 3 presents the conceptual design of the wearable allergen monitoring device. Airborne particles enter through the

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inlet filter and interact with aptamer-based capture probes on the sensing layer. The generated electrical signal is processed by embedded electronics and transmitted wirelessly to a smartphone for real-time exposure monitoring.

Figure 3. Wearable Allergen Detection Device.

Other Analytical Techniques

Advanced analytical approaches such as chromatography and mass spectrometry provide highly accurate allergen identification and quantification. However, these techniques require complex instrumentation, extensive sample preparation, and trained operators, which restricts their suitability for rapid on-site monitoring applications [6].

V. Proposed Design and Methodology

Design Objectives

An atmospheric allergen biosensor must provide high sensitivity, selectivity, and fast response to capture rapid environmental fluctuations. The proposed system uses functionalized electrodes coated with allergen-specific probes. Binding of airborne particles produces an electrochemical signal that is processed by embedded electronics and transmitted wirelessly to a smartphone using Bluetooth Low Energy communication. The sensing layer can be regenerated through mild rinsing, allowing continuous operation for several months and supporting long-term exposure tracking.

The compact device (30 mm × 30 mm × 15 mm) can be worn on a wristband or clipped onto clothing, enabling unobtrusive and continuous monitoring suitable for personalized healthcare.

Structural Components

Air Inlet and Prefilter

A molded polymer mesh regulates airflow, followed by a thin PTFE or foam filter that removes large particles and protects internal sensing layers.

Linker Layer

A self-assembled pyrene-butyric-acid interface anchors aptamer probes onto a graphene electrode

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while blocking nonspecific adsorption and allowing regeneration.

Capture Probe Layer

Multiple aptamer probes immobilized in separate sensing zones enable simultaneous detection of different allergens through electrical changes at the electrode.

Protective Membrane

A polyurethane coating shields the sensing region while permitting allergen diffusion and maintaining stable humidity.

Signal Processing Electronics

A low-power potentiostat, amplifier, analog-to-digital converter, and microcontroller process the signal and transmit allergen concentration data via Bluetooth.

Wearable Interface

A breathable, biocompatible silicone layer provides comfort during prolonged use.

VI. Functioning Mechanism

The proposed wearable sensing platform operates on an electrochemical detection principle in which biochemical interactions occurring at the sensing interface are translated into measurable electrical responses. Airborne allergenic particles, including pollen-derived proteins and dust-mite antigens, reach the sensing region and interact with a functionalized electrode coated with selective biorecognition elements such as antibodies or aptamers. Specific binding between the allergen and its complementary probe alters interfacial electrochemical characteristics, typically producing variations in current, potential, or electrical impedance at the electrode surface.

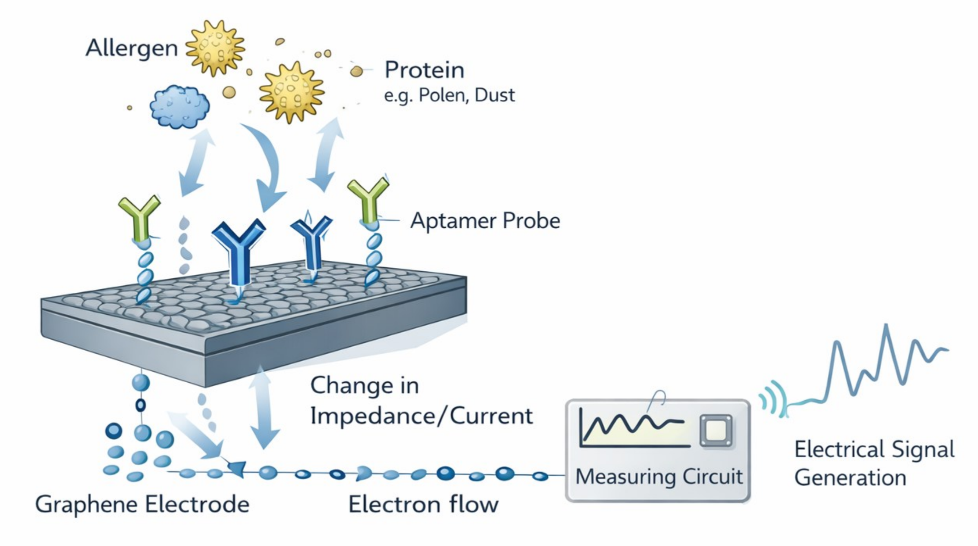

Figure 4. Allergen Binding Detection Mechanism

Figure 4 demonstrates the sensing mechanism at the molecular level. Airborne allergen proteins bind selectively to aptamer probes attached to the electrode surface. This binding modifies the interfacial electrical properties, causing changes in charge transfer resistance and electron flow. The resulting electrical variation forms the basis of allergen detection and quantification.

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These changes are captured by the electrochemical sensing layer and converted into an electrical signal proportional to the concentration of the target allergen. The generated signal is conditioned and amplified through a low-power potentiostat and analog front-end circuitry and subsequently digitized for processing by a microcontroller unit (MCU). The MCU performs real-time signal interpretation, converts the response into quantitative allergen exposure information, and transmits the processed data wirelessly through a Bluetooth Low Energy (BLE) interface to an external device such as a smartphone or computer.

