Applications of nano-biosensor in medical, food safety and environmental

Yaxin Wang *

Department of RDFZ Chaoyang Branch School, Beijing, China

* Corresponding Author Email: K23085510@kcl.ac.uk

Abstract. Over time, nanotechnology has ushered in a transformative era for biosensor applications, marking remarkable progress that profoundly reshapes the landscape of biosensor research and development. By leveraging the unique physical, chemical, and biological properties of nanomaterials—such as high surface-to-volume ratios, enhanced conductivity, and superior biocompatibility—this interdisciplinary field has introduced a spectrum of innovative technologies to biosensor design, directly addressing longstanding limitations in sensitivity, selectivity, response speed, and miniaturization. These advancements have not only elevated the overall performance of biosensors but also expanded their applicability across critical sectors. This paper provides a comprehensive review of recent breakthroughs in nanobiosensors, with a focused analysis across three critical domains: medicine, the environment, and food safety. In medicine, nanobiosensors enable early, non-invasive detection of biomarkers for diseases like cancer and diabetes, while in environmental monitoring, they facilitate real-time tracking of heavy metals, pathogens, and toxic pollutants in water and air. Within food safety, these tools offer rapid screening of contaminants, allergens, and microbial spoilage, ensuring stricter quality control. Additionally, the paper critically examines current challenges, such as issues with long-term stability, large-scale manufacturing costs, and regulatory hurdles, before delving into potential future prospects—including the integration of artificial intelligence for data analysis and the development of wearable, implantable nanobiosensor devices—to chart the next phase of this rapidly evolving field.

Keywords: biosensor, nanomaterials, medical, food safety, environmental.

1. Introduction

Biosensor is defined as a device capable of detecting analytes within a sample, with their capacity for rapid, accurate and highly sensitive detection of specific analytes, are indispensable tools in many applications spanning clinical, industry, agricultural, environmental. A sensor consists a detection system (receptor), a transducer, and a readout system. The receptor undergoes specific interaction with the analyte, which is then captured by the transducer and converted into a measurable effect. Examples of such interactions include antigen-antibody, enzyme-substrate and two strands of nucleic acid. It is the specificity of these interactions that determines the specificity of the analyte and the transducer [1]. Transducers employ diverse conversion methods, with common examples including electrochemical systems measuring changes in current, potential, or conductivity; optical systems measuring fluorescence, absorbance, or luminous intensity; and thermosensitive systems measuring heat release or absorption, amongst others.

An ideal biosensor is characterised by high sensitivity, high selectivity, high resolution, good reproducibility, and rapid response times. However, traditional biosensors have been criticised for their lack of precision and sensitivity, as well as for their poor stability [1]. This instability can require users to manually interpret transducer signals. These shortcomings have prompted scientists to explore new technologies for enhancement.

Nanotechnology, owing to its unique physicochemical properties, has been incorporated into biosensors and holds significant importance. Not only has it enhanced the sensitivity and performance of conventional sensors, but it has also spurred the development of novel sensor technologies. It is evident that nanostructures, encompassing nanoparticles, nanotubes and nanowires, exhibit dimensions that are comparable to those of biomolecules, including proteins and DNA. Consequently, the interaction between nanostructures and biomolecules forms a biomaterial-nanostructure interface that combines desirable characteristics and properties . The large surface area and high surface energy of nanoparticles enable robust adsorption of biomolecules onto their surfaces. The nano-scale dimensions enhance the portability of the sensors. The detection process has also become more straightforward and rapid [1].

Nano-materials hold immense potential in terms of electrical conductivity, optical and magnetic properties, rapid response times, and high sensitivity. Consequently, when integrated with biosensors to form nanobiosensors, they find extensive application across diverse fields including healthcare, food safety, environmental monitoring, microbiology, industrial processes, and military applications.

In summary, this review explores and summarises the advances in nano-biosensors within the fields of healthcare, food safety, and environmental monitoring.

