

How to Design Genetic Biosensors for Medical Purposes?

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Abstract

Genetic biosensors lead to a revolutionary integration of genetic engineering and biosensing techniques, suggesting high precision in molecular diagnostics and personalized medicine. These tools use nucleic acids and proteins to enabling early disease diagnosis, and real-time scanning of biological procedures like cancer. Their high sensitivity, specificity, and adaptability make them promising for clinical applications in spite of challenges in optimization and scalability. This review explores the design principles, technological advancements, and biomedical applications of genetic biosensors, focusing on their potential to improve healthcare through personalized medicine and more progress therapeutic interventions.

Keywords: DNA sensors- Personalized Medicine- cancer- riboswitch- genetic biosensors

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1- Introduction

In the field of molecular diagnosis and medical investigation, the merging of genetic engineering with biosensing techniques has led to the emergence of transformative tools known as genetic biosensors [1]. These complex molecular devices show great ability in disorder detection, drug development, and personalized medicine. Genetic biosensors represent a new category of analytical tools that employ the specificity and sensitivity of genetic factors to detect specific biomarkers or analytes with unique accuracy [2]. Via a detailed assessment of biosensing methods, genetic biosensors have emerged as promising tools for new biomedical applications [3].

The genetic biosensors involve a various array of plans that use genetic components such as nucleic acids, proteins, and genetically modified cells for distinguishing a vast spectrum of targets, from simple to complex molecules [4]. Using the basics of molecular detection and signal transduction, these biosensors show significant potential in simultaneous assessment of biological processes, early problem identification, and evaluation of cure response [5]. As genetic biosensors interface with the molecular procedures, they facilitate accurate medical methods by suggesting quick and precise diagnosis, prognosis, and cure interventions related to personalized medicine [6].

This review article represents a comprehensive

overview of the newest advances in genetic biosensors for medical applications, with a focus on modern developments, significant systems of technology, and emerging trends in this field. Through evaluating the profile standards, engineering plan, and uses of genetic biosensors, we aim to annotate their significant impacts on various angles of medical study and healthcare. Additionally, we will point out the challenges and opportunities associated with the complete capacity of genetic biosensors, with a special focus on their integration into clinical function.

Due to their natural capacity for a high level of sensitivity, specificity, and several abilities, genetic biosensors can work as powerful tools for improving our knowledge of complex biological processes, suggesting disorder symptoms, and speeding the progress of precision medication. The following part will provide the divergent applications of genetic biosensors in disease diagnosis, drug evaluation, ecological tracking, and more, focusing on their key role in promoting the future of medical fields and medical supply.

2- Genetic Biosensors

Genetic biosensors are modern molecular devices that recruit genetic elements to identify target substances

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with exceptional precision and sensitivity. Combining the specific binding qualities of nucleic acids, proteins, and genetically modified cells, these biosensors present a flexible form for real-time evaluation of biological processes and disorder biomarkers [7]. For instance, RNA-related biosensors relying on aptamers particular to target particles, such as the theophylline-binding RNA aptamer Theoph-1, facilitate selectively recognizing and quantifying small factors in complex biological materials [8]. Additionally, genetic biosensors using reporter genes, like the green fluorescent protein (GFP) gene, enhance visual tracking of cellular responses to induction, providing the origin for dynamic scanning and high-throughput assessment usage in medical study [9].

The involvement of genetic biosensors in medical fields shows great potential for upgrading personalized medicine, disorder diagnostics, and medical care. Genetic biosensors produced with gene editing approaches, such as CRISPR-linked devices intended for targeting particular genetic mutations (e.g., the BRAF V600E mutation related to melanoma), create a powerful method for accurate diagnostics and special treatment [10-12]. Furthermore, the advances of cell-based biosensors using genetically modified cell lines, generating manufactured facilities, facilitate drug expansion and pharmacological evaluation [13, 14]. As the topic of genetic biosensors is growing, their introduction into clinical applications and applied studies is aimed at improving the molecular diagnosis and personalized medicine. Genetic biosensors presented high sensitivity in detecting biomarkers at small concentrations, making them useful tools for medical goals. By genetic replication methods, such biosensors can recognize even the smallest amounts of markers, with a cut-off of detection as low as picomolar or femtomolar amounts [15]. This sensitivity causes early detection and tracking of disease, vital for a precision cure. However, problems may appear regarding background noise and interference, affecting the precision of the results.

