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AFFORDABLE INFECTIOUS DISEASE BIOSENSORS FOR FINANCIALLY SUSTAINABLE HEALTHCARE: A CONCEPTUAL FRAMEWORK INTEGRATING GREEN FINANCE READINESS AND AI-BASED DECISION SUPPORT

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Abstract

Infectious diseases continue to place a major clinical and financial burden on healthcare systems, particularly in low-resource settings where access to timely and affordable diagnosis remains limited. Conventional diagnostic methods such as polymerase chain reaction, enzyme-linked immunosorbent assay, microbial culture, and centralized laboratory testing are accurate but often expensive, time-consuming, infrastructure-dependent, and difficult to implement in rural and underserved areas. Delayed diagnosis can increase disease transmission, hospitalization, treatment costs, and pressure on public health systems. In this context, affordable infectious disease biosensors offer a promising pathway for rapid, low-cost, decentralized, and point-of-care diagnosis.

This article develops a conceptual framework explaining how affordable biosensor-based diagnostic solutions can contribute to financially sustainable healthcare. The framework is built around six readiness dimensions: technological readiness, financial readiness, environmental readiness, digital readiness, governance and compliance readiness, and supply-chain readiness. It also proposes the use of a Green Finance Readiness Index to assess whether biosensor-based healthcare innovations are suitable for sustainable financing, ESG investment, and large-scale implementation. In addition, the article highlights the role of artificial intelligence-enabled decision support in interpreting biosensor signals, classifying diagnostic results, reducing human error, improving prediction accuracy, and supporting real-time disease surveillance.

The article argues that biosensor-based diagnostics can reduce diagnostic delays, lower healthcare expenditure, minimize hospitalization, improve healthcare accessibility, strengthen outbreak surveillance, and support universal health coverage. By integrating green finance readiness and AI-enabled decision support, affordable infectious disease biosensors can be positioned as clinically useful, economically viable, environmentally sustainable, and socially accessible healthcare innovations. Future research should empirically validate the proposed framework using real patient samples, clinical testing, healthcare cost data, AI-based biosensor signal datasets, regulatory assessment, and field-level implementation studies.

Keywords: Infectious disease biosensors; financial sustainability; point-of-care diagnostics; green finance readiness; artificial intelligence; healthcare innovation; sustainable healthcare.

Introduction

Infectious diseases continue to represent one of the most persistent challenges to global healthcare systems, particularly in low- and middle-income countries where access to timely diagnosis and treatment remains uneven. Diseases such as tuberculosis, malaria, dengue fever, viral hepatitis, HIV/AIDS, influenza, COVID-19, and other emerging infections place a continuous burden on public health infrastructure, clinical services, and healthcare financing. The impact of infectious diseases is not limited to morbidity and mortality alone; it also extends to increased treatment costs, loss of productivity, pressure on hospitals, and disruption of public health systems. In this context, early and accurate diagnosis plays a central role in disease control, as it enables timely treatment, reduces complications, limits transmission, and supports effective public health response.

Delayed diagnosis is one of the major factors contributing to the rising cost of infectious disease management. When infections are not detected at an early stage, patients are more likely to experience disease progression, severe complications, prolonged illness, and increased need for hospitalization. In many cases, late diagnosis also allows pathogens to spread within families, workplaces, schools, and communities, thereby increasing the number of cases and multiplying the demand for healthcare services. This creates a cycle in which diagnostic delay leads to greater disease transmission, higher treatment expenditure, increased hospital admissions, and additional pressure on already limited healthcare resources. For healthcare systems working under financial constraints, particularly in resource-limited settings, this creates a serious challenge to long-term financial sustainability.

Conventional infectious disease diagnosis commonly depends on laboratory-based techniques such as polymerase chain reaction (PCR), enzyme-linked immunosorbent assay (ELISA), microbial culture, nucleic acid amplification tests, and centralized laboratory testing. These methods are widely recognized for their diagnostic accuracy and clinical value. PCR, for example, is highly sensitive for detecting pathogen genetic material, while ELISA is commonly used for antigen and antibody detection.

Microbial culture remains important for identifying bacterial and fungal infections and supporting antimicrobial susceptibility testing. However, despite their usefulness, these diagnostic methods are often associated with several limitations that reduce their accessibility and practical value in many healthcare settings.

A major limitation of conventional diagnostic systems is their dependence on specialized laboratory infrastructure. PCR and ELISA usually require expensive instruments, quality-controlled laboratory environments, trained personnel, stable electricity, cold-chain support, reagents, and well-established sample transportation systems. Microbial culture techniques may take several days or even weeks to produce results, especially for slow-growing organisms. Centralized testing models also require patients or samples to move from peripheral healthcare centers to laboratories, which increases turnaround time and creates additional logistical costs. In rural and underserved areas, the absence of nearby diagnostic laboratories often results in delayed testing, delayed treatment decisions, and preventable worsening of disease outcomes.

The COVID-19 pandemic highlighted the importance of rapid, decentralized, and scalable diagnostic systems. During large outbreaks, centralized laboratories can become overloaded due to sudden increases in testing demand. This experience demonstrated that healthcare systems need diagnostic technologies that can be deployed outside conventional laboratory settings, including primary health centers, community clinics, mobile health units, pharmacies, and field screening programs. Therefore, there is a growing need for diagnostic solutions that are affordable, rapid, portable, easy to operate, and suitable for use at the point of care. Such technologies are especially important for strengthening healthcare access in low-resource settings and for improving preparedness against future outbreaks.

Affordable point-of-care diagnostics can contribute significantly to healthcare financial sustainability. By enabling early detection, these tools can reduce unnecessary referrals, avoid repeated laboratory visits, shorten the time between testing and treatment, and prevent complications that require expensive medical intervention. Early diagnosis can also reduce hospitalization rates and support more efficient use of healthcare resources. From a public health perspective, rapid detection of infectious cases can help interrupt transmission chains and reduce the economic burden associated with outbreaks. Thus, investment in affordable diagnostic innovation should not be viewed only as a technological improvement, but also as a financial sustainability strategy for healthcare systems.

Biosensor technology has emerged as a promising solution to address these diagnostic and financial challenges. A biosensor is an analytical device that combines a biological recognition element, such as an antibody, enzyme, nucleic acid probe, aptamer, or antigen, with a transducer that converts a

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biological interaction into a measurable signal. In infectious disease diagnosis, biosensors can be designed to detect pathogens, antigens, antibodies, nucleic acids, toxins, or disease-specific biomarkers. Depending on their design, biosensors may generate electrochemical, optical, thermal, piezoelectric, or colorimetric signals. Recent advances in nanotechnology, microfluidics, printed electronics, paper-based platforms, and smartphone-based detection systems have improved the sensitivity, portability, and affordability of biosensor devices.

Compared with conventional laboratory diagnostics, biosensors offer several potential advantages. They can provide rapid results, require smaller sample volumes, reduce dependence on centralized laboratories, and support testing closer to patients. Paper-based biosensors and electrochemical biosensors are particularly attractive for low-resource settings because they can be produced at relatively low cost, are portable, and can be designed for simple operation by minimally trained healthcare workers. Nanomaterial-enhanced biosensors, including those based on gold nanoparticles, graphene, carbon nanotubes, and quantum dots, can improve sensitivity and enable detection of biomarkers at very low concentrations. Furthermore, biosensors can be integrated with smartphones, cloud-based platforms, artificial intelligence, and telemedicine systems to support real-time reporting, remote monitoring, and disease surveillance.

The integration of biosensors with digital health and artificial intelligence further strengthens their relevance for modern healthcare systems. AI-enabled biosensor platforms can support automated interpretation of diagnostic signals, reduce human error, improve classification accuracy, and assist healthcare providers in decision-making. When connected with digital reporting systems, biosensors can also contribute to real-time public health surveillance by identifying disease trends, detecting outbreaks earlier, and supporting faster resource allocation. These features make biosensors valuable not only for individual patient diagnosis but also for population-level disease management and health system planning.

In addition to clinical and technological value, affordable biosensor solutions also align with the broader goal of sustainable healthcare. By reducing reagent consumption, lowering energy requirements, minimizing sample transportation, and supporting decentralized testing, biosensors may reduce the environmental footprint of diagnostic services. This creates an important connection between healthcare innovation, environmental sustainability, and green finance readiness. In this regard, biosensor-based infectious disease diagnostics can be positioned as a sustainable healthcare innovation that contributes to clinical efficiency, cost reduction, public health resilience, and responsible resource use.

Based on this background, the present article aims to develop a conceptual framework explaining how affordable infectious disease biosensor solutions can support financial sustainability in healthcare. The article argues that low-cost, rapid, and decentralized biosensor-based diagnostics can reduce the economic burden of infectious disease management by enabling early detection, timely intervention, reduced hospitalization, improved surveillance, and efficient resource utilization. In addition, the article highlights the role of green finance readiness and AI-enabled decision support in strengthening the scalability, sustainability, and practical implementation of biosensor-based healthcare innovation.

Literature Review

Infectious Disease Burden and Diagnostic Challenges

Infectious diseases remain a major public health challenge across the world, particularly in low- and middle-income countries where healthcare systems often experience limited diagnostic capacity, inadequate infrastructure, and financial constraints. Diseases such as tuberculosis, malaria, dengue fever, viral hepatitis, HIV/AIDS, influenza, COVID-19, and other emerging infectious diseases continue to generate high levels of morbidity, mortality, and healthcare expenditure. These diseases also create indirect economic losses through reduced productivity, absenteeism, outbreak-related restrictions, and increased pressure on public health systems. Therefore, infectious disease management is not only a clinical concern but also a financial and developmental challenge.

The burden of infectious diseases is strongly linked to diagnostic delay. Early and accurate diagnosis allows healthcare providers to initiate treatment promptly, reduce complications, limit transmission, and improve patient outcomes. However, many healthcare systems, especially in rural and underserved areas, lack rapid and affordable diagnostic facilities. As a result, patients may remain undiagnosed for long periods or may receive treatment only after the disease has progressed. This delay increases the likelihood of hospitalization, severe complications, disease spread, and higher treatment costs. WHO emphasizes that diagnostics are central to identifying disease conditions and supporting early treatment, which can prevent complications and costly interventions (World Health Organization [WHO], 2025.).

The Lancet Commission on Diagnostics highlights that diagnostic services are a neglected but essential component of health systems and that inadequate access to diagnostics contributes to avoidable illness, delayed care, inappropriate treatment, and inefficient use of healthcare resources (Fleming et al., 2021). This is particularly relevant for infectious diseases because disease control depends heavily on timely detection and rapid response. In the absence of accessible diagnostics, infections can spread within households, communities, schools, workplaces, and healthcare facilities. Thus, strengthening diagnostic access is essential for improving public health outcomes and

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reducing the financial burden on healthcare systems.

Diagnostic challenges are more severe in resource-limited settings due to geographical barriers, shortage of trained personnel, lack of laboratory infrastructure, unreliable electricity supply, limited cold-chain systems, and high testing costs. In such contexts, patients may need to travel long distances to access testing facilities, which increases both direct and indirect costs. These barriers highlight the need for decentralized, affordable, and rapid diagnostic technologies that can be used closer to patients. Point-of-care diagnostic approaches have therefore received increasing attention as a strategy to improve healthcare accessibility and reduce delays in infectious disease management (Peeling & Mabey, 2010; Drain et al., 2014).