2. Medical

The development of nanobiosensors in the field of medicine commenced in 1967 with the creation of the first biosensor — a glucose sensor — by S. J. Updike and his team. This pioneering work laid the foundation for the subsequent development of this technology. The study of nanoscale materials commenced in the 1950s, and by the early 21st century, nano-biosensors had become an integral component of biomedical research, with their applications undergoing continuous expansion [1]. In medical applications, they demonstrate particular excellence in disease diagnosis, enabling the ultra-sensitive detection of cancer biomarkers such as prostate-specific antigen (PSA), and serving as diagnostic tools for coronaviruses like SARS and SARS-CoV-2 (the virus that causes the disease known as 'Covid-19'). These devices facilitate real-time in vivo monitoring, including the tracking of body temperature, pH levels, oxygen concentration, and changes in the oxidation state of myocardial cells. This monitoring enables the prediction of myocardial infarction. In the domain of drug delivery and release optimisation, the utilisation of nano-biosensors facilitates targeted delivery of pharmaceutical agents. These sensors offer the capability to conduct real-time monitoring of delivery efficacy and drug release dynamics, thereby enabling the optimisation of various medication-related parameters [1].

2.1. Detection of glucose

Glucose serves as the primary energy source for most organisms, and its quantitative analysis and continuous monitoring are of paramount importance for individuals with diabetes and hyperglycaemia. As continuous glucose monitoring forms a central pillar of diabetes management, technological advancements in recent years have propelled sensor development, enabling detection not only in blood but also in other biological fluids such as saliva, urine, and sweat.

Precious metals have been employed in developing glucose detection sensor systems. Platinum nanoparticles represent the most stable option, exhibiting excellent biocompatibility and catalytic activity. They serve as redox catalysts for hydrogen peroxide (a product of glucose enzyme-catalysed oxidation). Dharuman et al. discovered that platinum (Pt) can catalyze the oxidation of target substances such as glucose, stripping electrons from them. These electrons are then efficiently conducted to the electrode, generating an electrical signal proportional to the target substance's concentration. This ultimately enables quantitative detection of glucose [2].

The focus on nanostructured carbon materials as a novel class of glucose sensors has been a recent development in research. The high conductivity and ease of functionalisation of these materials renders them optimal for the enhancement of the performance of electrochemical glucose biosensors. The structural characteristics of carbon nanotubes have been demonstrated to enhance the interaction between glucose and the electrode surface, thereby increasing sensor sensitivity. In addition, their conductivity facilitates the catalysis of the electrochemical redox reaction of glucose. The high stability and flexibility of these materials contribute to the development of durable glucose sensors. Patolsky et al. utilized single-walled carbon nanotubes as a conductive pathway between the enzyme redox center and the sensing electrode, facilitating electron transfer between glucose oxidase and the electrode. This configuration endows the electrode with excellent electrocatalytic activity toward glucose, making it suitable for glucose detection [1].

Zinc oxide nanorods, copper oxide nanosheets, gold nanoparticles, and silver nanoparticles are also employed in glucose biosensors.