Taking into account specificity, genetic biosensors differentiate between targeted biomarkers and non-specific signals accurately, assuring proof and precise diagnosis. By specific DNA or RNA probes, genetic biosensors can selectively bind to the targeted biomarkers, decreasing false positives and increasing tracking accuracy. Despite this specificity, problems emerge in cross-reactivity with closely linked molecules, needing precise design and proof of biosensor agents [16, 17].

Considering speed, genetic biosensors reduce response times, with detection often between minutes to hours, according to the test strategy. This quick response time is helpful for point-of-care applications, causing early diagnosis and on-time therapeutic action [18]. Though genetic biosensors act faster than common settings in most cases, their overall efficacy can be impacted by the need for additional processing stages for special, complex tests. Additionally, there are differentiations in the potential of genetic biosensors; many are designed to be quickly applied in limited-source environments or in the field, whereas the rest may require distinct equipment and information, causing them to be inaccessible in a lot

of situations [19].

3- The role of Genetic biosensors in medicine

Genetic biosensors are a novelty in medical studies, offering flexible devices for accurate and sensitive recognition of targets in complex biological procedures. These biosensors, using genetic agents such as aptamers, engineered proteins, and reporter genes, upregulate personalized medicine and disorder diagnosis [5]. For instance, aptamers such as the theophylline-binding RNA aptamer Theoph-1 recognize specific small molecules selectively with proper sensitivity [20]. Additionally, genetic biosensors using reporter genes like green fluorescent protein (GFP) visually monitor cellular reactions to external forces, enabling dynamic imaging and high-throughput screening in various medical studies [5].

Genetic biosensors in medical applications revolutionize disorder diagnosis, drug design, and personalized medication. As this field improves, genetic biosensors will play a fundamental role in promoting translational research and generating the next generation of molecular diagnostics and effective medicine [21].

Genetic biosensors offer unique, quick identification abilities, revolutionizing the frequency and reliability of diagnosis and monitoring in medicine. Biosensors diagnose disorders fast through quickly recognizing biomarkers or genetic mutations, causing therapeutic intervention and monitoring of therapeutic consequences. This real-time potential is particularly essential in emergency clinics and infection management, in which rapid function significantly affects sufferer responses [22].

The potential of genetic biosensors to differentiate between nearly linked biomolecules and decrease false positives enhances diagnostic reliability, essential for immediate disease diagnosis and tracking [7]. This personalized system allows for tailored therapeutics according to individual genetic profiles and an individual's unique genetic makeup, ultimately optimizing therapeutic responses and reducing side effects [23].

Genetic biosensors have various functions in biomedical studies, confirming their role and impact across different domains. In disorder diagnosis, genetic biosensors have been active in finding specific genetic mutations linked with diseases like cancer, cystic fibrosis, and genetic disorders such as sickle cell anemia. By targeting these genetic biomarkers, biosensors offer early and accurate diagnosis, helping in personalized cure methods [23, 24]. Nevertheless, challenges may arise in recognizing mutations with low rates or high genetic variation, influencing their sensitivity and specificity.

In drug screening, genetic biosensors play a main role in evaluating drug effectiveness and toxicity by monitoring cellular responses to medication compounds. Such biosensors can identify changes in gene expression, protein function, or metabolic pathways, providing valuable insights into medicine's mechanisms and side effects [7, 25]. Moreover, genetic biosensors track cellular metabolism, assessing fundamental metabolites such as glucose, lactate, and ATP amounts. By monitoring metabolic modifications in real-time, biosensors enable

a deeper comprehension of cellular procedures and metabolic disorders [26-28]. In environmental tracking, genetic biosensors are used for identifying pollutants, pathogens, and toxins in water resources, air quality, and soil. These biosensors supply quick and sensitive recognition, presenting rapid environmental danger identification and mitigation approaches. However, challenges emerge in ensuring biosensor stability and specificity in complex environmental cases [29].