Conventional Diagnostic Methods and Their Limitations

Conventional infectious disease diagnosis commonly relies on laboratory-based techniques such as polymerase chain reaction (PCR), enzyme-linked immunosorbent assay (ELISA), microbial culture, microscopy, nucleic acid amplification tests, and rapid diagnostic tests. These methods play an important role in clinical diagnosis and disease surveillance. PCR is widely used because of its high sensitivity in detecting pathogen genetic material, while ELISA is commonly applied for antigen and antibody detection. Microbial culture remains important for identifying bacterial and fungal infections and for determining antimicrobial susceptibility. Despite their clinical value, these methods have several limitations when considered from the perspective of accessibility, affordability, and healthcare sustainability.

PCR-based diagnostics require specialized equipment, trained laboratory personnel, stable electricity, high-quality reagents, and controlled laboratory environments. Although PCR offers high accuracy, its dependence on centralized laboratory infrastructure limits its usefulness in many low-resource settings. In addition, the cost of machines, reagents, maintenance, and skilled operators can make PCR-based testing expensive for public health systems and patients. Yang and Rothman (2004) noted that PCR has strong diagnostic value but also faces challenges related to cost, technical complexity, contamination risk, and implementation in routine clinical settings.

ELISA is another widely used diagnostic method, particularly for detecting antibodies, antigens, and immune responses. However, ELISA usually requires laboratory equipment, trained technicians, multiple processing steps, and longer turnaround time. For acute infectious diseases requiring immediate treatment decisions, such delay can reduce clinical usefulness. Similarly, microbial culture methods, although highly valuable, may require several days or weeks to produce results depending on the pathogen. This delay can be problematic when rapid intervention is needed to prevent disease progression or transmission.

Rapid diagnostic tests have improved access to infectious disease screening because they are relatively simple, fast, and suitable for field use. However, some rapid tests may show limitations in sensitivity, specificity, and quantitative measurement, especially during early infection or when pathogen load is low. Yalley et al. (2022) emphasized that molecular techniques can improve infectious disease diagnosis in resource-limited settings, but their suitability depends on infrastructure, cost, technical capacity, and operational feasibility. Therefore, while conventional methods remain essential, they do not fully address the need for affordable, decentralized, and scalable diagnostics.

Centralized laboratory testing also creates logistical challenges. Samples often need to be transported from primary healthcare centers to district or tertiary laboratories. This increases turnaround time, transportation cost, risk of sample degradation, and administrative burden. During outbreaks, centralized laboratories may become overloaded, leading to delays in reporting results. The COVID-19 pandemic demonstrated that even advanced healthcare systems can face diagnostic bottlenecks when testing demand suddenly increases. These limitations have encouraged researchers and policymakers to explore alternative diagnostic technologies that are rapid, portable, low-cost, and suitable for point-of-care use.

Emergence of Biosensor-Based Diagnostics

Biosensor-based diagnostics have emerged as a promising response to the limitations of conventional diagnostic systems. A biosensor is an analytical device that combines a biological recognition element with a transducer to detect a target analyte and convert the biological interaction into a measurable signal. The biological recognition element may include antibodies, enzymes, nucleic acid probes, aptamers, cells, or molecular receptors. The transducer may generate electrochemical, optical, thermal, piezoelectric, or colorimetric signals depending on the biosensor design.

In infectious disease diagnosis, biosensors can detect pathogens, antigens, antibodies, nucleic acids, toxins, or other disease-specific biomarkers. Their value lies in their potential to provide rapid, sensitive, portable, and cost-effective detection. Compared with centralized diagnostic systems, biosensors can be designed for use at the point of care, allowing testing to occur closer to the patient. This can reduce diagnostic delay, lower transportation costs, support early treatment, and improve disease control. Parihar et al. (2025) explain that point-of-care biosensors have become increasingly important because of the growing demand for rapid, accurate, and accessible infectious disease diagnostics.

The emergence of biosensors has been supported by advances in nanotechnology, microfluidics, biotechnology, materials science, printed electronics, and digital health. Nanomaterials such as gold nanoparticles, graphene, carbon nanotubes, and quantum dots can improve signal amplification and enhance diagnostic sensitivity. Microfluidic systems allow small sample volumes to be processed efficiently, reducing reagent use and improving portability. Paper-based platforms and screen-printed electrodes support low-cost manufacturing, making biosensors attractive for resource-constrained environments.

Biosensor-based diagnostics also align with the REASSURED criteria for effective point-of-care testing. Land et al. (2019) expanded the earlier ASSURED framework and argued that point-of-care tests should be real-time connected, easy to collect, affordable, sensitive, specific, user-friendly, rapid and robust, equipment-free or simple, and deliverable to end users. These criteria are highly relevant for infectious disease diagnostics in low-resource settings. Affordable biosensors can potentially satisfy many of these requirements by combining portability, low-cost design, digital connectivity, and rapid diagnostic capability.

However, biosensor research is not without challenges. Many biosensor technologies remain in laboratory or prototype stages and require further clinical validation before large-scale adoption. Issues such as reproducibility, stability, standardization, regulatory approval, manufacturing scalability, and user training remain important barriers. Nevertheless, biosensors represent a significant technological pathway for transforming infectious disease diagnosis from centralized, delayed testing toward decentralized, rapid, and financially sustainable diagnostic systems.

Types of Biosensors for Infectious Disease Detection

Different types of biosensors have been developed for infectious disease detection, each with specific strengths, limitations, and application contexts. The major categories include electrochemical biosensors, optical biosensors, piezoelectric biosensors, microfluidic biosensors, paper-based biosensors, and nanotechnology-enhanced biosensors.

Electrochemical biosensors are among the most widely researched biosensor platforms for infectious disease diagnosis. They detect changes in electrical signals caused by biological interactions between the target analyse and the recognition element. These biosensors are attractive because they are sensitive, portable, relatively low-cost, and compatible with miniaturized devices. Electrochemical biosensors can be integrated with screen-printed electrodes and simple electronic readers, making them suitable for point-of-care applications. Kim et al. (2024) highlight that electrochemical biosensors are increasingly used in point-of-care testing because of their sensitivity, affordability, and ease of miniaturization.

Optical biosensors detect changes in light properties such as fluorescence, absorbance, reflection, luminescence, or refractive index. These sensors can provide high sensitivity and rapid detection, particularly when combined with

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nanomaterials or fluorescence-based probes. Optical biosensors have been used for detecting viral, bacterial, and parasitic infections. However, some optical platforms may require more complex instrumentation than electrochemical sensors, which can increase cost and limit field use. Pashchenko et al. (2018) compared optical, electrochemical, magnetic, and colorimetric biosensors and emphasized that each platform must be evaluated according to diagnostic accuracy, cost, simplicity, and field applicability.

Piezoelectric biosensors measure changes in mass or mechanical vibration when target molecules bind to the sensor surface. These sensors can detect pathogens, proteins, or nucleic acids with high precision. Although piezoelectric biosensors are scientifically valuable, they may require more specialized instrumentation and environmental control, which can limit their use in low-resource settings. Microfluidic biosensors, on the other hand, integrate small channels and chambers to manipulate tiny volumes of biological fluids. They can reduce reagent consumption, shorten analysis time, and allow multiple diagnostic steps to occur in a compact device. Choi et al. (2011) noted that microfluidic biosensors have strong potential for point-of-care detection of nucleic acids and proteins.

Paper-based biosensors are particularly important for affordable infectious disease diagnosis. These devices use paper or cellulose-based substrates to perform diagnostic reactions. They are lightweight, inexpensive, disposable, and suitable for mass production. Paper-based biosensors are valuable for rural and low-resource settings because they can reduce the need for expensive laboratory infrastructure. Their simple design also makes them suitable for community screening and field-based surveillance.

Nanotechnology-enhanced biosensors have significantly improved infectious disease detection by increasing surface area, improving signal amplification, and enabling detection of biomarkers at low concentrations. Graphene, gold nanoparticles, carbon nanotubes, magnetic nanoparticles, and quantum dots are commonly used to enhance biosensor performance. Ramalingam et al. (2023) observed that nanotechnology has strengthened both conventional and AI-based biosensing approaches, particularly in virus detection. Therefore, the selection of biosensor type should depend not only on technical sensitivity but also on cost, scalability, user-friendliness, and suitability for healthcare settings.

Biosensors, Point-of-Care Testing, and Healthcare Accessibility

Point-of-care testing refers to diagnostic testing performed near the patient rather than in a centralized laboratory. This approach is especially important for infectious diseases because timely diagnosis can support immediate treatment and reduce transmission. Biosensors are highly relevant to point-of-care testing because they can be designed as portable, rapid, and low-cost diagnostic devices. Their use in primary health centers, community clinics, mobile health units,

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pharmacies, and field screening programs can improve diagnostic access for underserved populations.

Healthcare accessibility remains a major challenge in many regions. Rural communities often face limited laboratory facilities, shortage of trained technicians, long travel distances, and high out-of-pocket costs. These barriers can delay diagnosis and worsen health outcomes. Point-of-care biosensors can address these barriers by bringing diagnostic services closer to patients. Drain et al. (2014) emphasized that diagnostic point-of-care tests can be especially valuable in resource-limited settings when they are affordable, accurate, easy to use, and integrated into healthcare delivery systems.

Biosensors may also support universal health coverage by reducing inequalities in diagnostic access. Universal health coverage requires that essential healthcare services be available without causing financial hardship. Affordable diagnostics are a critical part of this goal because treatment cannot be effective if diseases are not diagnosed in time. Biosensor-based testing may reduce patient costs by avoiding repeated hospital visits, reducing travel expenses, and enabling earlier treatment. At the health system level, early diagnosis may reduce unnecessary referrals, hospital admissions, and outbreak-related expenditure.

Point-of-care biosensors also offer advantages for public health surveillance. When connected to digital reporting platforms, biosensors can support real-time disease monitoring and outbreak detection. Rapid reporting of test results can help public health authorities identify disease clusters, allocate resources, and implement targeted interventions. This is particularly important for diseases such as dengue, malaria, COVID-19, tuberculosis, and influenza, where early detection of transmission patterns can improve response strategies.

Despite these benefits, implementation challenges remain. Point-of-care biosensors must be validated under real-world conditions, including variations in temperature, humidity, sample quality, and user skill. Healthcare workers need training to operate devices correctly and interpret results. Supply chains must ensure availability of test cartridges, reagents, batteries, and replacement components. Regulatory approval and quality assurance systems are also needed to ensure patient safety and diagnostic reliability.

Therefore, biosensors should not be viewed only as laboratory innovations; they must be embedded within practical healthcare delivery systems.

Digital Health, Smartphone Integration, and AI-Enabled Biosensors

The integration of biosensors with digital health technologies has expanded their potential role in infectious disease diagnosis and healthcare management. Modern biosensor platforms can be linked with smartphones, cloud computing systems, telemedicine platforms, and electronic health records. These integrations can improve usability, result interpretation, data storage, remote consultation, and real-time public health surveillance.

Smartphone-integrated biosensors are especially promising because smartphones are widely available and can function as data readers, image processors, communication tools, and decision-support interfaces. A smartphone camera can be used to analyze colorimetric or fluorescence-based biosensor outputs, while mobile applications can process sensor data and display results. Cloud connectivity can allow diagnostic results to be transmitted to healthcare providers, laboratories, or public health authorities. Xing et al. (2025) note that smartphone-based biosensors have advanced across different applications because of improvements in imaging, connectivity, portability, and digital analysis.

