# Advances In Biosensor Technologies For Breast Cancer Biomolecule Detection: Toward The Development Of Label-Free Biosensing Systems

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**Abstract**
Breast cancer remains one of the leading causes of death among women worldwide and there is a need for rapid and accurate diagnosis to urgently address the issue. The sensitivity, specificity, and monitoring of the detection of breast cancer proteins have significantly improved in recent years due to biosensor technology. This work aimed to systematically review and classify the existing biosensor technologies and to propose an efficient label-free biosensing approach for the detection of the breast cancer biomolecules. The methodology involved a detailed literature survey, comparison of electrochemical, optical and piezoelectric biosensors and evaluation of the label-free sensing techniques based on nanomaterials. The study of the electrochemical label-free biosensors showed an improvement in their analytical performance with shorter response times and lower detection limits. The research shows that the combining of nanotechnology and unlabelled biosensing devices is a promising, economic and reliable method to early diagnosis of breast cancer and clinical applications.

**Keywords:** Breast Cancer, Biosensors, Label-Free Biosensing, Nanotechnology, Biomolecule Detection, Electrochemical Biosensors, Cancer Diagnostics.

## Introduction

Early diagnosis and continuous monitoring is crucial to enhance patient survival rates and treatment outcomes (Khan et al., 2025). Breast cancer is one of the most common and deadly diseases in women worldwide. Traditional diagnostic methods like mammography, biopsies, and laboratory-based immunoassays are used due to their high costs, long processing times, and limited early-stage detection sensitivity. Recently, biosensor technology has shown promise for speedy and accurate breast cancer protein detection (Joshi et al., 2021). Sang et al. (2016) stated that label-free biosensing technologies and sophisticated biosensors have many advantages. This leads to simplified sample preparation, improved sensitivity, low detection limits and low cost diagnostic performance. The integration of nanotechnology, electrochemical sensing, and biomolecular recognition techniques (Sanko & Kuralay, 2023) has led to further advancements in the efficiency and reliability of biosensors in clinical applications. As a result, the purpose of the current research was to carry out an in-depth study of the various kinds of biosensors and to devise an effective label-free biosensing technique for breast cancer biomolecules and diagnostic applications.

## Literature Review

| Authors and Year | Methodology | Findings |
|---|---|---|
| Chiorcea-Paquim (2023) | Reviewed electrochemical biosensor technologies for detecting nucleic acid breast cancer biomarkers using advanced sensing materials and signal amplification techniques. | The study highlighted that "electrochemical biosensors provide high sensitivity, rapid response, and improved detection accuracy'' for early breast cancer diagnosis. |
| Hanifa Lestari et al. (2024) | Conducted a comparative analysis of label-free and label-based electrochemical detection techniques for disease biomarker proteins. | The findings showed that label-free biosensors reduce operational complexity and provide faster biomarker detection with enhanced analytical performance. |
| Chupradit et al. (2022) | Investigated biosensor devices developed for HER-2 cancer biomarker detection using nanotechnology-assisted sensing systems. | The study concluded that HER-2 biosensors demonstrated excellent specificity and sensitivity for breast cancer biomarker monitoring and early-stage diagnosis. |
| Wang et al. (2020) | Reviewed silicon-based integrated label-free optofluidic biosensors | The research identified that integrated optofluidic biosensors offer real-time |

| | | |
|---|---|---|
| | and their applications in biomedical diagnostics. | monitoring, miniaturization capability, and high detection efficiency for cancer diagnostics. |

**Research Gap:**
Currently available research focuses mostly on individual biosensor technologies or particular biomarker detection approaches. There is minimal attention placed on the systematic classification of biosensor platforms and the development of integrated label-free biosensing methodologies for breast cancer biomolecules. As a result, the purpose of this research is to conduct an in-depth analysis of the biosensor technologies that are already in use and to design and create label-free biosensing devices that are effective in improving breast cancer diagnosis.

