American Journal of Biology and Natural Sciences
https://biojournals.us/index.php/AJBNS
ISSN: 2997-7185

Application of Nano-Biosensors Combined with Microbiological Tests for Early Detection of Microbial Contaminants in Blood

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Received: 2025, 15, Jul
Accepted: 2025, 21, Aug
Published: 2025, 25, Sep

Annotation: Motivated by the characteristics of microbial contamination in blood, the prospects of nano-biosensors in terms of microbial detection are presented. Principles, modes, and recent advances of various aspects of nanosensors with microbiological tests are reviewed. A combination of microbiological testing and nano-biosensors can facilitate early detection of microbial contamination and reveal vital indicators of contamination. Microbes grow in blood and produce diverse hazardous byproducts, resulting in skin issue, allergies, organ failure and ultimately death. Although microbial contaminant types, sources, or formation mechanisms have been recognized and suitable preventive/suppressive steps are implemented, early identification remains a critical priority. Similarly, blood quality deterioration emerges as a result of

metabolic products of microbial contaminants. Different analytical or microbial tests are widely applied for microbial examination in blood. Nonetheless, the synergy between nano-biosensors and these techniques can ensure rapid and highly sensitive detection of microbial contaminants.

1. Introduction

Microorganisms, colloquially known as microbes, are unicellular entities including bacteria, fungi, protozoa, and archaea. Their omnipresence in various environments leads to frequent exposure and potential contamination. For instance, from earth's crust to air and water, pathogens like Salmonella enterica and Staphylococcus aureus, along with commensals such as Escherichia coli, readily contaminate water sources. Blood, integral to physiological systems, is susceptible to microbial contamination during collection and storage. Such contamination invokes localized and systemic immune responses, jeopardizing patient health and treatment efficacy. Swift and reliable microbial identification is thus indispensable in clinical and health sectors to curtail disease progression.

Nano-biosensors, playing a pivotal role in early microbial detection, combine microbiological tests with sensor technology to facilitate accurate identification. Microorganisms require host colonization and multiplication for detection; techniques employed include microscopy, biochemical analysis, culture, immunological assays, and molecular detection. Nano-biosensors, leveraging nanostructured materials and biospecific interfaces, transduce a biological response into quantifiable signals. Their specificity derives from bioreceptor–biomolecule interactions, encompassing antigen–antibody affinity, receptor–ligand bindings, enzymatic reactions, and nucleic acid hybridization. Classification encompasses electrochemical, optical, and mass-based sensors, with common types being amperometric, potentiometric, impedimetric, piezoelectric, and optical evanescent wave sensors. Integrating microbiological and nano-biosensor methodologies emerges as a potent strategy for early and precise detection of blood microbial contaminants [1] [2] [3].

2. Background on Microbial Contamination in Blood

Blood is defined as the main fluid that circulates in the arteries and veins of humans and other animals. Microbial detection in blood controls the blood quality of medical patients who seek blood transfusion during the hospital check-up [4]. Microbial contamination in blood is very detrimental as it spreads fast. Types of microbial contaminations that can be found in blood include dangerous viruses, parasites and pathogenic microorganisms [1]. These microorganisms or microbes can be introduced into the human body in two ways. The first way is the ingress of external agents. For example, medical instruments, surgical procedures and transfusion of contaminated blood. It also occurs when intravascular catheters are not managed properly. The second way is by intrusion of microbial endogenously where the microbe exist in the body at low or undetectable levels, but can multiply rapidly due to stressed diseases.

3. Importance of Early Detection

The emphasis on embracing the synergy between nano-biosensors and microbiological assays stems from the perils of microbial intrusion into blood. Such contamination cases look for

unwavering attention to eschew the occasions of fatalities in clinical and emergency care levels.

This accounts for the reason why an early detection strategy needs to be adopted prior to addressing the instances of contamination and infections that can occur. The remedial action of infections and deposit remains a significant approach to deal with the incriminated contaminant. The detection of microbial contamination through five process activities unfolds; 'inspection, monitoring, sensing, measurement, and control'. An efficient and reliable approach that can be useful to detect microbial contamination in blood prior to the sample analysis involves adopting micro and nanotechnology platforms joined with microbiological approaches. Microorganisms causing blood infection mostly constitute bacteria. Both bacterial detection and removal require paramount importance. The integration of nano-biosensors with microbiological tests has the potency to provide a highly reliable preventive index that branches to the identification of microbial contamination in blood for early remedial action. Nano-biosensors on the other hand rely on an integration of smart micro and nanotechnology-based sensors that specialises in the speedy detection and removal of microbial contaminant in sensitive groups such as blood. Micro and nanobiotechnology platforms pay reliance on an integration of smart nanosensors specialised in the speedy detection and removal of microbial contaminants in sensitive groups such as blood. Blood contamination added to a blood sample may exhibit a detrimental impact since it alters the blood behaviour and could be life-threatening before identification. The condition of acquiring blood during sample analysis is pliable to contamination from the environment it is obtained. This establishes the relation and reiterates the importance of early detection [1]. The nano-biosensors also operate as a functionary of five process activities; 'inspection, monitoring, sensing, measurement and control' during the detection of microbial contamination in the blood. The timely opt-out of samples that do not meet the standard is an effective approach to have accurate analysis results. Without an integration process of nano-biosensors and microbiological tests, this timely opt-out can hardly be found in microbial contaminant detection. The control department in nano-biosensors and microbiological test already have the potential capacity to detect microbes and can implement necessary isolations to avoid contaminant detection. This can save researchers from long procedures of regret and re-analysis [5]. The detection of microbial contamination in blood explains the entire psychoanalytic effect of the integration and actuates the solution of combined nano-biosensors with microbiological tests. The concept of a microbial contaminant refers to a living organism that causes disease on delicate matters if public or individual standards of hygiene are compromised. Among all the organic materials present in the environment, bacteria is the most predominant contaminant that causes lethal damages to health, infrastructure, behaviour, and environment. The estimated number of bacterial species in the world is more than trillion with over ten million in each area. Bacterial spores may not always be the primary cause of major contamination but can definitely result in an aggravation of contaminant once they indiscriminately grow.