Artificial intelligence and machine learning can further improve biosensor-based diagnostics. AI models can analyze complex biosensor signals, identify patterns, classify positive and negative cases, reduce human interpretation error, and improve diagnostic decision-making. Machine learning algorithms such as logistic regression, support vector machines, random forest, gradient boosting, artificial neural networks, and convolutional neural networks can be trained using biosensor signal data and clinical reference results. Bhaiyya et al. (2024) explain that machine learning-assisted biosensors have strong potential in point-of-care testing because they can improve analytical performance and support clinical decisions.

AI-enabled biosensors can also support predictive disease surveillance. When biosensor results are aggregated across locations, AI models can identify unusual disease trends, detect potential outbreaks, and support early warning systems. Flynn and Chang (2024) argue that artificial intelligence can improve the performance and reliability of point-of-care biosensing by supporting automated analysis, pattern recognition, and decision support. This is particularly important when biosensors generate complex electrochemical, optical, or time-series signals that may be difficult to interpret manually.

However, digital and AI-enabled biosensors also introduce new challenges. Data privacy, cybersecurity, algorithmic bias, interoperability, and regulatory compliance must be carefully addressed. Patient diagnostic data are sensitive and must be securely stored and transmitted. AI models must be trained using diverse and representative datasets to avoid inaccurate predictions across different populations. Digital systems must also be designed for low-resource settings where internet connectivity may be unstable. Therefore, AI integration should be developed alongside ethical, regulatory, and governance frameworks.

Green Finance and Sustainable Healthcare Innovation

Healthcare innovation is increasingly being evaluated not only in terms of clinical effectiveness but also in terms of financial, environmental, and social sustainability. The healthcare sector consumes large amounts of energy, water, chemicals, plastics, and disposable materials. Diagnostic laboratories, in particular, may require continuous electricity, refrigeration, reagents, sample transportation, and waste management systems. Therefore, sustainable healthcare innovation requires technologies that improve patient outcomes while reducing resource consumption and environmental impact.

WHO guidance on climate-resilient and environmentally sustainable healthcare facilities emphasizes the need to optimize resource use and minimize waste release into the environment (WHO, 2020). This is directly relevant to diagnostic innovation because decentralized and low-resource diagnostic tools can reduce transportation, energy use, reagent consumption, and laboratory waste. Biosensor technologies, especially paper-based, disposable, low-power, and miniaturized devices, may contribute to environmentally sustainable healthcare by lowering the material and energy intensity of diagnostic services.

Green finance refers to financial investment that supports environmentally sustainable and socially beneficial projects. In the context of healthcare, green finance can support technologies that reduce environmental burden while improving access, affordability, and public health outcomes. The Organisation for Economic Co-operation and Development (OECD, 2020) explains that sustainable finance taxonomies provide clarity on which economic activities can be considered environmentally sustainable. This is important for healthcare technologies because funding agencies, investors, and governments increasingly require evidence that innovations align with sustainability and ESG principles.

Affordable infectious disease biosensors can be positioned as sustainable healthcare innovations because they combine clinical value, cost reduction, environmental efficiency, and social accessibility. Financially, they may reduce diagnostic costs, prevent expensive hospitalization through early detection, and improve resource allocation. Environmentally, they may reduce reagent consumption, sample transportation, and energy requirements. Socially, they can improve diagnostic access for rural and underserved populations. Therefore, biosensor-based diagnostics can contribute to multiple sustainability objectives, including universal health coverage, health system resilience, and responsible resource use.

The proposed Green Finance Readiness perspective is useful because it connects biosensor innovation with broader healthcare financing and sustainability goals. Instead of assessing biosensors only through technical performance indicators such as sensitivity and specificity, a green finance readiness framework can evaluate financial readiness, environmental readiness, technological readiness, digital readiness, governance readiness, and supply-chain readiness. This approach helps determine whether a biosensor solution is not only scientifically valid but also affordable, scalable, environmentally responsible, and suitable for real-world healthcare adoption.

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Overall, the literature shows that infectious disease diagnostics require a transition from expensive, centralized, and delayed systems toward affordable, rapid, decentralized, digitally connected, and environmentally sustainable solutions. Biosensors provide a promising pathway for this transition, but their success depends on clinical validation, cost-effectiveness, digital integration, regulatory compliance, manufacturing scalability, and sustainable financing. The integration of biosensor-based diagnostics with AI-enabled decision support and green finance readiness therefore offers a strong conceptual foundation for achieving financial sustainability in healthcare.

Research Gap

Although biosensor-based diagnostics have received increasing scholarly and technological attention, several important gaps remain in the existing literature. Current research has largely focused on improving the technical performance of biosensors, particularly their sensitivity, specificity, response time, and ability to detect pathogens at low concentrations. Studies on electrochemical, optical, nanomaterial-enhanced, microfluidic and paper-based biosensors have demonstrated strong diagnostic potential for infectious diseases. However, the translation of these technologies into affordable, scalable, and financially sustainable healthcare solutions remains limited. Therefore, there is a need to move beyond laboratory-based performance evaluation and examine how biosensors can be implemented within real healthcare systems, especially in low-resource and financially constrained settings.

A major gap in the existing literature is the limited focus on affordability. Many biosensor studies emphasize advanced materials, nanotechnology, signal amplification, and high diagnostic accuracy, but fewer studies examine whether these technologies can be manufactured, distributed, and used at a cost suitable for public healthcare systems and underserved populations. The use of materials such as gold nanoparticles, graphene, carbon nanotubes, specialized reagents, and advanced microfabrication techniques may improve sensitivity, but these components can also increase production costs. As a result, many biosensor prototypes remain promising at the laboratory level but may not be economically viable for large-scale deployment. This creates a gap between technological innovation and practical affordability.

Another important gap is the lack of large-scale clinical validation. Many biosensor platforms have been tested using controlled laboratory samples, simulated biological fluids, or small clinical datasets. While these studies are useful for proof-of-concept development, they do not fully demonstrate how biosensors perform under real-world conditions. Diagnostic accuracy may vary according to sample type, disease stage, pathogen load, environmental conditions, operator skill, and patient diversity. Large-scale multicenter validation studies are therefore necessary to establish reliability, reproducibility, sensitivity, specificity, and clinical usefulness across different populations and healthcare settings. Without such validation, biosensor technologies may face difficulty in gaining regulatory approval and clinical acceptance.

There is also insufficient research on the implementation of biosensors in low-resource settings. Infectious diseases often impose the greatest burden in regions where laboratory infrastructure, trained personnel, electricity, internet connectivity, cold-chain systems, and supply chains are limited. However, many biosensor studies are conducted in advanced research laboratories or well-equipped healthcare environments. This creates uncertainty regarding whether biosensors can function effectively in rural clinics, primary healthcare centers, mobile diagnostic units, and community health programs. Future research must therefore examine device durability, usability, storage stability, training requirements; maintenance needs, and field-level performance in resource-constrained environments.

A further gap concerns the limited integration of biosensor technologies with healthcare information systems. Modern healthcare increasingly depends on digital reporting, electronic health records, telemedicine, public health dashboards, and real-time disease surveillance. Although recent studies have explored smartphone-based and AI-enabled biosensors, integration with broader healthcare data systems remains underdeveloped. Biosensor results should not remain isolated at the device level; they should be connected to clinical decision-making systems, disease surveillance networks, and public health response mechanisms. Limited interoperability, data privacy concerns, cybersecurity risks, and lack of standardized digital reporting frameworks continue to restrict the wider use of biosensors in healthcare systems.

The literature also shows a lack of detailed research on scalable manufacturing and commercialization models. Numerous biosensor prototypes have been developed, but fewer studies explain how these devices can be mass-produced at consistent quality and low cost. Questions related to supply-chain readiness, local manufacturing, quality control, regulatory pathways, packaging, distribution, and after-sales support are often not addressed in depth. This limits the movement of biosensor technologies from academic research into practical healthcare markets. For biosensors to support large-scale infectious disease diagnosis, future studies must investigate not only scientific design but also production feasibility and commercialization strategy.

Most importantly, there is an inadequate connection between biosensor innovation and healthcare financial sustainability. Existing studies often present biosensors as rapid and accurate diagnostic tools, but they rarely examine how these technologies can reduce healthcare expenditure, prevent hospitalization, improve resource allocation, or support sustainable health financing. The financial value of early diagnosis is often discussed generally, but

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systematic frameworks for evaluating cost-effectiveness, return on investment, green finance readiness, and long-term healthcare savings remain limited. This gap is particularly important because healthcare systems require technologies that are not only scientifically effective but also economically sustainable.

Similarly, the environmental and green finance dimensions of biosensor-based diagnostics remain underexplored. Sustainable healthcare innovation requires diagnostic technologies that reduce energy use, reagent consumption, biomedical waste, sample transportation, and carbon emissions. However, most biosensor studies focus primarily on technical performance and give limited attention to environmental sustainability. There is also limited research on how biosensor solutions can attract green finance, ESG investment, or sustainability-oriented healthcare funding. This shows the need for a framework that connects affordable diagnostics, environmental responsibility, financial readiness, and healthcare system sustainability.

Based on these gaps, the present article proposes a conceptual framework that links affordable infectious disease biosensors with financial sustainability in healthcare. The framework addresses the need to evaluate biosensor solutions through multiple dimensions, including affordability, technological readiness, clinical validation, low-resource implementation, digital integration, scalable manufacturing, environmental sustainability, and green finance readiness. By doing so, the article contributes to the literature by shifting the discussion from biosensor development alone to biosensor implementation as a financially sustainable and socially responsible healthcare innovation.

Conceptual Framework

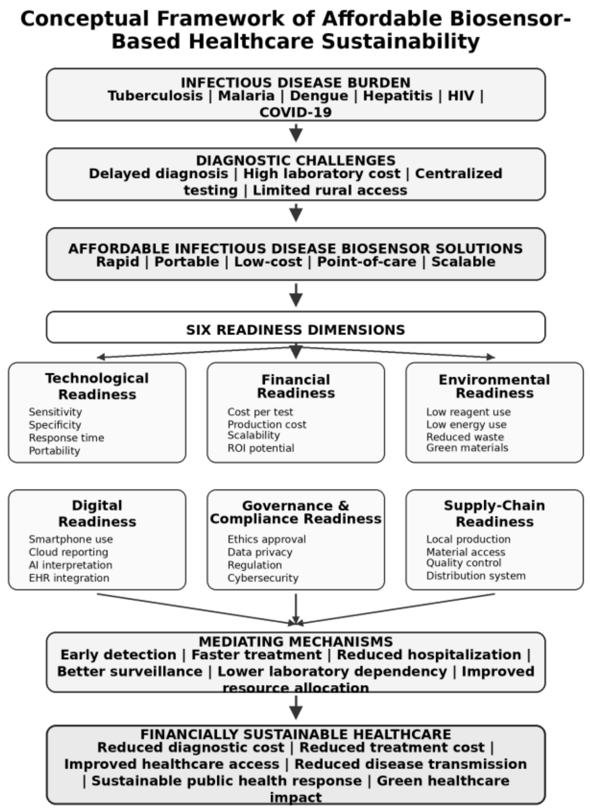

Figure 1. Proposed conceptual framework showing how affordable infectious disease biosensor solutions can contribute to financially sustainable healthcare through six readiness dimensions.