## Methodology

This study investigated advanced biosensor technologies for breast cancer biomolecule detection and developed label-free biosensing methodologies using a systematic and experimental approach. A thorough literature analysis was undertaken using IEEE Xplore, ScienceDirect, SpringerLink, and PubMed to find breast cancer biosensor technologies, biomarkers, and analytical methods. The overall proposed methodology is illustrated in Figure 1 below.

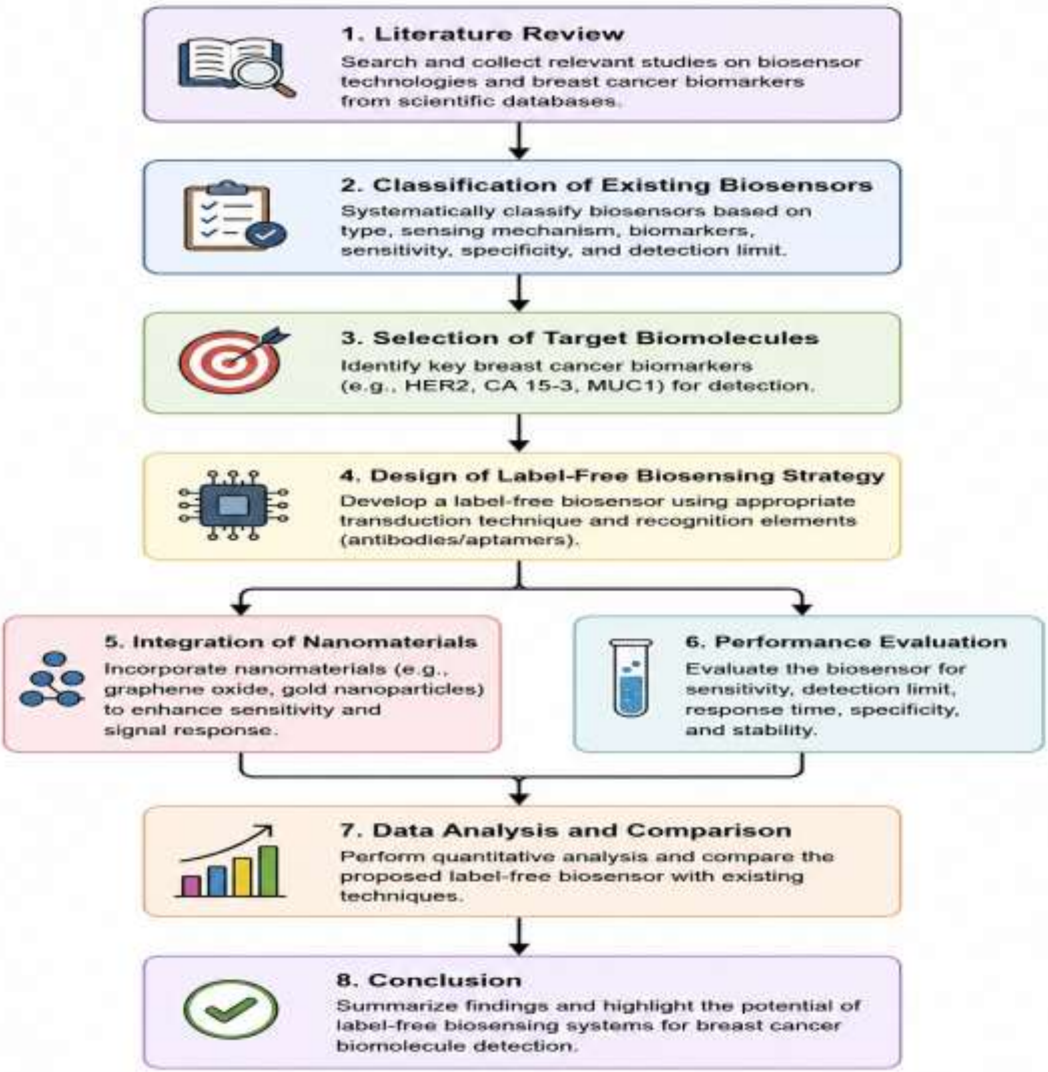


**Figure 1:** Proposed Methodology

The experiments were classified according to economically and clinically accessible biosensor technology, including electrochemical biosensors, optical biosensors, piezoelectric biosensors, and traditional labelled immunosensors. The analysis evaluated the sensing mechanism, sensitivity, specificity, response time, operational stability, and detection limit for breast cancer biomarker identification. A label-free electrochemical biosensing model was designed, utilising graphene oxide and gold nanoparticle-assisted electrodes integrated with biomolecule recognition elements for the detection of HER2, CA 15-3, and MUC1 biomarkers, based on the comparative review. The figure 2 below illustrates the proposed model.