Genetic biosensors have revolutionized therapeutic investigation and healthcare with their enhanced sensor sensitivity, novel model systems, and advanced imaging methods. Multiple important applications of genetic biosensors in medical studies are involved (Figure 1):

1. Early diagnosis and point mutation recognition: Using biosensors to recognize specific genetic biomarkers for diseases like cancer, Alzheimer's, and infectious diseases. For instance, NOX-A12, an RNA aptamer, attaches to CXCL12 as a chemokine in cancer progression and metastasis. Clinical assessment of NOX-A12 presents its ability to disrupt the CXCL12-CXCR4 interaction, enhancing immune responses against hematologic malignancies and solid tumors [30].

2. Medical tracking: Evaluating drug effectiveness and toxicity by monitoring cellular interactions using genetic biosensors. As a result of the Warburg effect, several tumors show significantly lower NAD⁺/NADH ratios than normal cells. The SoNar sensor was produced via insertion of a cpYFP construct between subunits of NAD (H) binding protein Rex arising from *Thermus aquaticus* (T-Rex). NAD⁺ saturation of SoNar increased fluorescence excited at 485 nm, whereas NADH binding progresses fluorescence excited at 420 nm. SoNar may particularly bind to NAD⁺ or NADH ($K_d \approx 5.0 \mu\text{M}$ and $\approx 0.2 \mu\text{M}$, respectively, at pH 7.4). It is a pH-stable, systematic ratiometric detector for NAD⁺, NADH, and their proportion. SoNar presents an 8-fold dynamic difference in living cells. Zhao et al. introduced SoNar as a proper candidate for HTS of the NAD⁺/NADH ratio in live tumors with drug tracking potentials [31].

3. Intracellular conception: Visualizing gene expression and cellular procedures in real-time with biosensors designed for imaging. Lately, several

genetically expressed fluorescent probes have been developed to present NO and its products in single cells. But only a couple of researchers used such helpful probes. It may require a while, as most of the researchers apply NO selective GES, which can permit studying on presently finished subjects. Novel FP-linked probes with enhanced sensitivity, selectivity, spectral effects, and relevance will motivate researchers in different areas to guide instructive single-cell NO imaging assessments in a short time. Such other GES, including unique Ca²⁺ markers and NO probes, may be applied in studies on NO signals in animal investigations. Along with the preferences of geNOPS, NOA-1, MT-FRET, pnGFP, and sNOOOp, the scientific frame has been established nowadays, we must follow a way in a structured and concentrated behavior [32].

4. Environmental tracking: identifying pollutants, toxins, and microbial contaminants in air, water, and soil by biosensors. The devices of resistance and detoxification for toxic metals were identified in the compounds of special complete-cell biosensors. The regulatory settings included regulatory proteins that might bind metals and promoter areas that cause detoxification or signal transduction interactions. For example, arsR and the promoter sequence from *Geobacter sulfurreducens* could be combined with a fluorescence reporter to enable arsenic tracking with a ppb recognition limitation. Fundamentally, the toxicants entered into the cells and subsequently activated detoxification and metabolism operons. Nevertheless, it has been approved that the two-component adjustment might be integrated into bacterial biosensors for sensing extracellular pollution. The regulatory membrane protein can attach chemicals and phosphorylate the other regulatory proteins that induce the signal transduction [33].

5. Signal Transduction Assessments: Studying signal transduction pathways and protein interactions by biosensors for detailed signal transduction network analysis. Based on the Findeiß et al. study, the plasma membrane can involve extremely highly divided areas for kinases. For example, receptor-associated kinases such as JAK could be organized by inducing STAT as a fundamental spatiotemporal factor that cannot yet be examined visibly. Findeiß et al. overcome this obstacle by presenting a sensitive genetically expressed biosensor based on fluorescence resonance energy transfer (FRET). They monitored the local promotion of STATs and enhanced their amount and kinetic alterations in different situations in biological systems. The visualization of the STAT dynamics aids in interpreting and associating practical signal transduction with single-cell RNA sequencing methods to show alteration within stem, progenitor, and immune cells [34].

Through such applications, genetic biosensors have significantly progressed our knowledge of biological tools, enabled immediate disorder diagnosis, and led to the development of targeted treatments, finally contributing to improved healthcare outcomes and accurate medicine methods.