Fig 1: Conceptual Framework

The conceptual framework of this article explains how affordable infectious disease biosensors can contribute to financially sustainable healthcare. The

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framework is based on the assumption that early, rapid, and decentralized diagnosis can reduce the economic burden associated with infectious disease management. When infections are detected at an early stage, healthcare providers can initiate timely treatment, prevent complications, reduce unnecessary referrals, minimize hospitalization, and limit disease transmission. These outcomes can reduce both direct healthcare costs and indirect economic losses caused by delayed diagnosis, disease progression, and outbreak spread.

The proposed framework positions affordable biosensor-based diagnostics as the central technological intervention. Biosensors can detect infectious disease biomarkers such as pathogens, antigens, antibodies, nucleic acids, and other disease-specific biological signals. Compared with conventional laboratory-based diagnostic methods, biosensors have the potential to provide rapid, portable, low-cost, and point-of-care testing. This makes them particularly useful for primary health centers, rural clinics, community health programs, mobile diagnostic units, and outbreak surveillance systems.

The framework suggests that affordable infectious disease biosensors contribute to financial sustainability through four main pathways. First, they support early disease detection, which reduces complications and lowers the need for expensive treatment. Second, they decentralize diagnostic services, reducing dependence on costly laboratory infrastructure and sample transportation. Third, they improve healthcare resource utilization by enabling faster clinical decision-making and targeted intervention. Fourth, they strengthen public health surveillance by supporting real-time detection and reporting of infectious disease trends.

However, the successful contribution of biosensors to healthcare financial sustainability depends on more than diagnostic accuracy alone. A biosensor may be scientifically effective, but it may fail in real-world healthcare settings if it is too expensive, difficult to manufacture, environmentally unsustainable, digitally disconnected, or unsuitable for regulatory approval. Therefore, this article proposes a six-dimensional conceptual framework that evaluates biosensor-based healthcare innovation through technological readiness, financial readiness, environmental readiness, digital readiness, governance and compliance readiness, and supply-chain readiness.

Structure of the Proposed Framework

The proposed framework follows a sequential but interconnected logic:

Infectious Disease Burden → Diagnostic Delay → Higher Healthcare Cost → Need for Affordable Biosensors → Six-Dimensional Readiness Assessment → Sustainable Healthcare Outcomes

In this model, infectious disease burden creates pressure on healthcare systems. Diagnostic delay increases healthcare expenditure through advanced disease progression, hospitalization, prolonged treatment, and wider disease transmission. Affordable biosensors are introduced as a solution to improve early diagnosis and reduce unnecessary healthcare expenditure. The six readiness dimensions then determine whether biosensor solutions can be practically adopted, scaled, financed, and sustained within healthcare systems.

The expected outcome of the framework is financially sustainable healthcare, supported by early detection, lower diagnostic costs, reduced hospitalization, improved disease surveillance, efficient resource allocation, and environmentally responsible diagnostic practices.

Six Dimensions of the Conceptual Framework

Technological Readiness

Technological readiness refers to the scientific and technical maturity of the biosensor solution. It examines whether the biosensor can accurately, rapidly, and reliably detect infectious disease biomarkers under laboratory and real-world conditions. This dimension includes sensitivity, specificity, and accuracy, limit of detection, response time, reproducibility, portability, and ease of use.

A technologically ready biosensor should be able to produce reliable diagnostic results with minimal sample volume and limited technical complexity. It should also be suitable for point-of-care use, especially in settings where laboratory infrastructure is weak.

Electrochemical biosensors, paper-based biosensors, nanomaterial-enhanced biosensors, and smartphone-integrated biosensors are particularly relevant under this dimension because they offer possibilities for low-cost, rapid, and decentralized testing.

Technological readiness is important because financial sustainability cannot be achieved if the diagnostic tool is unreliable. False-negative results may delay treatment and increase disease transmission, while false-positive results may lead to unnecessary treatment and resource wastage. Therefore, technical performance remains the foundation of the framework.

Financial Readiness

Financial readiness refers to the economic feasibility of developing, producing, deploying, and maintaining biosensor-based diagnostic systems. This dimension evaluates whether the biosensor can reduce the cost of infectious disease diagnosis and contribute to long-term healthcare savings.

Financial readiness includes cost per test, manufacturing cost, operational cost, maintenance cost, affordability for patients, scalability for public healthcare systems, and potential return on investment. It also considers whether the biosensor can reduce downstream costs such as hospitalization, repeated testing, delayed treatment, and outbreak management.

A financially ready biosensor should be affordable for large-scale use in public health systems and low-resource settings. It should reduce dependence on expensive laboratory

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equipment and minimize the need for highly specialized personnel. The financial value of biosensors should therefore be measured not only by the cost of the device but also by their ability to prevent expensive medical interventions through early detection.

Environmental Readiness

Environmental readiness refers to the extent to which biosensor-based diagnostics support environmentally sustainable healthcare. This dimension is important because healthcare systems generate significant environmental burdens through energy use, reagent consumption, plastic waste, chemical waste, sample transportation, and biomedical waste.

Environmentally ready biosensors should reduce laboratory resource consumption, minimize energy requirements, lower reagent use, and reduce sample transportation. Paper-based biosensors, biodegradable materials, recyclable polymers, low-power electronics, and miniaturized diagnostic platforms are especially relevant to this dimension.

This dimension connects biosensor innovation with green healthcare and green finance. If biosensor technologies can reduce environmental impact while improving healthcare access, they become more attractive for sustainability-oriented funding, ESG investment, and public health innovation programs. Environmental readiness therefore strengthens the connection between healthcare innovation and sustainable development.

Digital Readiness

Digital readiness refers to the ability of biosensor systems to connect with digital health infrastructure. Modern healthcare systems increasingly depend on digital reporting, electronic health records, telemedicine, cloud platforms, mobile applications, and real-time surveillance systems. A biosensor that produces diagnostic results but cannot share, store, or integrate data may have limited public health value.

Digital readiness includes smartphone compatibility, cloud-based data storage, electronic health record integration, real-time reporting, AI-assisted result interpretation, and disease surveillance capability. It also includes the ability to collect diagnostic data from multiple locations and support public health authorities in identifying disease trends and outbreak signals.

AI-enabled biosensors can strengthen digital readiness by improving diagnostic classification, reducing human interpretation error, and supporting predictive disease surveillance. Machine learning models can be used to analyze biosensor signals, classify infection status, and support clinical decision-making. Therefore, digital readiness transforms biosensors from isolated diagnostic devices into connected healthcare tools.

Governance and Compliance Readiness

Governance and compliance readiness refers to the ethical, regulatory, legal, and institutional suitability of biosensor-based diagnostic systems. Since biosensors are medical diagnostic tools, they must meet quality, safety, accuracy, and regulatory standards before they can be used in clinical practice.

This dimension includes medical device regulation, clinical validation, ethical approval, informed consent, patient data privacy, cybersecurity, quality assurance, standard operating procedures, and alignment with public health policies. It also considers whether the biosensor system supports transparency, accountability, and responsible healthcare innovation.

Governance readiness is especially important for AI-enabled and digitally connected biosensors because patient data must be protected. Diagnostic data should be anonymized, securely stored, and transmitted through safe digital systems. If governance and compliance issues are ignored, even technically strong biosensors may face barriers to adoption. Therefore, this dimension ensures that biosensor implementation is safe, ethical, and institutionally acceptable.

Supply-Chain Readiness

Supply-chain readiness refers to the availability of materials, manufacturing systems, distribution networks, and maintenance support required for large-scale biosensor deployment. Many biosensor prototypes perform well in research settings but fail to reach healthcare systems because they lack scalable production and reliable distribution mechanisms.

This dimension includes availability of raw materials, local manufacturing capacity, quality control, packaging, storage stability, transportability, supply of consumables, device maintenance, and partnerships with healthcare providers, manufacturers, and distributors. It also considers whether the biosensor can be produced at scale without compromising quality.

Supply-chain readiness is particularly important for low-resource settings because diagnostic tools must be consistently available at the point of care. A biosensor cannot support healthcare financial sustainability if test strips, cartridges, batteries, reagents, or replacement components are unavailable. Therefore, supply-chain readiness ensures that biosensor solutions can move from laboratory innovation to practical healthcare implementation.

Proposed Conceptual Model

The proposed conceptual model can be presented as follows:

Input:

High infectious disease burden, diagnostic delay, rising healthcare expenditure, limited laboratory access, and need for decentralized testing.

Intervention:

Affordable infectious disease biosensor solutions for rapid point-of-care diagnosis.

Readiness Dimensions:

Technological readiness, financial readiness, environmental readiness, digital readiness, governance and compliance readiness, and supply-chain readiness.

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Mediating Mechanisms:

Early detection, faster treatment initiation, reduced diagnostic delay, improved surveillance, reduced hospitalization, reduced laboratory dependence, and better resource allocation.

Outcome:

Financially sustainable healthcare through lower diagnostic and treatment costs, improved access, reduced disease transmission, environmental efficiency, and scalable public health response.

Table 1: Conceptual Framework Table

Framework Dimension	Meaning in the Study	Key Indicators	Contribution to Financial Sustainability
Technological Readiness	Technical maturity and diagnostic reliability of the biosensor	Sensitivity, specificity, accuracy, response time, portability, reproducibility	Prevents misdiagnosis, supports early treatment, and reduces unnecessary clinical costs
Financial Readiness	Economic feasibility and affordability of biosensor adoption	Cost per test, production cost, operational cost, scalability, return on investment	Reduces diagnostic expenditure, hospitalization cost, and outbreak management cost
Environmental Readiness	Sustainability of diagnostic materials, processes, and waste management	Low reagent use, low energy use, biodegradable materials, reduced transportation, lower waste	Supports green healthcare and reduces environmental cost of diagnostics
Digital Readiness	Ability to connect biosensors with digital health systems	Smartphone integration, cloud reporting, EHR compatibility, AI interpretation, real-time surveillance	Improves decision-making, disease monitoring, and efficient resource allocation
Governance and Compliance Readiness	Ethical, legal, regulatory, and institutional suitability	Regulatory approval, quality assurance, data privacy, cybersecurity, ethical compliance	Builds trust, supports clinical adoption, and reduces risk of implementation failure
Supply-Chain Readiness	Capacity for large-scale production, distribution, and maintenance	Material availability, local manufacturing, quality control, storage, distribution networks	Ensures continuous availability and supports scalable low-cost deployment

Expected Contribution of the Framework

The proposed conceptual framework contributes to the literature by shifting the discussion from biosensor development alone to biosensor implementation for financially sustainable healthcare. Existing studies often focus on technical performance, but this framework expands the evaluation by including affordability, environmental sustainability, digital integration, governance, and supply-chain feasibility. This broader perspective is important because healthcare systems require diagnostic solutions that are not only accurate but also affordable, scalable, ethical, environmentally responsible, and operationally practical.

The framework also provides a foundation for developing a Green Finance Readiness Index for biosensor-based healthcare innovation. By assessing financial, environmental, technological, digital, governance, and supply-chain readiness, policymakers, researchers, healthcare administrators, and investors can evaluate whether a biosensor solution is suitable for sustainable financing and large-scale deployment.

Overall, the framework suggests that affordable infectious disease biosensors can support financially sustainable healthcare when they are developed and implemented through a multidimensional readiness approach. Such an approach can help healthcare systems reduce diagnostic delays, control infectious disease spread, lower treatment costs, improve surveillance, and promote sustainable healthcare innovation.