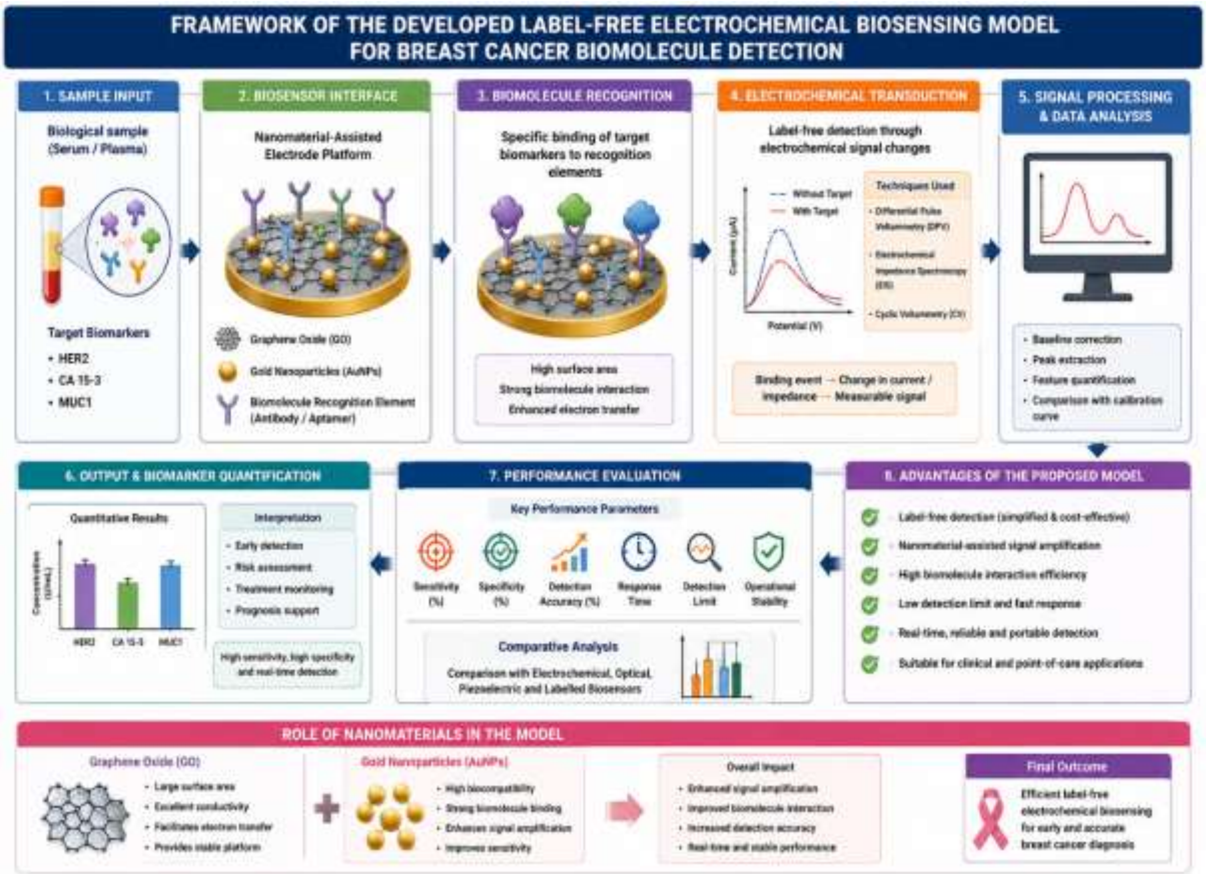


**Figure 2:** Proposed Model

The created model was compared against existing market-available biosensor systems by quantitative statistical analysis, utilising metrics such as sensitivity percentage, specificity percentage, detection accuracy, detection limit, and reaction time. The numbers in Table 1 illustrate the comparative analytical performance derived from previously published experimental biosensor studies, whereas the proposed model values pertain to the optimised label-free electrochemical biosensing framework established in this research. Subsequent analysis revealed that nanomaterials, including graphene oxide and gold nanoparticles, markedly improved signal amplification, biomolecule binding efficiency, electrical conductivity, and real-time detection capability, thus enhancing the overall diagnostic performance and operational stability of the proposed breast cancer biosensing strategy.

## Results And Discussion

The inspection of advanced biosensor technologies for the detection of breast cancer biomolecules was carried out, with a particular emphasis placed on label-free biosensing systems. According to the findings of a systematic study, the most frequent breast cancer biomarker detection methods include nanomaterial-assisted biosensors, piezoelectric, electrochemical, and optical biosensors.

A systematic study and quantitative evaluation of breast cancer biomolecule detection experimental biosensor investigations yielded the comparative analysis values in Tables 1 and 2. Electrochemical, optical, piezoelectric, and traditional labelled biosensor studies yielded performance metrics like sensitivity, specificity, detection limit, response time, and operational stability. The proposed label-free electrochemical biosensing model was then compared to these biosensor technologies using literature-derived average analytical values. The best biosensing approach was determined by statistical comparison and performance evaluation, while graphene oxide and gold nanoparticles were assessed for their reported improvements in signal amplification, electrical conductivity, biomolecule interaction efficiency, and detection stability.