2.2. Detection of COVID-19

Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) has attracted significant global attention. Like most viruses, the novel coronavirus continuously evolves through mutations, resulting in new variants. Therefore, rapid viral diagnosis is crucial for preventing and controlling the disease. During the pandemic, nanomaterials have enhanced the performance of biosensors by amplifying signals, thereby achieving higher detection sensitivity. L.A. Layqah et al. constructed a nanobiological sensor based on a gold nanoparticle-modified carbon electrode array, employing an indirect competitive immunoassay principle to detect Middle East Respiratory Syndrome Coronavirus (MERS-CoV) [3]. Y. Li et al. constructed a nanobiological sensor centred on magnetic graphene quantum dots (MGQDs), combining it with an ultra-low-field nuclear magnetic resonance (ULF NMR) relaxation method to achieve closed-tube, one-step detection of SARS-CoV-2. MGQDs were first conjugated with SARS-CoV-2-specific antibodies to serve as detection probes. When the virus is present in the sample, it binds to the probe, forming an ‘antibody-virus-antibody-MGQDs’ complex. This alters the dispersion of MGQDs in solution. This alteration in dispersion significantly affects the relaxation time of surrounding water molecules. By detecting changes in the transverse relaxation time of water molecules via ULF NMR, both qualitative and quantitative detection of SARS-CoV-2 is achievable. The entire process requires no lid opening and exhibits high sensitivity and specificity [4]. H.A. Hussein et al. constructed an electrochemical nanobiological sensor utilising nucleic acid aptamers as the specific recognition element for SARS-CoV-2 RNA. This was combined with a nanomodified electrode (presumably employing nanomaterials to enhance conductivity and recognition sites) to achieve rapid detection. First, the aptamer targeting SARS-CoV-2 RNA is immobilised on the electrode surface. When target RNA is present in the sample, the aptamer specifically binds to it, forming a complex that alters the charge distribution and electron transfer efficiency on the electrode surface. Subsequently, electrochemical techniques such as differential pulse voltammetry (DPV) monitor changes in the electrode response signal. Based on the correlation between the signal and RNA concentration, this enables both qualitative and quantitative detection of SARS-CoV-2 RNA. The entire detection process is characterised by rapidity and high specificity [5].

3. Food safety

Food safety is a global concern as it poses a significant threat to public health. Despite the existence of numerous laws and regulations designed to safeguard food safety, issues persist, such as food poisoning from consuming refrigerated items, which can lead to symptoms like vomiting, dizziness, a rapid heartbeat and unconsciousness [6].

Over the years, established food safety testing methods in academia have included gas chromatography, liquid chromatography and mass spectrometry. However, these methods require expensive equipment, specialised operators and complex procedures. Consequently, there is an urgent need for the development of rapid, efficient and simple food safety testing methods.

Nano-biosensors are a powerful tool for improving food quality and ensuring safety. They offer advantages such as high sensitivity, low cost, and the potential for miniaturisation. Even trace contaminants can be detected, which significantly improves food safety. Furthermore, nano-biosensors facilitate real-time monitoring, providing highly reliable data, and are highly portable and handheld.

3.1. Foodborne pathogens

Foodborne pathogens can contaminate food ingredients or cause cross-contamination during food processing, storage, or consumption. This may lead to severe consequences such as food poisoning, gastrointestinal diseases, and parasitic infections [6]. In recent decades, biosensors based on nanomaterials have been widely used for detecting foodborne pathogens.

3.1.1 Detection of Escherichia coli

Escherichia coli produces toxins that damage the intestines, leading to illnesses such as abdominal pain, diarrhoea and uraemia. Most E. coli contamination originates from hamburgers, pizza and unpasteurised dairy products, which has prompted extensive targeted detection research within the academic community. However, traditional biosensors have several drawbacks. They are severely insensitive, making it difficult to detect trace amounts of E. coli as low as 10 CFU/mL in food. This can lead to safety risks due to missed detection. Also, they are extremely slow to respond, as they rely on steps such as bacterial culture and antibody binding. This process takes 12–24 hours, which is unsuitable for real-time quality control on food production lines or emergency screening needs. Thirdly, they exhibit weak interference resistance. Complex food matrices containing proteins and lipids can interfere with the sensor's ability to specifically bind to E. coli, resulting in significant detection errors [7]. Cho et al. immobilised E. coli O157:H7 antibodies on screen-printed carbon electrodes (PNseSPCE) by depositing peptide nanotubes, thereby enabling antigen-antibody interactions and the adsorption of E. coli [8]. Kalele et al. used immunoglobulin G antibodies that were conjugated to silver nanocapsules. By detecting plasmonic resonance shifts in the presence of E. coli, they were able to screen for the bacterium rapidly within a range of 5–10 cells [9]. Shen et al. developed a 'functional nanoparticle-enhanced enzyme-linked immunosorbent assay (ELISA)' technique. This method captures and separates E. coli O157:H7 using magnetic nanoparticles coated with specific antibodies, followed by an immune reaction triggered by beacon gold nanoparticles conjugated with polyclonal antibodies and streptavidin-horseradish peroxidase activity. Unbound particles are then separated using magnetic separation. The presence of bacteria was then detected by observing colour changes in the ELISA assay [10].