Green Finance Readiness Index for Biosensor-Based Healthcare Innovation

The Green Finance Readiness Index (GFRI) is proposed as a structured assessment tool for evaluating whether biosensor-based infectious disease diagnostic solutions are suitable for sustainable financing, ESG investment, and large-scale healthcare implementation. In the context of healthcare innovation, financial readiness alone is not sufficient. A diagnostic technology must also be environmentally responsible, technologically reliable, digitally compatible, ethically governed, and scalable through stable supply chains. Therefore, the GFRI provides a multidimensional framework for assessing the overall preparedness of affordable biosensor-based diagnostics for sustainable healthcare adoption.

Green finance refers to financial support for projects that generate environmental, social, and economic benefits. Within healthcare, green finance is increasingly relevant because the healthcare sector consumes substantial energy, uses chemical reagents and disposable materials, generates biomedical waste, and contributes to carbon emissions. Sustainable healthcare innovation therefore requires technologies that improve health outcomes while reducing environmental burden and supporting efficient resource use. Biosensor-based diagnostics are suitable for this discussion because they can potentially reduce laboratory dependence, minimize reagent consumption, lower energy use, reduce sample transportation, and support decentralized point-of-care testing.

The Green Finance Readiness Index proposed in this article evaluates biosensor-based healthcare innovation through six major dimensions: technological readiness, financial readiness, environmental readiness, digital readiness, governance and compliance readiness, and supply-chain readiness. These dimensions are selected because they collectively determine whether a biosensor solution can move from laboratory development to real-world healthcare implementation. A biosensor may be scientifically advanced, but if it is too costly, environmentally harmful, digitally disconnected, unregulated, or difficult to manufacture, it may not be suitable for sustainable financing or large-scale adoption.

Purpose of the Green Finance Readiness Index

The main purpose of the GFRI is to provide a systematic method for assessing the sustainability and implementation potential of

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biosensor-based diagnostic solutions. It can be used by researchers, healthcare administrators, policymakers, medical device manufacturers, funding agencies, and ESG investors to determine whether a biosensor project is ready for sustainable healthcare financing.

The index has four major purposes. First, it evaluates whether the biosensor technology is technically reliable and clinically useful. Second, it examines whether the solution is financially affordable and capable of reducing healthcare costs. Third, it assesses whether the technology supports environmental sustainability by reducing waste, emissions, and resource use. Fourth, it determines whether the biosensor can be practically implemented through digital integration, regulatory compliance, and supply-chain readiness.

In this way, the GFRI shifts the evaluation of biosensors from a narrow technical perspective to a broader sustainability-oriented perspective. Instead of asking only whether a biosensor can detect an infectious disease biomarker, the index asks whether the biosensor can be affordably produced, responsibly financed, safely regulated, digitally connected, environmentally sustainable, and widely deployed.

Dimensions of the Green Finance Readiness Index

Technological Readiness

Technological readiness refers to the scientific and diagnostic maturity of the biosensor system. This dimension evaluates whether the biosensor can produce accurate, reliable, reproducible, and timely results under laboratory and real-world conditions. Important indicators include sensitivity, specificity, accuracy, limit of detection, response time, portability, user-friendliness, sample compatibility, and stability.

This dimension is important because sustainable financing cannot be justified if the technology itself is unreliable. A biosensor with poor sensitivity may produce false-negative results, leading to delayed treatment and increased disease transmission. Similarly, poor specificity may produce false-positive results, resulting in unnecessary treatment, patient anxiety, and wastage of healthcare resources. Therefore, technological readiness forms the scientific foundation of the index.

Technologically ready biosensors should also be suitable for point-of-care testing. This means that they should be portable, rapid, simple to operate, and usable in primary healthcare centers, rural clinics, mobile diagnostic units, and community screening programs. Biosensors that meet these requirements are more likely to support decentralized diagnosis and reduce pressure on centralized laboratories.

Financial Readiness

Financial readiness evaluates the economic feasibility of biosensor-based diagnostic solutions. This dimension examines whether the biosensor can be produced, distributed, operated, and maintained at a cost that is acceptable for public health systems, private healthcare providers, and low-resource communities.

Key indicators of financial readiness include cost per test, device production cost, maintenance cost, training cost, manufacturing scalability, affordability for patients, cost savings from early diagnosis, and return on investment. A financially ready biosensor should not only be cheaper than conventional laboratory testing but should also reduce downstream healthcare costs by preventing complications, reducing hospitalization, and limiting outbreak-related expenditure.

Financial readiness is central to the article because the main argument is that affordable infectious disease biosensors can support financially sustainable healthcare. If early diagnosis prevents severe disease progression, then the healthcare system may save costs on hospitalization, intensive care, prolonged medication, and emergency outbreak management. Therefore, the economic value of biosensors should be assessed across the full healthcare pathway rather than only through the initial cost of the device.

Environmental Readiness

Environmental readiness refers to the ability of biosensor-based diagnostics to reduce environmental burden and support green healthcare practices. Conventional diagnostic systems often require large laboratory facilities, electricity, refrigeration, sample transportation, chemical reagents, plastic consumables, and biomedical waste disposal. These processes can increase the environmental footprint of healthcare delivery.

Biosensors can improve environmental readiness by reducing reagent use, requiring lower energy, minimizing sample transportation, and using biodegradable or recyclable materials. Paper-based biosensors, miniaturized electrochemical sensors, low-power devices, and disposable biodegradable platforms are especially relevant in this dimension.

Environmental readiness is also important for attracting green finance and ESG investment. Funding agencies and sustainability-focused investors increasingly prefer innovations that demonstrate measurable environmental benefits. A biosensor solution that reduces waste, energy consumption, and transportation-related emissions may therefore be more suitable for green healthcare financing. This dimension connects diagnostic innovation with climate-resilient and environmentally sustainable healthcare objectives.

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Digital Readiness

Digital readiness evaluates the ability of the biosensor system to integrate with digital health infrastructure. Modern healthcare systems increasingly depend on electronic health records, telemedicine, cloud-based platforms, mobile applications, data dashboards, and real-time disease surveillance systems. A biosensor that can generate digital data and transmit results securely has greater value than a standalone device.

Indicators of digital readiness include smartphone compatibility, cloud reporting, artificial intelligence-based result interpretation, electronic health record integration, telemedicine support, real-time surveillance, data storage capacity, interoperability, and cybersecurity protection. Digital readiness allows biosensor results to be used not only for individual patient care but also for public health monitoring and outbreak response.

AI-enabled biosensors can improve diagnostic interpretation by analyzing complex electrochemical, optical, or image-based signals. Machine learning models can classify test results, reduce human interpretation errors, support predictive analytics, and assist healthcare providers in making faster clinical decisions. Therefore, digital readiness strengthens both clinical efficiency and public health preparedness.

Governance and Compliance Readiness

Governance and compliance readiness refers to the ethical, legal, regulatory, and institutional suitability of biosensor-based diagnostic solutions. Since biosensors are medical diagnostic devices, they must meet safety, accuracy, quality, and regulatory requirements before clinical adoption.

Key indicators include institutional ethics approval, informed consent procedures, clinical validation, medical device regulatory compliance, quality assurance protocols, standard operating procedures, patient data protection, cybersecurity safeguards, and alignment with public health policies. This dimension is particularly important when biosensors are integrated with digital systems and AI models because diagnostic data must be handled responsibly.

Governance readiness builds trust among healthcare providers, patients, regulators, and investors. Without proper governance, even an affordable and technically effective biosensor may face barriers to adoption. Regulatory uncertainty, weak quality control, poor data protection, or lack of ethical oversight can reduce confidence in the technology. Therefore, governance and compliance readiness are essential for responsible healthcare innovation.

Supply-Chain Readiness

Supply-chain readiness evaluates whether the biosensor solution can be manufactured, distributed, stored, and maintained at scale. Many biosensor prototypes remain at the laboratory stage because researchers do not fully address production systems, raw material availability, packaging, distribution, quality control, and maintenance requirements.

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Total	100%

Key indicators include availability of raw materials, local manufacturing capacity, cost-effective mass production, stable storage conditions, quality assurance, packaging, distribution networks, supply of consumables, device maintenance, and partnerships with healthcare providers and manufacturers. A supply-chain-ready biosensor should be capable of reaching healthcare facilities consistently and affordably.

This dimension is especially important for low-resource settings. If biosensor cartridges, test strips, batteries, reagents, or replacement components are not available when needed, the diagnostic system cannot support healthcare sustainability. Therefore, supply-chain readiness ensures continuity, scalability, and reliability of biosensor-based healthcare delivery.

5.3 Proposed Weightage for the Green Finance Readiness Index

The Green Finance Readiness Index can be developed using weighted scores assigned to each of the six dimensions. The proposed weightage reflects the relative importance of each dimension for sustainable financing and healthcare implementation.

Table 2: Proposed Weightage for the Green Finance Readiness Index

Dimension	Proposed Weightage
Financial Readiness	20%
Environmental Readiness	20%
Technological Readiness	20%
Digital Readiness	15%
Governance and Compliance Readiness	15%
Supply-Chain Readiness	10%

The equal weightage assigned to financial, environmental, and technological readiness reflects their central role in the proposed framework. A biosensor must be affordable, environmentally responsible, and scientifically reliable to qualify as a sustainable healthcare innovation. Digital readiness and governance readiness are also highly important because modern healthcare implementation requires secure data systems, AI integration, ethical oversight, and regulatory compliance. Supply-chain readiness is assigned a lower but still significant weight because scalability depends on production and distribution capacity.

The GFRI may be calculated using the following formula:

$$\mathbf{GFRI = (FR \times 0.20) + (ER \times 0.20) + (TR \times 0.20) + (DR \times 0.15) + (GCR \times 0.15) + (SCR \times 0.10)}$$

Where:
FR = Financial Readiness
ER = Environmental Readiness
TR = Technological Readiness
DR = Digital Readiness
GCR = Governance and Compliance Readiness
SCR = Supply-Chain Readiness

Each dimension can be scored on a scale of 1 to 5, where 1 indicates very low readiness and 5 indicates very high readiness. The weighted score provides an overall readiness value that can be used to classify the biosensor solution.

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Table 3: Suggested Readiness Classification

GFRI Score	Readiness Level	Interpretation
1.00–1.80	Very Low Readiness	The biosensor is not suitable for sustainable financing or large-scale implementation.
1.81–2.60	Low Readiness	The biosensor requires major improvement before adoption.
2.61–3.40	Moderate Readiness	The biosensor shows potential but needs further validation and development.
3.41–4.20	High Readiness	The biosensor is suitable for pilot implementation and possible sustainable financing.
4.21–5.00	Very High Readiness	The biosensor is highly suitable for ESG investment, green finance, and large-scale healthcare deployment.

This classification helps decision-makers understand the maturity of a biosensor solution in a simple and practical way. For example, a biosensor with high technological readiness but low supply-chain readiness may be scientifically strong but not yet ready for large-scale deployment. Similarly, a biosensor with good environmental readiness but weak governance readiness may require regulatory and ethical strengthening before implementation.

Relevance of the GFRI to Sustainable Financing and ESG Investment

The Green Finance Readiness Index is relevant to sustainable financing because it provides measurable indicators for evaluating the environmental, social, and economic value of biosensor-based healthcare innovation. ESG investors and green finance institutions require evidence that a project contributes to sustainability objectives. The GFRI helps provide this evidence by showing how biosensor diagnostics can reduce healthcare costs, improve access, reduce environmental burden, support digital health systems, and comply with governance standards.