Figure 5 illustrates the data acquisition and transmission pathway of the device. The sensing electrode generates an electrical signal that is conditioned by a potentiostat and amplifier, converted into digital form using an analog-to-digital converter, and processed by a microcontroller. The processed data are transmitted through a Bluetooth Low Energy module to a smartphone application for real-time monitoring.

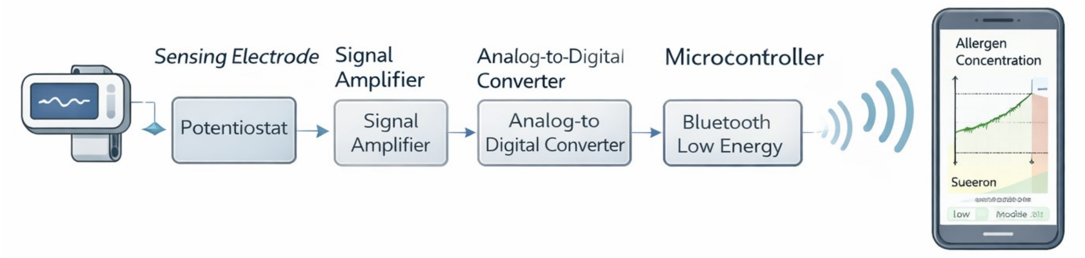

Figure 5. Signal Processing and Wireless Transmission

All sensing and electronic components are enclosed within a biocompatible silicone encapsulation that protects the electronics from environmental disturbances while ensuring safe and comfortable contact with the wearer.

VII. Results and Discussion

The performance of the proposed biosensor is evaluated in terms of analytical parameters including sensitivity, selectivity, detection limit, operational stability, and usability under environmental conditions. Initial observations indicate consistent signal generation for multiple allergen types, with detection levels falling within clinically meaningful ranges (Lee et al., 2024; Ma et al., 2023). Additional investigations are required to assess response time, interference from other airborne particulates, and long-term stability in varying humidity and temperature conditions (Li et al., 2023). The incorporation of multiple aptamer-based recognition sites enables simultaneous detection of different allergens, supporting multiplex monitoring capability.

Previous electrochemical sensing systems have demonstrated effectiveness in monitoring various biological markers, although comparable approaches have rarely been applied to atmospheric allergen surveillance (Curulli, 2022).

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VIII. Perspective and Future Trends

Current developments in personalized medicine emphasize continuous monitoring technologies for chronic disease management. Wearable biosensing devices are expected to play a critical role in managing respiratory disorders such as asthma and allergies through ongoing environmental exposure tracking.

Future research will likely focus on device miniaturization, reduced power consumption, and seamless integration into daily wearable accessories. Advances in nanomaterials are expected to improve electron transfer efficiency and enhance sensitivity. In particular, carbon quantum dots can increase electrical conductivity, shorten response time, and enable multiplex detection due to their tunable optical and electronic properties (Xiong et al., 2024). Their chemically active surface also facilitates stable attachment of biomolecules including antibodies and aptamers.

Figure 6. Personalized Healthcare Application

Figure 6 illustrates the integration of the wearable biosensor within a personalized healthcare framework. Continuous monitoring enables real-time exposure tracking, while wireless communication allows mobile devices or cloud platforms to alert users and healthcare providers. Such monitoring may support preventive management of asthma and allergic reactions.

IX. Conclusion

This review highlights the potential of electrochemical biosensing technologies for monitoring airborne allergens and supporting improved management of asthma and related allergic conditions. Conventional allergen detection methods are typically laboratory-based and unable to provide continuous environmental exposure information. In contrast, wearable biosensor platforms offer a practical approach for real-time and location-specific monitoring, enabling individuals to better understand personal exposure patterns and take preventive measures.

The proposed system integrates selective biorecognition elements with miniaturized

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electrochemical transduction and wireless communication, allowing rapid detection of allergenic particles in the surrounding environment. The compact and wearable design supports continuous operation while maintaining user comfort, making it suitable for everyday use. Multiplex sensing capability further enhances its applicability by enabling detection of multiple allergens simultaneously.

Overall, electrochemical wearable biosensors represent a promising tool for personalized healthcare and environmental health monitoring. By providing timely exposure information and supporting early intervention, such systems may reduce the severity of allergic reactions and improve quality of life for affected individuals. Continued development in materials, device integration, and data processing is expected to further enhance performance and facilitate practical deployment in real-world healthcare settings.

Author Contributions

X and Y contributed to the conceptualization and methodology of the study. Software development was performed by X and Y. Validation and investigation were carried out by X, Y, and Z. Formal analysis was conducted by Y and Z. The original draft of the manuscript was prepared by X and Y. Reviewing and editing were undertaken by Y and Z. Supervision was provided by Z. All authors have read and approved the final version of the manuscript.

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Data Availability Statement *(Optional)*

(Sample-The data associated with this study are available from the corresponding author(s) upon reasonable request.)

Declaration of Competing Interest *(Optional)*

The authors declare no competing financial interests or personal relationships that could have influenced the work reported in this manuscript.

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