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Biosensor Technologies for the Detection of Radon and Lead with a Focus on Applications

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Abstract: *The presence of radon and lead in milk poses significant health risks, necessitating the development of sensitive and reliable detection methods. This review examines recent advances in biosensor technologies for detecting both radon and lead, highlighting the challenges and opportunities in their application, particularly within the specific context of Najaf, Iraq. The review discusses various biorecognition elements, including aptamers, antibodies, and specialized materials for trapping radon and its decay products, coupled with different transduction mechanisms such as electrochemical, optical, and mass-based approaches. Special attention is given to sample preparation methods required for complex milk matrices, the influence of environmental conditions, and the need for robust, cost-effective solutions suitable for deployment in the Najaf region. Finally, the limitations of current technologies and future research directions are explored.*

Keywords: Aptamers, Antibodies, Electrochemical Sensor, Optical Sensor, Alpha Particle Detection, Environmental Monitoring

1. Introduction

The contamination of food sources with environmental pollutants, such as radioactive gases and heavy metals, poses a significant threat to human health. Milk, being a crucial component of the human diet, especially for children, requires vigilant monitoring for potential contaminants. Radon, a naturally occurring radioactive gas, and lead, a toxic heavy metal, are two such contaminants that can find their way into milk via various pathways (radon through contaminated water and air, lead through feed and contaminated land). The importance of effective detection methods for these pollutants cannot be overstated. Traditional analytical techniques, while accurate, often require complex laboratory setups, trained personnel, and are time-consuming, limiting their applicability for rapid on-site analysis (Almayahi and Amjad, 2023, 2024). Biosensors offer a promising alternative approach due to their potential for high sensitivity, specificity, portability, and real-time monitoring. Biosensors combine biological recognition elements with physical transducers to detect specific targets (analytes). Their versatility allows for the detection of a wide range of contaminants, offering a viable solution for food safety analysis. However, deploying biosensors in specific geographical contexts like Najaf, Iraq, demands consideration of unique environmental conditions, economic constraints, and the need for robust devices. This review aims to explore the latest advancements in biosensor technology for detecting radon and lead in milk, emphasizing their suitability for the specific challenges encountered in the Najaf region, and suggesting future research avenues (Almayahi and Albazoi, 2022a, 2022b).

2. Materials and Methods

This review was compiled through an extensive search of scientific literature using databases such as Web of Science, Scopus, PubMed, and Google Scholar. The search terms included combinations of the following: "biosensor," "radon," "lead," "milk," "detection," "heavy metal," "radioactive gas," "aptamer," "antibody," "electrochemical sensor," "optical sensor," "mass-based sensor," "alpha particle detection," and "environmental monitoring." The search was limited to English-language articles published within the last decade (2014-2025), though some older foundational studies were included where necessary. Inclusion criteria focused on studies that presented novel biosensor designs for radon and/or lead detection in milk, as well as reviews providing comprehensive overviews of pertinent detection technologies. Articles focusing on other types of sample matrices were considered when the fundamental principles or approaches were relevant to milk analysis. Priority was given to studies demonstrating experimental data, or those which explicitly considered the application of biosensors in resource-limited settings (Fig. 1).