From an environmental perspective, the GFRI captures reductions in reagent use, waste generation, energy consumption, and sample transportation. From a social perspective, it evaluates whether biosensors improve access to diagnostics for rural, underserved, and low-income populations. From a governance perspective, it assesses whether the system protects patient data, follows ethical standards, and meets regulatory requirements. From an economic perspective, it examines affordability, scalability, and healthcare cost savings.

Thus, the GFRI can help position affordable infectious disease biosensors as investable healthcare innovations. It can support funding applications, policy evaluation, pilot project selection, public-private partnerships, and technology commercialization. It also helps bridge the gap between scientific research and sustainable healthcare implementation.

Overall Significance of the Index

The proposed Green Finance Readiness Index adds value to the literature by connecting biosensor innovation with sustainable healthcare financing. Existing biosensor studies often focus mainly on diagnostic performance, while fewer studies examine whether the technology is financially, environmentally, digitally, and institutionally ready for real-world use. The GFRI addresses this limitation by offering a structured tool for multidimensional evaluation.

The index also strengthens the practical relevance of affordable infectious disease biosensors. By identifying readiness gaps, the GFRI can guide researchers, policymakers, and investors in improving biosensor design, reducing costs, strengthening regulatory compliance, enhancing digital integration, and preparing scalable manufacturing strategies. Therefore, the index supports a transition from laboratory innovation to sustainable healthcare deployment.

In summary, the Green Finance Readiness Index provides a systematic framework for assessing whether biosensor-based diagnostic solutions are suitable for green finance, ESG investment, and large-scale healthcare implementation. By integrating financial, environmental, technological, digital, governance, and supply-chain dimensions, the GFRI supports the broader goal of developing infectious disease diagnostic technologies that are clinically useful, economically viable, environmentally sustainable, and socially accessible.

AI-Enabled Diagnostic Decision Support Model

Artificial intelligence (AI) can play an important role in improving the performance, interpretation, and practical usefulness of biosensor-based infectious disease diagnostics. While biosensors generate measurable signals in response to biological interactions, the interpretation of these signals may be affected by noise, weak signal intensity, environmental variation, sample quality, and operator-dependent judgment. AI-enabled diagnostic decision support can address these challenges by processing biosensor signals, identifying meaningful patterns, classifying diagnostic results, reducing human error, and supporting faster clinical decision-making.

In the proposed framework, AI is not treated as a replacement for clinical expertise. Instead, it functions as a decision-support layer that improves the reliability, speed, and scalability of biosensor-based diagnosis. The biosensor detects infectious disease biomarkers such as antigens, antibodies, nucleic acids, or pathogen-specific molecules. The raw signal generated by the biosensor is then processed using AI or machine learning algorithms. These algorithms can classify the test result as positive, negative, borderline, or requiring confirmatory testing. This process can improve the consistency of diagnostic interpretation and reduce dependence on manual reading.

Role of AI in Biosensor Signal Interpretation

Biosensor signals may be electrochemical, optical, colorimetric, fluorescence-based, image-based, or time-series signals. In many cases, these signals are complex and require careful interpretation. For example, electrochemical biosensors may produce current or voltage responses that vary according to biomarker concentration. Optical biosensors may generate changes in color intensity, fluorescence, or absorbance. Smartphone-based biosensors may produce image data that need digital analysis.

AI can assist in extracting useful information from these signals. Signal-processing methods can remove noise, correct background interference, normalize readings, and identify signal patterns associated with infection. Machine learning models can learn the relationship between biosensor output and clinical reference results such as PCR, ELISA, or standard rapid diagnostic tests. Once trained, the model can classify new biosensor readings and support rapid diagnosis at the point of care.

This is particularly useful when the signal is weak, borderline, or affected by external conditions. AI can improve interpretation by comparing the input signal with patterns learned from previous validated samples. As a result, AI can reduce subjectivity in result interpretation and improve the reliability of biosensor-based diagnostics.

Diagnostic Classification and Prediction

The main function of the AI-enabled decision support model is to classify diagnostic results. The model can be trained using labeled datasets that include biosensor signals and confirmed diagnostic outcomes. For infectious disease diagnosis, the output may be classified into categories such as infected, not infected, low-risk, high-risk, or inconclusive.

Several machine learning and deep learning models can be used for this purpose. Logistic Regression can be used as a baseline classification model because it is simple, interpretable, and useful for binary diagnostic outcomes. Support Vector Machine (SVM) is suitable for separating complex diagnostic classes, especially when the dataset contains high-dimensional signal features. Random Forest can handle nonlinear relationships and improve prediction robustness by combining multiple decision trees. XGBoost can further improve classification accuracy through gradient boosting and is useful when dealing with structured biosensor datasets.

Artificial Neural Networks (ANNs) can model complex nonlinear relationships between biosensor signals and infection status. Convolutional Neural Networks (CNNs) are especially useful when the biosensor produces image-based outputs, such as colorimetric strips, fluorescence images, microscopy images, or smartphone-captured test results. CNNs can automatically extract image features such as color intensity, texture, shape, and spatial patterns. These models can

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improve diagnostic accuracy when traditional manual interpretation is difficult.

Proposed AI Model Workflow

The proposed AI-enabled diagnostic decision support model can follow a structured workflow:

Step 1: Data Collection

Data are collected from the biosensor platform and matched with reference diagnostic results. These data may include electrochemical signals, optical readings, smartphone images, biomarker concentration values, patient demographic variables, clinical symptoms, and PCR or ELISA results.

Step 2: Data Preprocessing

The collected data are cleaned and prepared for analysis. This includes noise removal, signal smoothing, normalization, missing value handling, background correction, and conversion of raw biosensor output into machine-readable formats.

Step 3: Feature Extraction

Important features are extracted from the biosensor signals. These may include peak current, voltage change, signal intensity, fluorescence value, absorbance level, color density, reaction time, signal-to-noise ratio, and image-based features.

Step 4: Model Training

Machine learning models are trained using labeled datasets. The dataset is divided into training, validation, and testing subsets. During training, the model learns how biosensor signal patterns correspond to diagnostic outcomes.

Step 5: Model Validation

The trained model is evaluated using diagnostic performance metrics such as accuracy, sensitivity, specificity, precision, recall, F1-score, area under the ROC curve, positive predictive value, and negative predictive value. These metrics help determine whether the model is clinically useful.

Step 6: Decision Support Output

The model generates a diagnostic recommendation, such as positive, negative, borderline, or repeat test required. The result can be displayed through a smartphone application, portable reader, or cloud-based dashboard.

Step 7: Disease Surveillance Integration

When connected to digital health platforms, the diagnostic results can be securely transmitted to healthcare providers and public health authorities. Aggregated results can support real-time surveillance, outbreak detection, and resource planning.

6.4 Possible AI and Machine Learning Models

The following models are suitable for the proposed AI-enabled biosensor decision support system:

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Table 4: AI-enabled biosensor decision support system

Model	Possible Use in Biosensor Diagnosis	Key Strength
Logistic Regression	Binary classification of positive and negative results	Simple, interpretable, useful as a baseline model
Support Vector Machine	Classification of complex biosensor signal patterns	Effective for high-dimensional data
Random Forest	Classification using multiple signal and clinical features	Robust, handles nonlinear relationships
XGBoost	High-performance classification and prediction	Strong accuracy and feature importance analysis
Artificial Neural Network	Learning nonlinear relationships in biosensor data	Useful for complex signal interpretation
Convolutional Neural Network	Analysis of image-based biosensor outputs	Suitable for smartphone images and colorimetric tests

These models can be compared during the development phase to identify the most accurate and clinically appropriate algorithm. For example, Logistic Regression may be selected if interpretability is a priority, while XGBoost or Random Forest may be preferred when accuracy and feature importance are important. CNNs may be selected when the biosensor output is image-based.

Reducing Human Error and Improving Prediction Accuracy

Manual interpretation of biosensor results may be affected by visual judgment, operator skill, lighting conditions, device handling, and subjective reading of borderline results. AI can reduce these errors by providing standardized and automated interpretation. For example, in smartphone-based biosensors, AI can analyze image intensity more consistently than the human eye. In electrochemical biosensors, machine learning can detect subtle signal differences that may not be easily recognized through manual analysis.

AI can also improve prediction accuracy by learning from large datasets. As more validated biosensor results are collected, the model can be retrained and improved. This continuous learning process can help refine diagnostic thresholds, reduce false positives and false negatives, and improve performance across different patient groups and healthcare settings. However, the model must be validated carefully to avoid overfitting and algorithmic bias.

Real-Time Disease Surveillance

AI-enabled biosensors can contribute not only to individual diagnosis but also to public health surveillance. When biosensor results are digitally connected, they can be collected from multiple healthcare locations in real time. AI models can analyze these data to identify unusual increases in infection rates, detect geographical clusters, and provide early warning of potential outbreaks.

This surveillance function is particularly important for diseases such as dengue, malaria, influenza, tuberculosis, COVID-19, and other emerging infections. Real-time diagnostic data can help public health authorities allocate resources, plan testing campaigns, identify high-risk areas, and respond faster to outbreaks. Therefore, AI-enabled biosensors can support both clinical decision-making and population-level disease management.

Ethical, Regulatory, and Data Governance Considerations

The use of AI in diagnostic decision support must be guided by ethical and regulatory safeguards. Patient data must be anonymized, securely stored, and protected from unauthorized access. AI models should be transparent, explainable where possible, and validated across diverse populations. Data privacy, cybersecurity, informed consent, and clinical accountability are essential for responsible implementation.

AI-based diagnostic recommendations should support, not replace, professional medical judgment. In cases where the model produces borderline or uncertain results, confirmatory testing through standard diagnostic methods such as PCR or ELISA may still be required. Therefore, the AI-enabled model should be used as part of a broader diagnostic workflow rather than as an isolated decision-maker.

Contribution of the AI-Enabled Model to Financial Sustainability

The AI-enabled decision support model contributes to financial sustainability in several ways. First, it improves the speed and accuracy of diagnosis, allowing timely treatment and reducing complications. Second, it reduces human interpretation errors, which can prevent unnecessary treatment, repeated testing, and delayed intervention. Third, it supports decentralized testing by enabling minimally trained healthcare workers to use biosensor devices with automated interpretation support. Fourth, it strengthens disease surveillance, allowing public health systems to detect outbreaks early and allocate resources more efficiently.

By improving diagnostic reliability and supporting real-time healthcare decision-making, AI-enabled biosensors can reduce avoidable healthcare expenditure and improve the cost-effectiveness of infectious disease management. In this way, AI strengthens the overall value of affordable biosensor solutions as tools for financially sustainable, digitally connected, and accessible healthcare delivery.

Discussion

The proposed framework highlights the potential of affordable infectious disease biosensors to support financially sustainable healthcare by improving early diagnosis, reducing treatment costs, strengthening public

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health surveillance, and promoting environmentally responsible diagnostic practices. Infectious disease management depends heavily on timely and accurate detection. When diagnosis is delayed, patients are more likely to experience disease progression, complications, hospitalization, and continued transmission within communities. The proposed framework addresses this problem by positioning affordable biosensor-based diagnostics as a decentralized and rapid testing solution that can be used closer to patients.