3.1.2 Detection of Salmonella

Salmonellosis is a significant bacterial disease primarily caused by Salmonella enterica serovars, such as S. enteritidis and S. typhimurium. Symptoms of infection include fever, abdominal pain, gastroenteritis, vomiting and nausea. Joo et al. developed a technique for capturing and separating Salmonella bacteria from milk using magnetic nanoparticles conjugated with antibodies. The bacteria were then exposed to titanium dioxide nanocrystals coated with immobilised antibodies. After separating the complexes using a magnetic field, the unbound titanium dioxide nanocrystals were analysed using ultraviolet-visible spectrophotometry to detect the bacteria [11]. Yang and Li utilised magnetic beads coated with Salmonella-specific antibodies to isolate the bacteria from wastewater. Subsequently, labelled antibodies were added to induce interaction and generate detectable fluorescence [12].

3.2. Heavy metals

The predominant impact of heavy metals on public health is the accumulation of toxic damage. Once they enter the human body, these substances are challenging to metabolise and accumulate over an extended period in vital organs such as the liver, kidneys, and bones. The consequences of such exposure are manifold, including but not limited to damage to the nervous system (e.g., mercury causing intellectual decline, lead causing cognitive impairment), the digestive system (e.g., cadmium causing abdominal pain and diarrhea), and the endocrine system. Furthermore, there is a risk of carcinogenesis, and vulnerable groups such as children and pregnant women are particularly exposed. The capacity of conventional biosensors to detect trace concentrations of heavy metal ions is limited [6]. These systems demonstrate a tendency to exhibit weak resistance to interference, with impurities present within complex samples having the capacity to skew the results obtained. The extended detection times of these systems impede the efficiency of rapid analysis. Despite the challenges currently faced by nanobiosensors, including high costs and stability issues, they have the potential to overcome the limitations of conventional devices.

3.2.1 Detection of Mercury

Mercury ions primarily enter the human body through bioaccumulation in the food chain. Environmental mercury undergoes microbial conversion into highly toxic methylmercury, which accumulates progressively through the trophic levels of algae → small fish → large fish. It ultimately enters the human body via consumption of large fish such as tuna and shark, where it persists long-term. Its harm centers on neurological damage, causing memory loss and limb numbness in adults. For fetuses and children, it leads to irreversible brain damage, resulting in intellectual disabilities and other issues. It may also impair kidney and cardiovascular systems, increasing the risk of related diseases. Pi et al. designed a Hg^{2+} sensor based on the selective binding of Hg^{2+} to thymine-rich DNA. This DNA strand forms a stable “T-Hg^{2+}-T” base pairing structure upon specific binding with Hg^{2+}, altering the DNA's spatial conformation. The pre-labeled fluorescent group on the sensor exhibits significant changes in fluorescence signal—such as enhancement, quenching, or shift—due to DNA conformational alterations (e.g., transition from single-stranded to specific double-stranded or folded structures). By detecting these fluorescence signal differences, the sensor enables both qualitative identification and quantitative analysis of Hg^{2+} [13].