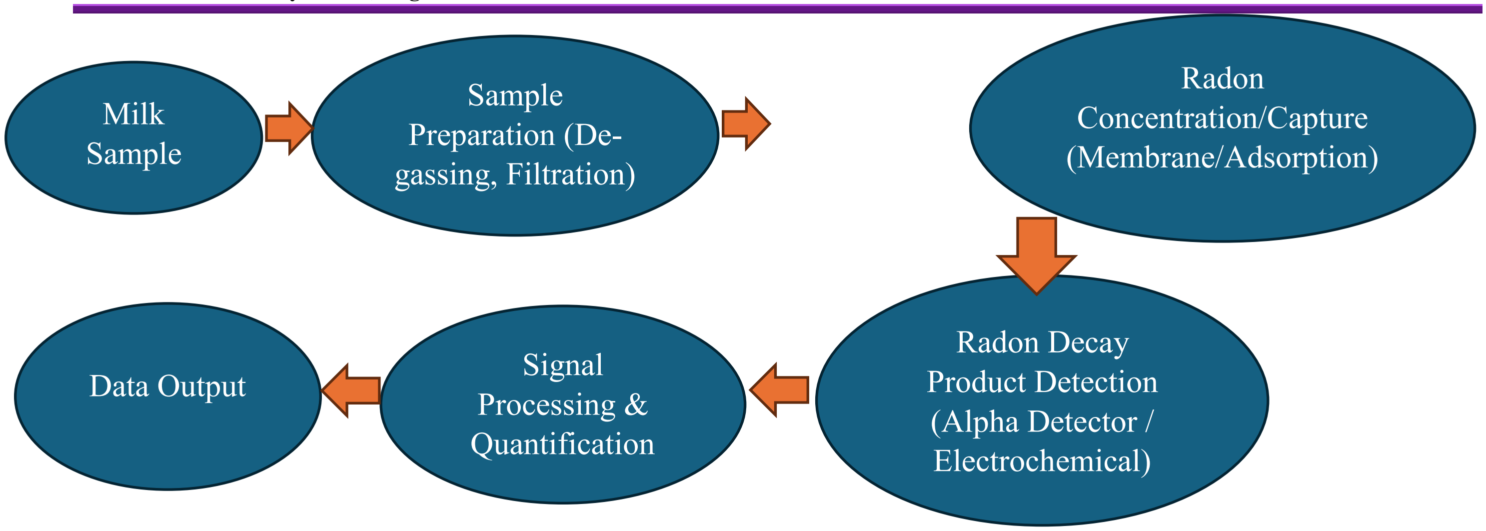

Figure 1 Methodology steps for sampling in this study

3. Results and Discussion

3.1. Radon Detection in Milk

Direct detection of radon by biosensors is inherently difficult due to its inert nature. However, detection of its radioactive decay products (especially polonium isotopes) is feasible. Research has explored several methods including the following:

- **Alpha Particle Detection:** Solid-state detectors, such as silicon-based devices, and scintillation detectors, have been used to detect alpha particles emitted by radon decay products. These are usually paired with a method of concentrating the decay products, such as filtering materials that capture polonium isotopes.
- **Electrochemical Sensing**: Studies have shown that Polonium isotopes, produced by radon decay, can be detected by electrochemical sensors, utilizing their electrochemical properties. This requires a method of capturing the polonium isotopes (eg. by selective adsorption), or separating them from the rest of the sample matrix.
- **Challenges:** The major challenge remains the low concentration of radon and its short-lived decay products and the need for preconcentration. Further research is needed to develop methods for efficient radon trapping and to integrate these preconcentration methods with the detection methods.

3.2. Lead Detection in Milk

Several biosensor strategies have been developed for lead detection in milk:

- **Aptamer-based Sensors:** Aptamers, highly selective DNA or RNA molecules, have shown great potential for lead detection. They are often combined with electrochemical transducers (e.g., electrodes modified with aptamers and electrochemically active reporters) or optical transducers. Studies have shown aptamers coupled to electrochemical impedance spectroscopy to be highly sensitive for lead detection.
- **Antibody-based Sensors:** Antibodies are frequently used in immunosensors to capture specific target molecules. Studies have used antibodies specific to lead coupled to electrochemical (voltammetric) and optical transducers.
- **Electrochemical Sensors:** Electrochemical methods, such as voltammetry and amperometry, are widely used due to their simplicity, sensitivity, and cost-effectiveness. Lead ions can be directly detected at electrodes or after binding to bioreceptors.