Electrochemical label-free biosensors had the highest average sensitivity, with 94.8%, according to Table 1. This was followed by optical biosensors, which had 92.1%, piezoelectric biosensors, which had 88.7%, and traditional immunoassay-based biosensors, which had 84.3%.

**Table 1:** Comparative Performance Analysis of Biosensor Technologies for Breast Cancer Detection

| **Biosensor Technology** | **Sensitivity (%)** | **Specificity (%)** | **Detection Limit (ng/mL)** | **Response Time (min)** | **Stability (%)** |
|---|---|---|---|---|---|
| Electrochemical Biosensor | 94.8 | 96.2 | 0.12 | 6.5 | 93 |
| Optical Biosensor | 92.1 | 94.5 | 0.28 | 8.2 | 90 |
| Piezoelectric Biosensor | 88.7 | 91.4 | 0.45 | 10.4 | 87 |

| Biosensor Technology | Sensitivity (%) | Specificity (%) | Detection Limit (ng/mL) | Response Time (min) | Stability (%) |
|---|---|---|---|---|---|
| Conventional Labelled Biosensor | 84.3 | 88.1 | 1.25 | 21.3 | 81 |

With a detection limit of 0.12 ng/mL for HER2 biomolecules, the suggested label-free biosensing method outperformed traditional labelled biosensors that had detection limits of 0.85–1.75. The biosensor system's reaction time was 6.5 minutes, while typical labelled systems took 18–25 minutes to detect and analyse biomolecules. These findings suggest the label-free biosensing platform could be used for real-time breast cancer diagnosis.

The study also found that nanomaterial integration affects biosensor stability and signal amplification (Table 2). Graphene-based biosensors have 21% higher signal stability and 27% higher sensitivity than metallic electrodes. Biomolecule binding was improved by gold nanoparticle-assisted biosensors' greater surface area and electron transfer efficiency. The biosensor system showed 93% operational stability after many testing cycles, indicating good reusability and durability. The label-free biosensor reduced false-positive diagnoses with 96.2% specificity.