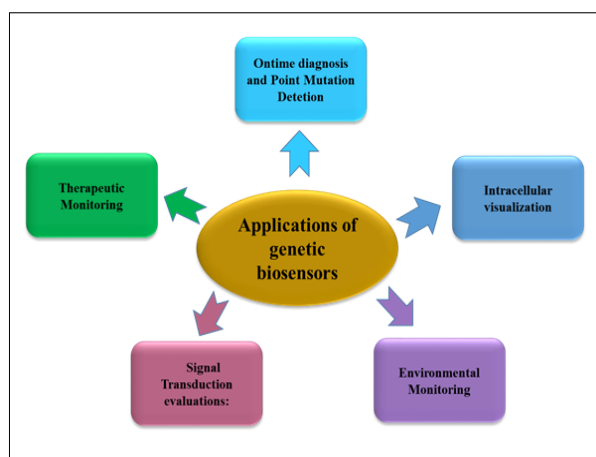


Figure 1. The Biomedical Applications of Genetic Biosensors.

4- Design and Development

In the design of genetic biosensors for biomedical uses, careful selection of genetic elements like transcription factors and riboswitches is essential. Transcription factors are important regulators of gene expression, suggesting precise control over sensor output in reaction to specific biological signals [19, 35]. Their selection is according to their ability to bind to target DNA sequences and adjust gene transcription efficiently. On the other hand, riboswitches are RNA molecules that can change their structure upon attaching specific ligands, enabling direct detection and response to cellular metabolites or small molecules. When choosing riboswitches for biosensors, considerations involve their ligand-binding specificity, structural stability, and responsiveness to targets [36, 37].

Riboswitches may also be engineered by the CRISPR approach to diagnose metabolites or ions critical for developmental checkpoints. For example, small molecule-inducible riboswitches have been manipulated to enable reversible, dose-dependent management of gene expression *in vitro* and *in vivo*, showing their potential use for biological investigation [38]. In a study, Bruckhoff et al. engineered splice-controlling riboswitches to manage exon skipping, enabling chemically inducible isoform switching *in vitro* and suggesting a new method for gene regulation via alternative splicing [39]. Potential and Optimization of Mammalian Splice Riboswitches for the Regulation of Exon Skipping-Dependent Gene Expression and Isoform Switching within the ALOX5 Gene [39]. These genetic parts are fundamental for constructing biosensors that can accurately recognize and report biological signals, making them valuable means in advancing biomedical study and diagnostics.

4-1- Fundamentals of Engineering:

The design of genetic revolutions encompasses the organization of genetic components such as promoters, transcription factors, and reporter genes in a way that facilitates precise control over gene expression levels in response to specific biological signals. These revolutions usually employ feedback processes and signal amplification methods to increase sensor sensitivity and dynamic spectrum [40]. Sensor structure in genetic biosensors is accurately engineered to identify and assess specific biomolecules within biological systems. Essential components involve sensor factors such as riboswitches or aptamers that interact with target molecules, causing conformational modifications that are transduced into measurable results. Coupling these sensor factors with signal transduction pathways and output modules such as fluorescent proteins or enzymes allows for the conversion of molecular recognition events into quantifiable signal transduction, enabling the precise identification and screening of biomolecule levels in real-time [41, 42].

Generally, the construction fundamental of genetic biosensors for biomedical applications intricately weaves together genetic uses and sensor structures to create robust and sensitive identification platforms. By leveraging the interactions between genetic components and sensor factors, these biosensors enable the precise

assessment of specific biomolecules in complicated biological environments, paving the way for improvement in disorder detection, therapeutic screening, and basic evaluation. The modular nature of genetic biosensors allows customization and optimization to target different biomolecules of interest, making them versatile means for addressing a wide range of biomedical challenges and driving novelty in precision medicine [43, 44].

4-2- Performance Metrics and Evaluation Criteria

When assessing and optimizing genetic biosensors for biomedical applications, both *in vitro* and *in vivo* examination are key components. *In vitro* testing includes assessing the efficacy and specificity of genetic biosensors in controlled laboratory settings. Assessment of metrics like sensitivity, dynamic range, response time, and signal-to-noise ratio is usually used to measure biosensor performance [45, 46]. Experimental designs frequently involve calibration curves, dose-response research, and specificity assays to validate the biosensors' ability to accurately recognize and measure target biomolecules in complicated biological samples. In contrast, *in vivo* evaluation emphasizes visualizing and tracking the manner of genetic biosensors within living cells. Different imaging methods like optical imaging, magnetic resonance imaging (MRI), and computed tomography (CT) can be employed to monitor the spatial distribution and temporal dynamics of biosensor function in real-time. Optimizing biosensors for *in vivo* applications includes considerations of biocompatibility, tissue penetration, signal stability, and longevity to ensure reliable discharge and minimal interference with physiological procedures [47, 48].