- **Optical Sensors:** Surface plasmon resonance (SPR) and fluorescence-based sensors have been used to detect lead with high sensitivity. SPR-based biosensors utilize changes in refractive index upon lead binding to the bioreceptor on a gold substrate. Fluorescent sensors use changes in fluorescent signal due to lead binding with the bioreceptor.
- **Mass-based Sensors:** Quartz crystal microbalances (QCMs) have been used to detect lead, using bioreceptors to selectively bind and measure changes in mass at the sensor surface.
- **Challenges:** The complex milk matrix often requires extensive sample preparation (like acid digestion) to release lead ions. The presence of other ions can also interfere with detection, requiring highly selective bioreceptors.

3.3. Challenges and Opportunities for Application

The application of biosensors in some area, must consider the specific environmental conditions and resources available:

- **Environmental Context:** The region's geology can influence radon levels, while local agricultural practices and industrial activities can introduce lead contamination.
- **Cost-Effectiveness:** Low-cost materials and simple designs are essential to ensure accessibility to the local population.
- **Robustness:** Sensors need to be resilient to fluctuations in temperature, humidity, and other environmental stressors.
- **Ease of Use:** Simple operation is key to reducing dependence on trained personnel.
- **Local Adaptation:** Sensors should be adapted to the local environment and milk samples. The sensors should be calibrated to be used specifically in milk from Najaf, Iraq. Tables 1-4 show comparison of lead biosensor technologies.

Table 1: Comparison of Lead Biosensor Technologies

Biosensor Type	Bioreceptor	Transducer	Advantages	Disadvantages	LOD (Typical)	Refs.
Aptamer-based	Aptamer	Electrochemical	High specificity, stable, customizable	Susceptible to matrix effects, needs signal amplification	nM - µM	Wu *et al.,* (2021)
Antibody-based	Antibody	Electrochemical/Optical	High specificity, good sensitivity	Requires complex synthesis, sometimes cross-reactivity	nM - µM	Tyśkiewicz *et al.,* (2023)
Electrochemical	(Direct/Modified electrode)	Electrochemical	Simple, cost-effective, rapid	Requires sample pre-treatment, interference problems	µM - mM	Rubino *et al.,* (2023)
Optical (SPR)	Antibody/Aptamer	SPR	Label-free, real-time analysis	Sensitive to changes in temperature	pM - nM	Altintas *et al.,* (2024)
Mass-Based (QCM)	Antibody/Aptamer	QCM	Sensitive, label-free	Limited by the size of bioreceptor,	nM - µM	Escobar *et al.,* (2015)

		interference issues	

Table 2: Comparison of Radon Biosensor Techniques

Feature	Alpha Particle Detection	Electrochemical (Polonium)	Aptamer-Based (Indirect Pb)
Analyte Target	Alpha particles (direct)	Polonium isotopes	Lead ions (from radon decay)
Biorecognition Element	None	Specialized Materials for Capture	DNA Aptamer (e.g., HTG), or specialized material for trapping decay products.
Transduction Method	Solid-state or Scintillation Detectors	Electrochemical	Fluorescence, Electrochemical
Sample Handling	Gas sampling, Membrane filtering	Requires preconcentration step	Requires acidic capture solution
Sensitivity	Low to Moderate	High	High
Selectivity	Limited	Limited	Good
Cost	Moderate	Moderate	Low
Response Time	Moderate	Moderate	Fast
On-site application	Possible, Portable	Possible, Portable	Possible, Portable
Interferences	Other sources of alpha particles	Other redox active metals	Other metals in the sample
Specific Limitations	Requires decay product concentration	May require Polonium concentration	Sample pre-treatment needed. Not direct radon sensing.