One of the most important contributions of the framework is its emphasis on early disease detection. Conventional diagnostic approaches such as polymerase chain reaction, enzyme-linked immunosorbent assay, and microbial culture are clinically valuable but often require centralized laboratory facilities, trained personnel, and longer processing time. These limitations can delay treatment decisions, especially in rural and low-resource settings. Biosensors, by contrast, can be designed for point-of-care testing and can provide rapid diagnostic information at primary health centers, community clinics, mobile health units, and field screening locations. Early detection allows healthcare providers to begin treatment sooner, reduce complications, and prevent the progression of mild infections into severe disease.

The framework also contributes to reduced diagnostic costs. Traditional diagnostic systems often involve high costs related to laboratory infrastructure, equipment, reagents, sample transportation, skilled personnel, and repeated patient visits. Affordable biosensors can reduce some of these costs by using miniaturized platforms, paper-based materials, low-power electronics, smaller sample volumes, and simplified testing procedures. From a healthcare financing perspective, the economic value of biosensors should not be measured only by the cost per test. Their broader value lies in reducing downstream expenditure by preventing delayed treatment, unnecessary hospitalization, wider transmission, and outbreak-related emergency spending.

Reduced hospitalization is another major contribution of the proposed framework. When infectious diseases are diagnosed early, patients can receive timely treatment before the condition becomes severe. This can reduce the need for prolonged hospital admission, intensive care, advanced medication, and emergency interventions. In public healthcare systems, hospitalization is one of the most expensive components of infectious disease management. Therefore, even moderate reductions in hospital admissions can produce meaningful savings for healthcare systems. The proposed framework shows that biosensors can contribute to financial sustainability by shifting healthcare response from late-stage treatment to early-stage detection and intervention.

The framework further improves healthcare accessibility. Many underserved communities face barriers such as distance from laboratories, transportation costs, shortage of trained technicians, and limited diagnostic infrastructure. Biosensor-based point-of-care testing can reduce these barriers by bringing diagnostic services closer to patients. This is particularly relevant for rural areas, low-income communities, and regions with weak laboratory networks. By supporting decentralized testing, biosensors can reduce diagnostic inequality and improve access to essential healthcare services. This aligns with the broader goal of universal health coverage, which emphasizes access to necessary health services without financial hardship.

Another important contribution is improved outbreak surveillance. Infectious disease outbreaks require rapid detection, reporting, and response. Conventional centralized testing systems may become overloaded during outbreaks, leading to delayed results and slower public health action. The proposed framework integrates biosensors with digital health and AI-enabled decision support, allowing diagnostic results to be collected, analyzed, and reported in real time. When biosensor data are connected to cloud platforms, electronic health records, or public health dashboards, healthcare authorities can identify disease clusters, monitor transmission patterns, and allocate resources more effectively. This surveillance function increases the value of biosensors beyond individual diagnosis and positions them as tools for population-level disease management.

The environmental sustainability contribution of the framework is also significant. Conventional laboratory diagnostics may involve high electricity use, chemical reagents, plastic consumables, cold-chain systems, sample transportation, and biomedical waste generation. Biosensor-based diagnostics can reduce environmental burden by using smaller sample volumes, fewer reagents, low-power devices, biodegradable materials, and decentralized testing models that reduce sample transportation. This environmental advantage strengthens the relevance of biosensors for green healthcare innovation. By integrating environmental readiness into the framework, the article shows that diagnostic technologies should be evaluated not only for clinical performance but also for their contribution to sustainable healthcare systems.

The framework also supports universal health coverage by linking affordability, accessibility, and early diagnosis. Universal health coverage cannot be achieved without accessible diagnostics because treatment decisions depend on accurate disease identification. Affordable biosensors can reduce out-of-pocket expenditure by lowering travel costs, minimizing repeated visits, and enabling faster treatment decisions. They can also support public health programs by providing low-cost screening tools for high-burden diseases. Therefore, biosensor-based diagnostics can contribute to both financial protection and equitable access to healthcare.

Compared with existing diagnostic approaches, the proposed framework offers a broader and more integrated perspective. Conventional methods such as PCR, ELISA,

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and microbial culture remain important because of their accuracy, reliability, and clinical acceptance. However, they are often expensive, time-consuming, infrastructure-dependent, and less accessible in low-resource settings. Rapid diagnostic tests are more accessible but may face limitations in sensitivity, specificity, and quantitative interpretation. Biosensors can bridge some of these gaps by offering rapid, portable, and potentially low-cost testing with opportunities for digital integration and AI-supported interpretation.

The proposed framework differs from existing diagnostic approaches because it does not evaluate biosensors only as technical devices. Instead, it evaluates them as healthcare sustainability tools. The six readiness dimensions, namely technological readiness, financial readiness, environmental readiness, digital readiness, governance and compliance readiness, and supply-chain readiness, provide a multidimensional basis for assessing whether a biosensor can move from laboratory development to real-world implementation. This is important because many biosensor studies focus primarily on sensitivity, specificity, and detection limits, while giving less attention to affordability, manufacturing scalability, regulatory compliance, environmental impact, and healthcare financing.

The inclusion of the Green Finance Readiness Index further strengthens the framework. It provides a structured method for determining whether biosensor-based healthcare innovations are suitable for sustainable financing, ESG investment, and large-scale implementation. This is particularly important because healthcare systems need technologies that are not only scientifically effective but also economically viable and environmentally responsible. By connecting biosensor diagnostics with green finance readiness, the framework creates a bridge between biomedical innovation, healthcare economics, and sustainability policy.

The AI-enabled decision support component also adds value when compared with conventional diagnostic systems. Manual interpretation of diagnostic results can be affected by operator skill, subjective judgment, lighting conditions, and borderline readings. AI models can assist in signal processing, classification, prediction, and automated interpretation. Models such as Logistic Regression, Support Vector Machine, Random Forest, XGBoost, Artificial Neural Networks, and Convolutional Neural Networks can support diagnostic classification and improve prediction accuracy when trained on validated biosensor datasets. This can reduce human error and support consistent interpretation across different healthcare settings.

However, the framework also recognizes that biosensor-based diagnostics cannot fully replace conventional laboratory systems. Confirmatory testing may still be required in complex cases, regulatory approval remains essential, and clinical validation is necessary before large-scale deployment. The framework should therefore be understood as a complementary model

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rather than a complete replacement for existing diagnostics. Biosensors can serve as first-line, point-of-care, screening, and surveillance tools, while centralized laboratories can continue to provide confirmatory testing, advanced analysis, and quality assurance.

Overall, the proposed framework contributes to the literature by shifting the focus from biosensor development alone to biosensor implementation for financially sustainable healthcare. It shows that affordable infectious disease biosensors can support early detection, reduce healthcare expenditure, minimize hospitalization, improve diagnostic access, strengthen outbreak surveillance, promote environmental sustainability, and support universal health coverage. By integrating technological, financial, environmental, digital, governance, and supply-chain dimensions, the framework provides a practical pathway for transforming biosensor innovation into sustainable healthcare impact.

Practical and Policy Implications

The proposed framework has important practical and policy implications for healthcare providers, public health authorities, technology developers, policymakers, and green finance institutions. By linking affordable infectious disease biosensors with financial sustainability, digital readiness, environmental responsibility, and governance compliance, the framework provides a practical pathway for improving diagnostic access while reducing the economic burden of infectious disease management. The framework is particularly useful for healthcare systems that face high infectious disease burdens, limited laboratory infrastructure, and constrained public health budgets.

Implications for Primary Healthcare Centers

Primary healthcare centers can benefit significantly from affordable biosensor-based diagnostic solutions. In many healthcare systems, primary healthcare centers serve as the first point of contact for patients with infectious disease symptoms. However, these centers often lack advanced laboratory facilities and may depend on referral systems for diagnostic confirmation. This can delay treatment and increase patient movement between healthcare facilities.

The proposed framework supports primary healthcare centers by enabling rapid point-of-care testing. Biosensors can allow healthcare workers to screen patients at the primary care level and make faster decisions regarding treatment, referral, isolation, or confirmatory testing. This can reduce unnecessary referrals to higher-level hospitals, improve patient management, and reduce the burden on tertiary healthcare facilities. In addition, AI-enabled interpretation can support healthcare workers by reducing manual reading errors and improving diagnostic confidence.

For primary healthcare centers, the framework also encourages practical readiness assessment before adopting biosensor solutions. Decision-makers can evaluate whether the biosensor is affordable, easy to

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operate, digitally compatible, clinically reliable, and supported by a stable supply chain. This prevents the adoption of technologies that appear promising but are not suitable for routine primary care use.

Implications for Rural Clinics and Low-Resource Settings

The framework is especially relevant for rural clinics and low-resource healthcare settings, where diagnostic access is often limited by distance, cost, infrastructure, and shortage of trained personnel. Rural patients may need to travel long distances to access laboratory testing, which increases out-of-pocket costs and delays treatment. Affordable biosensor-based diagnostics can reduce this barrier by bringing testing closer to patients.
Biosensors designed for rural clinics should be portable, low-cost, easy to use, stable under field conditions, and capable of functioning with minimal infrastructure. Paper-based biosensors, electrochemical biosensors, and smartphone-integrated biosensors are particularly suitable for these settings because they can reduce dependence on centralized laboratories. The framework also highlights the need for training, standard operating procedures, quality control, and supply-chain support to ensure reliable use in rural environments.

From a policy perspective, governments can use this framework to prioritize rural diagnostic strengthening. Biosensor deployment can be integrated into rural health missions, infectious disease control programs, school health programs, and community screening campaigns. This can improve equity in diagnostic access and support the broader objective of universal health coverage.

Implications for Mobile Diagnostic Units

Mobile diagnostic units can use the proposed framework to expand infectious disease testing in underserved, remote, and outbreak-affected areas. These units are particularly useful during health camps, emergency outbreaks, disaster response, and community-level screening programs. Affordable biosensors can enhance the effectiveness of mobile units by enabling rapid testing without requiring fully equipped laboratories.

The framework supports mobile diagnostic units in three ways. First, it promotes portability and rapid result generation. Second, it encourages digital readiness through smartphone-based reporting and cloud connectivity. Third, it supports real-time surveillance by allowing test results to be transmitted to public health authorities. This can help identify disease clusters, monitor local outbreaks, and guide targeted intervention.

For successful implementation, mobile diagnostic units require biosensors with strong field stability, simple sample handling, low power requirements, and reliable consumable supply. The supply-chain readiness dimension of the framework is therefore essential for ensuring that mobile testing programs remain functional and scalable.

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Implications for Public Health Surveillance Systems

The framework has strong implications for public health surveillance. Infectious disease control depends on timely reporting, early detection of clusters, and rapid response to outbreaks. Traditional surveillance systems may suffer from delays because diagnostic results are often generated in centralized laboratories and reported through multiple administrative layers.

Biosensor-based diagnostics, when integrated with digital platforms, can support real-time or near-real-time disease surveillance. Smartphone-connected biosensors and AI-enabled reporting systems can transmit diagnostic results directly to public health databases. This can help public health authorities monitor disease trends, detect unusual increases in cases, identify geographical hotspots, and allocate resources more efficiently.

The AI-enabled decision support component can further strengthen surveillance by identifying patterns that may not be visible through manual reporting. For example, aggregated biosensor data can help detect early signs of dengue, malaria, influenza, tuberculosis, COVID-19, or other infectious disease outbreaks. This supports faster intervention and reduces the social and economic costs of uncontrolled disease spread.