Successful optimization of genetic biosensors for biomedical applications needs a comprehensive understanding of their performance characteristics and manner in both controlled laboratory environments and living systems. Using a combination of *in vitro* and *in vivo* testing strategies allows investigators to completely evaluate biosensor functionality, specificity, and reliability across various experimental contexts. By carefully considering key parameters like sensitivity, specificity, spatial resolution, and signal persistence, scientists can fine-tune genetic biosensors to meet the specific requirements of biomedical applications, facilitating their successful translation into practical means for disorder diagnosis, therapeutic screening, and biological investigation [46].

4-3- The significance of genetic biosensors

Genetic biosensors are valuable means in biomedical study, especially in the field of natural product biosynthesis. These biosensors are designed to detect specific biological molecules or processes within living cells, allowing researchers to monitor and regulate the production of bioactive compounds such as antibiotics, anticancer agents, and immunosuppressants. For example, scientists have successfully used genetic biosensors to track the synthesis of artemisinin, a potent antimalarial compound that originates from the sweet wormwood plant. By

integrating biosensor systems into microbial hosts, scientists can optimize metabolic pathways and increase the outcome of natural products, finally contributing to the development of more efficient drugs for different disorders [49, 50].

In the realm of biomedicine, genetic biosensors play a key role in disorder management and diagnosis. These biosensors can be engineered to diagnose specific biomarkers linked with certain problems, enabling immediate detection and accurate tracking of disorder progression. For example, genetic biosensors detect tumor markers in blood samples, providing a non-invasive strategy for diagnosing different kinds of cancer at an early stage [51, 52]. Furthermore, genetic biosensors can be instrumental in the development of new therapeutic strategies, like personalized medicine methods that target specific molecular pathways in patients. By harnessing the power of genetic biosensors, researchers and clinicians can revolutionize the way diseases are diagnosed, treated, and controlled in the medical field [53, 54].

In the realm of genetic biosensors for biomedical applications, the future holds promise in increasing sensor sensitivity, pioneering imaging techniques, and advancing model systems. In striving for improved sensor sensitivity, scientists are finding innovative nanomaterials, signal amplification approaches, and bioconjugation strategies to enhance detection signals and lower detection limits, enabling the accurate monitoring of molecular targets within biological samples [55]. Concurrently, novel imaging techniques like super-resolution microscopy and spectroscopic imaging are revolutionizing the visualization of molecular interactions and cellular processes, providing researchers with unprecedented insights into biological mechanisms at the subcellular level [56, 57].

Furthermore, the development of advanced model systems, leveraging organ-on-a-chip technology, organoids, and patient-derived cells, is redefining the landscape of genetic biosensor applications in biomedical research. These cutting-edge model systems faithfully recapitulate complex physiological environments, disease conditions, and drug responses, offering a platform for validating biosensor performance in clinically relevant settings and facilitating the discovery of novel biomarkers and therapeutic targets [58, 59]. By integrating enhanced sensor sensitivity, state-of-the-art imaging modalities, and innovative model systems, the future of genetic biosensors in biomedicine promises to revolutionize diagnostics, drug development, and personalized treatment strategies, ushering in a new era of precision medicine and transformative healthcare innovations.

5- Introduction of Genetic Biomarkers

The selection and integration of genetic markers with biomedical devices for genetic biosensors in biomedical applications involves a meticulous process guided by key considerations to ensure optimal performance and relevance in high-impact applications. Initially, the choice of genetic markers is critical and hinges upon factors such as the specificity, sensitivity, and clinical significance of the biomarkers in detecting and monitoring specific biological

processes or disease states [60, 61]. Genetic markers selected should exhibit high selectivity towards the target analytes while maintaining robustness in complex biological matrices. Subsequently, the integration of these genetic markers with biomedical devices necessitates the design and fabrication of sensors that can efficiently capture, transduce, and amplify signals generated by the interaction between the markers and target molecules [62]. Critical considerations in this integration process include the development of biocompatible and stable sensor platforms, the incorporation of signal amplification strategies, and the optimization of detection mechanisms to enhance sensitivity and accuracy.