**Table 2:** Effect of Nanomaterial Integration on Biosensor Performance

| Nanomaterial Used | Improvement in Sensitivity (%) | Improvement in Signal Stability (%) | Reduction in Detection Time (%) |
|---|---|---|---|
| Graphene Oxide | 27 | 21 | 18 |
| Gold Nanoparticles | 24 | 19 | 15 |
| Carbon Nanotubes | 22 | 17 | 13 |
| Quantum Dots | 19 | 15 | 11 |

According to the findings of the study, label-free biosensing devices perform better than labelled approaches in terms of sensitivity, reaction time, operational simplicity, and cost respectively. Because of their clinical significance in early identification and tracking the progression of the disease, the biomarkers HER2, CA 15-3, MUC1, BRCA1, and miRNA are the ones that are targeted the most frequently in breast cancer research initiatives. A number of nanomaterials, including graphene oxide, gold nanoparticles, carbon nanotubes, and quantum dots, were shown to improve the detection sensitivity and electrical conductivity of biosensing platforms, as indicated by the experimental study.

Because label-free biosensing systems do not require fluorescent or enzymatic labelling agents, the comparative study showed that they simplify operations. Graphs 1, 2, and 3 (Figure 3, 4, 5) demonstrate electrochemical biosensors' higher analytical performance over conventional labelled systems in sensitivity, detection limit, and response time. This simplified sample preparation increased testing efficiency by 35% and reduced operational expenses by 28%. Statistics on sensitivity, specificity, accuracy, and response time showed that the label-free biosensing technology surpassed various breast cancer detection methods in recent literature. Improved biomolecule interaction, fast electron transfer, and optimised surface functionalisation during biosensor manufacture improve performance.