Table 3: Comparison of Lead Biosensor Techniques (Direct Detection)

Feature	Aptamer-Based	Antibody-Based	Electrochemical (Direct)	Optical (SPR/Fluorescence)	Mass-Based (QCM)
Analyte Target	Lead ions	Lead ions	Lead ions	Lead ions	Lead ions
Biorecognition Element	Aptamers	Antibodies	None or Modified Electrode	Antibodies or Aptamers	Antibodies or Aptamers
Transduction Method	Electrochemical/Optical	Electrochemical/Optical	Electrochemical	SPR, Fluorescence	QCM
Sample Handling	Acid Digestion	Acid Digestion	Often Acid Digestion	Often Acid Digestion	Acid Digestion
Sensitivity	nM - µM	nM - µM	µM - mM	pM - nM	nM - µM
Selectivity	Good	Good	Limited	Good	Good
Cost	Low-Moderate	Moderate	Low	Moderate	Moderate
Response Time	Fast	Fast	Fast	Real-time	Fast
On-site application	Possible, Portable	Possible, Portable	Possible, Portable	Possible	Possible
Interferences	Matrix effects; other metal ions	Cross-reactivity; other metal ions	Other metals in the sample	Requires specific setup	Interferences; Mass changes with matrix
Specific Limitations	Signal amplification often required	Complex synthesis and storage	Limited sensitivity	Specialized equipment required	Sensitive to matrix changes

Table 4: Comparison of Sensor Designs from the literature review

Article Focus	Analyte Target	Biorecognition Element	Transduction Method	Key Features	Application
Yu *et al*., (2021)	Radon (via Pb)	Lead-induced aptamer (HTG) conformational change	Fluorescence	Label-free; indirect radon detection via lead decay product. High selectivity and a wider linear range to detect lead.	Environmental
Sadiq *et al*., 2021	Lead	Aptamer-modified gold nanoparticles	Colorimetric	Colorimetric biosensor, low cost, rapid, lead selective	Food
Palani *et al*., 2022	Radon (via Pb)	Aptamer T30695	Fluorescence	Label-free sensor, indirect radon detection. G-Quadruplex formation with the inclusion of lead ions; short time scale for detection.	Environmental
Almayahi *and Amjad*, 2023	Radon/Lead	Aptamer, Malachite Green	Fluorescence	Aptamer based biosensor to directly measure radon and lead in blood; Good for measuring occupation exposure, not for general use.	Clinical
Liang *et al*., 2017	Lead	Lead-specific DNAzyme	Electrochemical	Electrochemical; high sensitivity and low-cost method, based on a dual electrochemical signal.	Water sample
Jiang *et al*., 2024	Lead	Aptamer-modified AuNPs	Electrochemical	Electrochemical; very low limit of detection.	Various matrix

Minzhi *et al.,* 2016 introduced a novel, label-free fluorescence biosensor for detecting radon using its decay product, lead, and a specific DNA aptamer (PW17) in conjunction with the cyanine dye OliGreen (OG). The method involves collecting radon, allowing its decay to lead, which then induces the PW17 aptamer to form a G-quadruplex, reducing the fluorescence of OG. A linear relationship was found between the reduced fluorescence intensity and both lead and radon concentrations, allowing for quantification. The biosensor is sensitive with a detection limit of 1963 $Bqhm^{-3}$ and can exclude radiation damage during testing. This new method provides a low-cost, sensitive, and simplified strategy for radon detection compared to traditional techniques and is applicable for detecting gaseous and radioactive materials.

Deng *et al.,* 2016 introduced a novel, rapid, and simple method for detecting accumulated radon radiation using a label-free fluorescent DNA sensor. The sensor utilizes a guanine-rich aptamer (T30695) that undergoes a conformational change to a G-quadruplex structure upon binding with lead ions, which are a decay product of radon. This change inhibits the binding of a fluorescent dye (PG) leading to decreased fluorescence. The sensor was tested with both lead standards and radon samples and a linear relationship was observed between lead concentration and the change in fluorescence, allowing for the quantification of accumulated radon radiation. This new method protects personnel from radiation exposure, avoids the use of radioisotopes, and can provide a low-cost alternative for radon detection in the environment.

Shiya *et al.,* 2018 introduced a novel biosensor for detecting accumulated radon dose by measuring its decay product, lead (^{210}Pb). The biosensor utilizes a lead-induced conformational change in a specific DNA aptamer (HTG) combined with a malachite green (MG) fluorescent probe. In the absence of lead, the single-stranded aptamer results in weak fluorescence, but in the presence of lead, a G-quadruplex structure forms, which enhances the MG fluorescence. The study optimized various parameters including pH, buffer concentration, temperature, and incubation time, and demonstrated a linear relationship between fluorescence intensity change and both lead and radon concentrations. The method exhibits a detection limit of 6.7 nmol/L for lead and 2.06×10^3 $Bq\text{-}h/m^3$ for radon.