Overall, the successful selection and integration of genetic markers with biomedical devices for genetic biosensors hold profound implications for high-impact biomedical applications, offering significant advancements in diagnostics, personalized medicine, and therapeutic monitoring. By effectively leveraging the unique molecular signatures provided by genetic markers, these biosensors can enable rapid and precise detection of biomolecules, facilitate early disease diagnosis, monitor treatment responses, and customize therapies based on individual genetic profiles. The seamless integration of advanced sensor technologies and genetic markers in biosensors not only enhances analytical capabilities but also paves the way for innovative biomedical devices that have the potential to revolutionize healthcare delivery and improve patient outcomes on a broad scale.

5-1- Introduction of Genetic Marker

Molecular genetic markers, encompassing single-nucleotide polymorphisms (SNPs), gene mutations, and epigenetic alterations, play a pivotal role in distinguishing disease biomarkers or specific biological processes with high specificity and accuracy [63, 64]. Complementarily, gene expression profiles offer valuable insights into the dynamic regulation of gene activity [65, 66] and molecular pathways, providing a comprehensive view of cellular responses and disease states [67, 68]. By integrating both molecular genetic markers and gene expression data, genetic biosensors can achieve enhanced detection capabilities and diagnostic accuracy, facilitating breakthroughs in high-impact scientific research across diverse biomedical fields such as disease diagnostics, therapeutics development, and personalized medicine [2, 16]. This integrative approach not only enables the precise profiling of genetic signatures but also propels advancements in translational research, offering transformative opportunities for targeted treatments and biomarker-driven clinical interventions in precision healthcare settings.

5-2- Embedding into medical tools

The integration of genetic biosensors with biomedical devices represents a significant advancement in the field of biomedicine, offering a promising avenue for precision diagnostics and personalized healthcare [69, 70]. By harnessing the power of genetic information in real-time monitoring, these integrated systems hold the potential

Table 1. Comprehensive Overview of Genetic Biosensors: Types, Applications, and Challenges [5, 80-84].

Aspect	Description	Examples of Applications	Advantages	Challenges
Type of Biosensor	different types of genetic biosensors (e.g., DNA sensors, RNA sensors, protein biosensors)	Pathogen detection, gene expression evaluation	High specificity and sensitivity	Producing complexity
Detection Method	Strategies used for detection (e.g., fluorescence, electrochemical, colorimetric)	Real-time PCR, LAMP	Rapid consequences and real-time tracking	Needs specialized tool
Target Molecule	Molecules aimed by the biosensors (e.g., DNA, RNA, proteins, metabolites)	Genetic mutations, pathogen recognition	Ability to assess specific genetic sequences	Variability in aim molecule stability
Sample Types	Biological samples proper for assessment (e.g., blood, saliva, urine, tissue biopsies)	Blood tests for genetic diseases	Non-invasive sample collection options	Sample preparation
Applications in Diagnostics	Use of biosensors for disease diagnosis and tracking	Cancer diagnostics, infectious diseases	Early detection causing better prognosis	Accuracy in different populations
Therapeutic Monitoring	Monitoring cure effectiveness and patient response	Monitoring drug amounts and responses	Personalized medicine strategies	Divergence in sufferer responses
Point-of-Care Testing	Implementation in clinical settings for immediate results	Quick testing for STIs or genetic predispositions	Enhanced accessibility to healthcare	Regulatory and validation obstacles
Research Applications	Utilization in academic and pharmaceutical research	Gene editing studies, environmental monitoring	Enhanced data accuracy and reproducibility	Integration with existing research workflows
Multiplexing Capability	Ability to detect multiple targets simultaneously	Simultaneous detection of several pathogens	Time-saving and cost-effective	Complexity in design and interpretation
Data Analysis Techniques	Methods used for processing and interpreting data	Machine learning, statistical analysis	Improved accuracy in results	High volume of data management
	Challenges in gaining approval for clinical use	Compliance with FDA or CE markings	Potential for innovation in diagnostics	Long timelines for approval processes
Cost-effectiveness	Economic feasibility of biosensor production and application	Cost comparisons with traditional methods	Reduction in healthcare costs through efficient testing	High manufacturing and development costs
User-friendliness	Ease of use for clinicians and researchers	User interfaces, automated systems	Greater adoption in clinical practice	Need for training and support
Field Deployment	Application in real-world settings, including remote areas	Portable diagnostic devices	Accessibility in low-resource settings	Stability and robustness in diverse environments
Integration with IT Systems	Compatibility with electronic health records and laboratory information systems	Data sharing between labs and clinics	Streamlined workflows and improved patient management	Cybersecurity concerns
Ethical Considerations	Ethical implications of genetic testing and data privacy	Informed consent processes	Increased awareness and education	Potential for misuse of genetic information