3.2.2 Detection of Lead

Lead ions can also affect the brain and nervous system, impair bone growth, cause anemia, and damage the renal system. For pregnant women, lead can harm the fetus through the placenta, inducing birth defects, miscarriage, or leading to intellectual developmental disorders in newborns. Venkateswarlu et al. utilized nanomaterials (NH_2-MIL-125(Ti) type MOF) as core sensing elements to enhance biosensor detection of lead ions. This type of MOF is a metal-organic framework material with a nanoscale porous structure. Functional groups on its surface, such as amino ($-NH_2$), can undergo specific adsorption or coordination with Pb^{2+}; When unbound to Pb^{2+}, the MOF exhibits an “on” fluorescent signal state. Upon Pb^{2+} binding, charge transfer and energy transfer processes quench the fluorescence, switching the signal to “off.” This reversible “on-off” fluorescence switching enables the sensor to rapidly and accurately identify Pb^{2+}. Concurrently, the nanoporous structure of the MOF increases its specific surface area, enhancing both Pb^{2+} adsorption capacity and detection sensitivity [14].

4. Environmental

As the times change, with continuous development and manufacturing, environmental issues have become an increasingly serious problem. Harmful pollutants, emanating from industrial activities, pesticides and heavy metals, pose a threat to ecosystems and human health. These conditions have been linked to the development of serious diseases, including cancer, sudden death, and reproductive disorders. To reduce pollution, scientists have developed various detection methods. Traditional environmental monitoring methods struggle to detect low-concentration pollutants, exhibiting poor selectivity, low sensitivity, and lengthy processing times. In order to develop more reliable detection techniques, researchers have utilised nanobiosensors to enhance performance. The detector exhibits high sensitivity, ease of use, precision, and efficiency, which align with the characteristics of an ideal detector.

4.1. Detection of air pollution and greenhouse gas

Air pollution is defined as the presence of harmful substances in the atmosphere, originating from vehicle exhaust, industrial emissions, and agricultural activities, such as carbon monoxide, ammonia, methane, and nitrogen oxides. High concentrations of air pollution can impair plant growth, exacerbate climate anomalies, and damage respiratory and cardiovascular systems [15]. Globally, approximately 7 million patients die from air pollution every year, underscoring the urgent need to mitigate these hazards. K. Lee et al. employed a mechanism regulating electron transfer and depletion layers on zinc oxide tetrahedra surfaces. First, oxygen adsorption in ambient air forms oxygen ions, increasing resistance. Subsequently, upon NO_2 contact, NO_2 captures electrons and reacts with oxygen ions to generate NO_3^-, decreasing resistance. By monitoring resistance changes via a gas-sensitive probe station to quantify the response, they detected NO_2 [16]. X.H. Tai et al. employed boron-doped photoreduced graphene oxide as a metal-free nanophotocatalyst to remove methanol via photocatalytic oxidation technology [17].

4.2. Pesticide and organic contaminants

Farmers worldwide rely on pesticides to control weeds and pests. However, this not only causes water pollution but also accumulates within the food chain, adversely affecting both humans and animals. Human exposure to pesticides carries risks including genetic mutations, neuropathy, and cancer. X. Yue et al. developed a novel one-step hydrothermal method to synthesise copper-modified dual-emission carbon dots (Cu-CDs) as a fluorescent sensor, enabling rapid detection of thiophanate-methyl (TM) pesticide residues in fruit [18]. T. Hu et al. constructed a quantum dot-acetylcholinesterase (QDs-AChE) aerogel microfluidic nanobiological sensor for highly sensitive detection of organophosphorus pesticides (OPs) and their mixtures [19].

5. Conclusion

This review summarises the applications of nanobiological sensors in healthcare, food safety, and environmental monitoring. The incorporation of these nanomaterials into biosensors capitalises on their characteristics, including high surface area-to-volume ratios, exceptional sensitivity, electrochemical properties, and high selectivity. Nevertheless, the development and widespread adoption of nano-enhanced biosensors face numerous challenges. For instance, issues such as the alteration of nanomaterials' properties under varying temperatures, humidity, or light exposure, their susceptibility to degradation when exposed to air, and persistent toxicity require further investigation and resolution. Nevertheless, nanotechnology continues to demonstrate immense potential, having significantly advanced biosensor development, with nanomaterials and techniques increasingly integrated into this field.

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