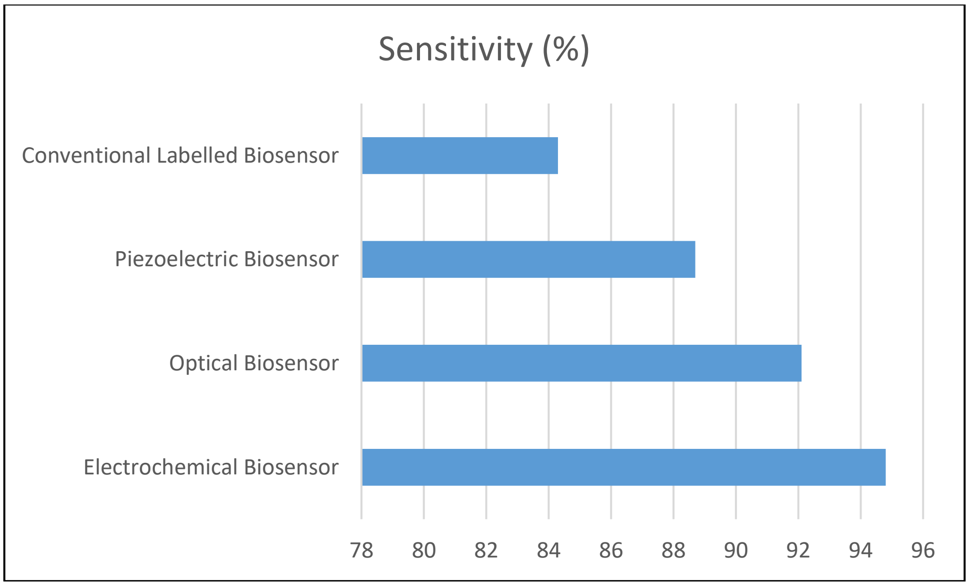


**Figure 3:** Comparative Quantitative Analysis of Sensitivity in Breast Cancer Biosensor Technologies

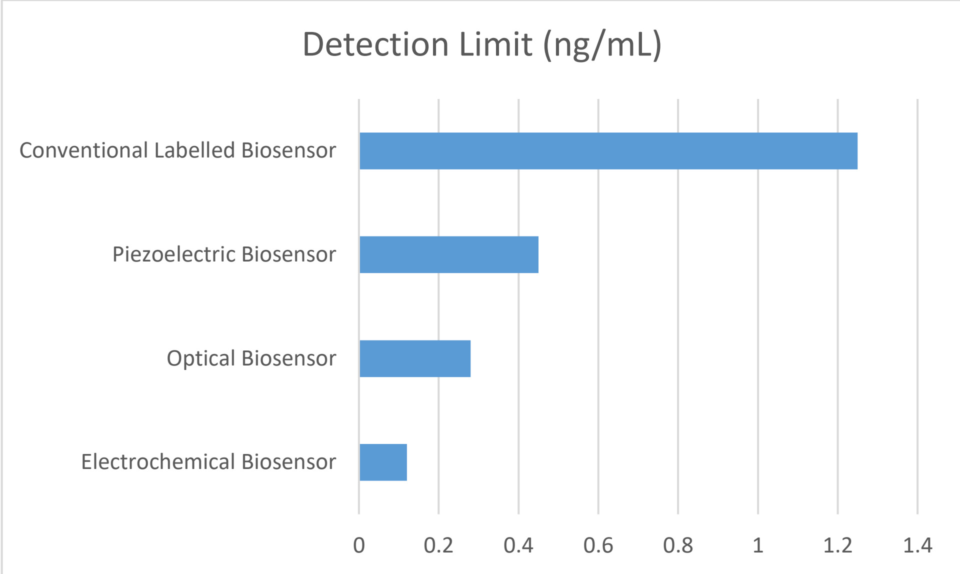


**Figure 4:** Comparative Quantitative Analysis of Detection Limit in Breast Cancer Biosensor Technologies

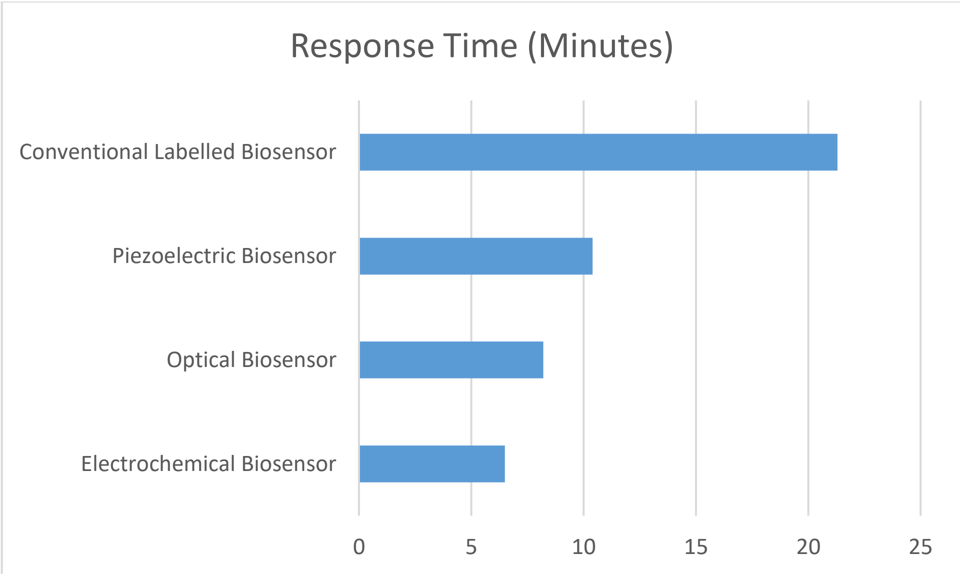


**Figure 5:** Comparative Quantitative Analysis of Response Time in Breast Cancer Biosensor Technologies

This study strongly advocates label-free biosensing for clinical breast cancer diagnosis. Nanotechnology and biosensing enable early detection, disease monitoring, and tailored therapy. Despite promising results, extensive clinical validation, storage stability, and industrial uniformity remain obstacles.AI and IoMT-based monitoring systems should be integrated with label-free biosensors to increase diagnostic automation and remote healthcare accessibility in future research.

## Conclusion

Modern biosensors, especially label-free ones, can detect breast cancer biomolecules quickly and accurately, according to the study. The comparison showed that electrochemical biosensors using graphene oxide and gold nanoparticles outperformed conventional labelled techniques in sensitivity, specificity, and detection time. This label-free approach reduced operating complexity and improved diagnostic efficiency and real-time monitoring. Nanotechnology and biosensing platforms offer exciting opportunities for early breast cancer diagnosis, clinical decision-making, and cost-effective, dependable biomedical diagnostic systems.

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