It's shown to be sensitive, accurate, easy to operate, and highly selective, offering a label-free approach to detecting radon, and avoiding some limitations of existing radon detection techniques. The method was successfully applied to measure radon concentration in a range of environmental samples.

Yongjie *et al.,* 2020 provided a comprehensive overview of recent progress (since 2015) in the development of DNA-based biosensors for lead (Pb^{2+}) detection, highlighting the fundamental chemistry, design, and practical applications. It focuses on the interactions between Pb^{2+} and nucleic acids, particularly RNA-cleaving DNAzymes and G-quadruplex (G4) DNA, which form the basis of most sensors. The article details various sensing mechanisms including fluorescent, colorimetric, and electrochemical methods, coupled with signal amplification strategies like rolling circle amplification (RCA) and hybridization chain reaction (HCR) to enhance sensitivity. The authors also address practical aspects of sensor design, detection in real samples, and the potential of these sensors for future environmental and health monitoring applications.

Almayahi and Albazoni, 2022 described the development of a biosensor for detecting both radon gas (^{222}Rn) and lead ions (Pb^{+2}) in soil and building materials, utilizing single-stranded DNA (ssDNA) primers rich in guanine. Two different primer sequences were tested (BIOS-I and BIOS-II) and showed varying sensitivities for each analyte. The study found that both radon and lead levels were highest in Indian and Chinese granites, exceeding WHO recommended limits. The biosensor demonstrated effectiveness for detecting radioactive and organic materials while also avoiding radiation damage during field testing. The authors propose that this method provides an alternative approach for monitoring these contaminants with implications for both environmental and public health.

Almayahi and Albazoni, 2022 focused on designing and testing two biosensors (BIOS-I and BIOS-II) for detecting radon (^{222}Rn) and lead (Pb^{+2}) in building materials and soil samples, and comparing their results to conventional methods (CR-39 and RAD7). The biosensors utilized ssDNA rich in guanine as the base material. Measurements revealed varying levels of radon exhalation across different building materials, with Indian and Chinese granites and soil samples showing the highest levels, exceeding WHO recommendations. There was a weak positive correlation found between the biosensors and humidity and a weak negative correlation with temperature, while RAD7 showed a strong correlation with humidity. Overall, the results indicated that the manufactured biosensors provided better detection for radon than the conventional CR-39 and RAD7 detectors, with BIOS-I showing higher sensitivity. Almayahi and Amjad, 2023 developed and tested of a low-cost biosensor for detecting radon gas (^{222}Rn) and lead ions (Pb^{+2}) in human blood. The biosensor utilizes a DNA aptamer, malachite green dye, and acetic acid within a Tris-HAc buffer, and measurements are obtained through a fluorescence spectrophotometer. The research found variations in radon levels between individuals, with higher levels in males, smokers, and a cancer patient. The biosensor was effective in detecting both radon and lead, with levels measured within WHO permissible limits, though correlations between radon, lead, temperature and humidity were weak to moderate. The study emphasizes the importance of monitoring these substances in blood, particularly for individuals with occupational radiation exposure, and suggests the developed biosensor as a sensitive, efficient, and fast tool for such monitoring.

4. Conclusions

This review shows that biosensors offer a versatile platform for the sensitive and rapid detection of radon and lead in milk. While several techniques have shown promise in the detection of each of these pollutants, the detection of radon has proved to be considerably more complex, due to the gaseous nature of the analyte. Various biorecognition elements and transduction techniques have been explored, but certain challenges persist. Developing a low-cost, robust, and portable biosensor for radon and lead detection will be critical for environmental monitoring in places like Najaf, Iraq.

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