to revolutionize disease detection, treatment monitoring, and therapeutic interventions [71]. Recent developments have showcased the ability of genetic biosensors to detect specific biomarkers with high sensitivity and specificity, paving the way for early disease detection and tailored treatment strategies [72]. The convergence of genetic biosensors with biomedical devices opens up new possibilities for continuous health monitoring, point-of-care diagnostics, and targeted drug delivery systems. Future directions in this field involve optimizing sensor performance, enhancing device miniaturization, and exploring novel applications in areas such as wearable technology and implantable devices, ultimately shaping the landscape of human healthcare with precision and efficiency [69].

The process of genetic marker selection for genetic biosensors in biomedical applications is a crucial step in ensuring the accuracy and reliability of these diagnostic tools. The selection of molecular genetic markers and gene expression profiles plays a pivotal role in determining the sensitivity and specificity of the biosensors in detecting specific biomolecules associated with various diseases. This process involves identifying genes or genetic

sequences that are known to be biomarkers for specific conditions, such as genetic mutations, gene expression levels, or specific genetic variations. By carefully selecting the appropriate genetic markers, researchers can optimize the performance of genetic biosensors, enhancing their ability to accurately detect and quantify target molecules in biological samples. This meticulous selection process is essential for the successful development of genetic biosensors that meet the stringent requirements of biomedical applications, ensuring their effectiveness in clinical diagnostics and personalized medicine.

5-3- The importance in treatment

Genetic biosensors have appeared as powerful tools in the field of personalized medicine, suggesting tailored diagnostic and cure strategies according to individual genetic variations. By such biosensors, clinicians can detect specific genetic biomarkers linked with an individual's susceptibility to certain diseases or their response to specific treatments, enabling a precision medical approach that considers the unique genetic makeup of each sufferer [1]. The flexibility of genetic biosensors enables not only the recognition of genetic

mutations and variations but also the tracking of gene expression patterns in real-time, providing valuable views into the molecular mechanisms underlying disorder progression and cure response. This personalized strategy has the potential to revolutionize healthcare by optimizing cure regimens, minimizing side effects, and improving patient outcomes [73].

By targeting specific genetic biomarkers or molecules related to different pathological conditions, these biosensors can identify minute modifications in gene expression profiles or detect disease-linked mutations with high precision [73]. The real-time monitoring of the potentials of genetic biosensors not only enables quick and accurate disorder diagnosis but also leads to continuous tracking of disease progression and cure response, providing clinicians with valuable data for optimizing medical interventions. This personalized and precise strategy for disease diagnosis decreases healthcare costs and advances our knowledge of complicated diseases at the molecular level [74].

Advancements in sensor sensitivity are fundamental for overcoming the limits of detection and precision in genetic biosensors. Approaches to achieve this involve the exploration of new materials with increased optical properties, surface changes to optimize sensor-target interactions, and the integration of nanotechnology applications for signal amplification and increased signal-to-noise ratios [22, 75]. By using these innovative methods, researchers aim to increase the detection restrictions of genetic biosensors, leading to the accurate and real-time tracking of molecular events within biological settings with unprecedented sensitivity. These advancements hold hope for revolutionizing disorder diagnostics, drug development, and personalized medicine by providing clinicians with highly sensitive devices for early detection and precise tracking of biomolecular interactions [76].

In parallel, the study of new model systems represents a border in the evolution of genetic biosensors. Emerging plans like synthetic biology systems, cell-free expression systems, and decreased organ-on-a-chip techniques offer a unique chance to expand the relevance and flexibility of genetic biosensors. These model systems create mimetic environments that nearly mimic physiological conditions, allowing for the testing and validation of biosensor function in complex biological fields [22]. By using these innovative model settings, researchers can gain deeper insights into cellular processes, disorder mechanisms, and drug responses, developing next-generation genetic biosensors for specific biomedical applications. The integration of these new model systems with progressed genetic biosensors accelerates the translation of biosensor techniques from the laboratory to clinical practice, finally advancing precision medicine and personalized healthcare.