Implications for Government Healthcare Programs

Government healthcare programs can use the proposed framework as a decision-support tool for evaluating and selecting diagnostic technologies. Public health systems often need to balance cost, accuracy, accessibility, scalability, and sustainability. The six readiness dimensions provide a structured way to assess whether biosensor-based solutions are appropriate for public procurement, pilot testing, or national-level deployment.

The framework can support infectious disease control programs by identifying biosensor technologies that are suitable for screening, early detection, surveillance, and field deployment. It can also guide policy decisions related to diagnostic decentralization, rural health access, pandemic preparedness, and universal health coverage. By including financial and environmental readiness, the framework helps governments select technologies that reduce healthcare expenditure while supporting sustainable healthcare goals.

Government agencies can also use the Green Finance Readiness Index to evaluate whether biosensor projects qualify for sustainability-oriented funding. This is important because public healthcare investment increasingly needs to demonstrate not only clinical value but also financial efficiency, environmental responsibility, and social impact.

Implications for Medical Device Manufacturers

The framework provides practical guidance for medical device manufacturers developing biosensor-based diagnostic technologies. Many biosensor prototypes fail to move from laboratory research to market because they do not adequately address affordability, manufacturing scalability, regulatory requirements, usability, and distribution. The proposed framework helps manufacturers identify these requirements early in the product development process.

Manufacturers can use the technological readiness dimension to improve diagnostic accuracy, sensitivity, specificity, stability, and response time. Financial readiness can guide decisions related to material selection, cost per test, manufacturing efficiency, and pricing strategy. Environmental readiness can encourage the use of recyclable, biodegradable, low-waste, and low-energy design approaches. Digital readiness can support the development of smartphone-compatible readers, cloud reporting, and AI-assisted interpretation. Governance readiness can help manufacturers prepare for regulatory approval, clinical validation, data protection, and quality assurance.

The supply-chain readiness dimension is particularly important for commercialization. Manufacturers must ensure that raw materials, test cartridges, electrodes, reagents, packaging, and device components can be produced and distributed reliably at scale. By addressing these dimensions, manufacturers can develop biosensor products that are not only scientifically effective but also commercially viable and suitable for public health adoption.

Implications for Green Finance Institutions and ESG Investors

The proposed framework is also useful for green finance institutions, ESG investors, development banks, and healthcare innovation funds. These institutions increasingly seek projects that generate measurable environmental, social, and economic benefits. Biosensor-based diagnostics can be attractive for such financing because they can support early disease detection, reduce healthcare costs, improve access for underserved populations, and lower environmental burden.

The Green Finance Readiness Index provides investors with a structured tool to assess whether a biosensor project is suitable for sustainable financing. Financial readiness shows whether the project has cost-saving potential and scalable economic value. Environmental readiness shows whether the technology reduces energy use, reagent consumption, waste generation, and sample transportation. Social value is reflected through improved diagnostic access, rural healthcare support, and universal health coverage. Governance readiness demonstrates ethical compliance, data protection, regulatory alignment, and transparency.

Through this framework, green finance institutions can identify biosensor innovations that align with ESG principles and sustainable healthcare investment goals. The framework can also support funding decisions, project evaluation, impact reporting, and public-private partnerships.

Policy Recommendations

Based on the proposed framework, several policy recommendations can be made. First, governments should strengthen investment in affordable point-of-care diagnostics for infectious diseases, particularly in rural and underserved regions. Second, biosensor deployment should be integrated into national infectious disease control programs, primary healthcare systems, and public health surveillance networks. Third, regulatory agencies should establish clear approval pathways for biosensor-based diagnostics, including standards for clinical validation, quality assurance, and digital data security.

Fourth, healthcare policies should promote local manufacturing and supply-chain development for low-cost diagnostic devices. This can reduce dependence on imported technologies and improve availability during outbreaks. Fifth, public health agencies should encourage digital integration of biosensor results with electronic health records and disease surveillance platforms. Sixth, sustainability criteria should be included in diagnostic technology procurement, ensuring that selected technologies reduce environmental burden and support green healthcare.

Finally, green finance institutions and government funding bodies should develop financing mechanisms for sustainable healthcare technologies. Biosensor-based diagnostics that demonstrate financial, environmental, technological, digital, governance, and supply-chain readiness should be prioritized for grants, pilot programs, public-private partnerships, and ESG-linked investment.

Overall Practical Significance

Overall, the proposed framework provides a practical roadmap for moving affordable biosensor technologies from research laboratories into real healthcare systems. It supports primary healthcare centers by enabling rapid diagnosis, rural clinics by improving access, mobile diagnostic units by strengthening outreach, public health surveillance systems by enabling real-time reporting, government programs by guiding policy decisions, manufacturers by supporting scalable product development, and green finance institutions by providing an investment-readiness assessment tool.

The framework therefore has practical value beyond academic discussion. It can guide implementation, financing, regulation, manufacturing, and policy planning. By integrating affordability, technological reliability, environmental sustainability, digital connectivity, governance compliance, and supply-chain scalability, the framework supports the development of biosensor-based diagnostic solutions that are clinically useful, economically viable, socially accessible, and environmentally responsible.

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Limitations and Future Research

The proposed framework provides a useful way to understand how affordable infectious disease biosensors can support financially sustainable healthcare. However, this framework has some limitations. Since it is a conceptual framework, it has not yet been tested with real data. Therefore, future research is needed to confirm whether the proposed ideas work in real healthcare settings.

First, the framework needs empirical validation. The relationship between biosensor-based diagnosis, cost reduction, early disease detection, and healthcare financial sustainability should be tested using actual data. Without empirical testing, the framework can only be considered a proposed model.

Second, the biosensor system needs clinical testing. Future studies should test biosensors using real patient samples such as blood, saliva, nasal swabs, urine, or serum. The results should be compared with standard diagnostic methods such as PCR, ELISA, microbial culture, or approved rapid diagnostic tests. This will help confirm the accuracy, sensitivity, specificity, and reliability of the biosensor.

Third, large-scale clinical validation is required. Many biosensor studies are tested only in laboratories or with small sample sizes. Future research should test the biosensor in hospitals, primary healthcare centers, rural clinics, and mobile diagnostic units. This will show whether the biosensor works effectively in different healthcare conditions.

Fourth, cost-effectiveness needs to be evaluated. Although affordable biosensors are expected to reduce healthcare costs, this must be proven with real cost data. Future studies should compare biosensor-based diagnosis with conventional diagnostic methods in terms of cost per test, equipment cost, training cost, patient travel cost, treatment cost, and hospitalization cost.

Fifth, the Green Finance Readiness Index also needs validation. The six dimensions of the index, namely technological readiness, financial readiness, environmental readiness, digital readiness, governance and compliance readiness, and supply-chain readiness, should be tested using measurable indicators. Future studies can use expert validation, pilot testing, reliability analysis, and factor analysis to strengthen the index.

Sixth, regulatory approval is necessary before biosensor-based diagnostic systems can be used widely in clinical practice. Since biosensors are medical diagnostic devices, they must meet safety, quality, accuracy, and ethical standards. Future research should examine the regulatory requirements needed for approval and clinical use.

Seventh, field-level implementation studies are needed. A biosensor may work well in the laboratory, but its success in real healthcare settings depends on user training, device handling, storage conditions, sample collection, internet connectivity, availability of consumables, and patient acceptance. Therefore, future studies should test biosensors in primary healthcare centers, rural clinics, mobile vans, and community screening programs.

Eighth, the AI-enabled diagnostic model requires high-quality biosensor signal datasets. Machine learning models such as Logistic Regression, Support Vector Machine, Random Forest, XGBoost, Artificial Neural Networks, and Convolutional Neural Networks should be trained and tested using real biosensor signals and confirmed clinical results. This will help improve diagnostic prediction and reduce human error.

Ninth, data privacy and cybersecurity must be considered. If biosensors are connected with smartphones, cloud platforms, or electronic health records, patient data must be protected. Future studies should focus on secure data storage, safe transmission, informed consent, and ethical use of AI.

Tenth, the environmental impact of biosensor-based diagnostics should be studied. Future research should examine whether biosensors actually reduce reagent use, energy consumption, sample transportation, biomedical waste, and carbon emissions. This will help confirm their value as sustainable healthcare technologies.

Finally, future research should explore partnerships among hospitals, government agencies, medical device manufacturers, public health programs, and green finance institutions. Such partnerships are important for large-scale production, funding, distribution, and adoption of biosensor-based diagnostic solutions.

In conclusion, the proposed framework is useful, but it needs further testing. Future research should use real patient samples, healthcare cost data, biosensor signal datasets, clinical validation results, and environmental indicators. This will help confirm whether affordable infectious disease biosensors can truly support financially sustainable, accessible, and environmentally responsible healthcare.

Conclusion

Affordable infectious disease biosensors offer a promising pathway for developing financially sustainable healthcare systems. Infectious diseases continue to create major clinical, social, and economic burdens, especially in settings where diagnostic facilities are limited or expensive. Delayed diagnosis often leads to disease progression, increased transmission, higher hospitalization rates, and greater pressure on public health resources. In this context, rapid, low-cost, and decentralized diagnostic solutions are essential for improving healthcare delivery and reducing unnecessary expenditure.

The proposed framework shows that biosensor-based diagnostics can support early disease detection by bringing testing closer to patients. Unlike conventional diagnostic methods that often require centralized laboratories, trained personnel, expensive equipment, and longer processing time, biosensors can be designed for point-of-care use in primary healthcare centers, rural clinics, mobile diagnostic units, and community screening programs. This can reduce diagnostic delays, support timely treatment, limit disease transmission, and improve access to healthcare services.

The article also highlights that the value of biosensors should not be assessed only through technical performance. A biosensor may be sensitive and accurate, but it must also be affordable, scalable, environmentally responsible, digitally connected, ethically governed, and supported by reliable supply chains. Therefore, the six-dimensional framework, consisting of technological readiness, financial readiness, environmental readiness, digital readiness, governance and compliance readiness, and supply-chain readiness, provides a broader way to evaluate biosensor-based healthcare innovation.

The Green Finance Readiness Index strengthens this framework by assessing whether biosensor-based diagnostic solutions are suitable for sustainable financing, ESG investment, and large-scale healthcare implementation. By including financial, environmental, technological, digital, governance, and supply-chain dimensions, the index connects healthcare innovation with sustainability and responsible investment. This is important because modern healthcare systems require technologies that are not only clinically useful but also economically viable and environmentally sustainable.

The integration of AI-based decision support further increases the practical value of biosensor-based diagnostics. AI can help interpret biosensor signals, classify diagnostic results, reduce human error, improve prediction accuracy, and support real-time disease surveillance. When biosensors are connected with smartphones, cloud systems, and public health databases, they can support both individual diagnosis and population-level outbreak monitoring.

In conclusion, affordable infectious disease biosensors can contribute to financially sustainable healthcare by enabling rapid, low-cost, decentralized, and accessible diagnosis. The integration of green finance readiness and AI-enabled decision support strengthens the environmental, economic, and practical value of biosensor-based healthcare innovation. However, future research is needed to validate the proposed framework through real patient samples, clinical testing, healthcare cost data, AI-based biosensor signal datasets, regulatory assessment, and field-level implementation studies. With proper validation and policy support, biosensor-based diagnostic systems can become an important tool for sustainable, inclusive, and resilient healthcare delivery.

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