6-Economic effectiveness of genetic biosensors

The use of genetic biosensors in technical applications suggests a cost-effective strategy for healthcare delivery, leading to decreased general healthcare costs and elevated efficiency. For instance, the performance of genotyping

biosensors for pharmacogenetics testing allows for the identification of genetic differences that may influence an individual's response to treatment, thereby decreasing adverse drug reactions and unnecessary cures [77]. In addition, the use of genetic biosensors for early detection of genetic biomarkers related to diseases, like cancer susceptibility, enables proactive and preventive assessments that can reduce the need for expensive treatments at later stages of the disorder. Moreover, the development of point-of-care genetic biosensors, like portable tools for rapid infectious disease evaluation, streamlines the diagnostic procedures, reduces the time to treatment initiation, and decreases healthcare-related costs [78]. Generally, the cost-effectiveness of genetic biosensors in medical applications lies in their potential to optimize cure approaches, control disease progression, and increase healthcare efficiency, ultimately leading to substantial economic benefits for healthcare settings and improved sufferer care. A comprehensive overview of the types, applications, and challenges of genetic biosensors is presented in Table 1.

The potential of genetic biosensors to collect and evaluate genetic information faces multiple serious ethical questions, specifically around privacy, agreement, equity, and safety. To begin, genetic data is extremely personal and can be predictive not only for the person but also for their family members. Biosensors, particularly those used in point-of-care systems or presented directly to consumers, can produce sensitive information. Subsequently, receiving informed consent for genetic testing through these biosensors can be completely challenging. Ultimately, collecting genetic data, especially concerning disease risk, can have significant psychological effects [22, 79].

7- Conclusion and Future perspectives

The future of genetic biosensors holds promising progress in technology, especially in the integration of Artificial Intelligence (AI) to increase their potential. AI-driven genetic biosensors can revolutionize medical studies and applications by permitting more precise and effective detection and assessment of genetic data. One application lies in the production of AI-increased genetic biosensors for early diagnosis and tracking of genetic biomarkers linked with complex disorders, like cancer. AI algorithms can assess vast amounts of genetic information to detect patterns and trends that may be typical of disease progression, enabling proactive and personalized cure methods. Another exciting anticipation is the use of AI in genetic biosensors for real-time tracking of infectious disease outbreaks. By integrating AI algorithms with portable genetic biosensors, quick identification and monitoring of pathogen mutations can be reached, facilitating proper public health interventions. In addition, AI-increased genetic biosensors can be used in precision medicine strategies, where AI algorithms can assess genetic divergence and anticipate individual responses to cures, causing more personalized and effective healthcare interventions. AI algorithms can evaluate vast amounts of genetic information to detect patterns and trends that may

be typical of disease progression, enabling proactive and personalized cure methods. Another exciting anticipation is the use of AI in genetic biosensors for real-time tracking of infectious disease outbreaks. AI algorithms, especially those based on deep learning, have the remarkable potential to sift through vast multi-omics datasets think genomics, transcriptomics, and proteomics to reveal complex predictive patterns that traditional statistical strategies usually miss. It can also use reinforcement learning algorithms to plan the perfect CRISPR guide RNA, ensuring it hits the aim effectively while decreasing off-target impacts. This strategy significantly increases the accuracy of a CRISPR-based biosensor even before we begin producing it in the lab. Moreover, a well-trained machine learning model can evaluate this signal in real-time, not just assessing the aim's concentration but also eliminating any unclear signals from contaminants. This produces consequences that are not only more reliable but also reproducible.

The integration of AI techniques with genetic biosensors presents a promising direction in progressing medical study and applications, with the potential to significantly impact healthcare results and patient care.

Ethics approval and consent to participate

Not applicable.

Consent for publication

All authors agree to publish this paper.

Availability of data and material

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Author contribution statement

All authors listed have significantly contributed to the design, the development and the writing of the manuscript. All authors have read and agreed to the published version of the manuscript.

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