4. Overview of Nano-Biosensors

Nano-biosensors offer outstanding advantages including enhanced electrocatalytic activity and strong signal amplification stemming from their large surface area and high surface-to-volume ratio, enabling ultrasensitive, rapid, and portable detection. These properties make nano-biosensors excellent candidates for early microbial detection in blood sampling. Integration of nano-biosensors with microbiological tests improves accuracy and speed of microbial contaminant detection.

Biosensors detect bacterial pathogens by combining a bioreceptor that selectively recognizes specific bacterial components and a transducer that converts biorecognition events into measurable signals. The emergence of nanotechnology enables cost-effective miniaturized biosensors with high selectivity, accuracy, and sensitivity [6].

Nano-biosensors leverage nanoscience, engineering, and biotechnology to observe, measure, and analyze biological events. Constructed from quantum dots, nanoparticles, nanowires, and

nanofilms, they exploit the nanometer scale of biological systems to achieve greater sensitivity, specificity, and faster response compared to traditional biosensors [7]. Nanomaterials such as metal nanoparticles, oxide nanoparticles, magnetic nanomaterials, and quantum dots enhance electrochemical signals, serving as key components in sensing, signal amplification, and transduction. By employing nanomaterials as both sensing elements and carriers, nano-biosensors provide rapid and sensitive bacterial detection [1].

5. Types of Nano-Biosensors

Nano-biosensors are analytical devices comprising biological or biomimetic recognition elements immobilized onto a physicochemical transducer, enabling real-time and in situ detection of targeted analytes. Electrochemical, optical, and mass-based nano-biosensors are the most commonly employed types for blood analysis applications. Electrochemical sensors measure perturbations in current, potential, or impedance caused by the interaction between the target analyte and the recognition element. Optical sensors detect changes in properties such as fluorescence or absorbance. Mass-based sensors measure variations in oscillation frequency resulting from the binding of analytes onto a sensitive layer. The appropriate transduction system is selected dependent on the target analyte and operational conditions. Consequently, nano-biosensors can be engineered to operate in gas or liquid phases and can be designed for single or multiplex analysis of specific targets, offering high flexibility and a broad application scope [6].

5.1. Electrochemical Nano-Biosensors

Biomedical Perspective of Electrochemical Nanobiosensor [8] emphasizes the potential of electrochemical nano-biosensors in medical diagnostics, particularly for microbial detection in blood samples. Bioreceptor molecules (enzymes, nucleic acids, antibodies, dyes, and metal ions) are immobilized on electrodes to enhance analyte and biomarker signal detection. Electron transfer is controlled by applying a potential to the working electrode relative to a reference electrode, facilitating analyte oxidation or reduction. Techniques such as cyclic voltammetry, differential pulse voltammetry, and square wave voltammetry analyze reaction behavior in electrolytic solutions, while impedance spectroscopy detects target analytes through changes in the Nyquist plot's semicircle radius. Nanomaterials (graphene, nanotubes, silica-based nanoparticles, metallic nanoparticles, TiO2, and ZnO) provide exceptional sensitivity and selectivity with low detection limits. Electrochemical sensing methods—including amperometric, voltammetric, conductometric, and impedimetric approaches—identify disease markers for conditions such as cardiac diseases, cancer, AIDS, hepatitis, and urinary infections. Miniaturized implantable biosensors enable in vivo detection of metabolites (blood glucose, triglycerides, cholesterol) and protein biomarkers, bacteria, and viruses without patient intervention. Enzymes—particularly oxidases like glucose-1-dehydrogenase, glucose oxidase, and hexokinase—serve as selective biomarkers, with glucose oxidase-modified electrodes playing a central role in blood sugar testing.

5.2. Optical Nano-Biosensors

Optical nano-biosensors utilize light as the main source for detection and offer several advantages such as simple instrumentation, low cost, and the possibility of miniaturization. Numerous methods have been developed for detecting target chemical species using optical transducers such as absorption, fluorescence, luminescence, Raman scattering, reflectance, surface plasmon resonance, ellipsometry, and interferometry [9].

Nanoparticle-based optical nanosensors have attracted significant attention for on-site and real-time bacterial detection. The optical properties of nanoparticles, which include surface plasmon resonance (SPR), Rayleigh scattering, and fluorescence, render them ideal to serve as "optical antennas" to selectively enhance the intensity of optical signals from microbial analytes. Surface plasmon resonance assays have been utilized to detect Campylobacter jejuni and Listeria monocytogenes in food samples. Colorimetric assays based on gold nanoparticles permit the rapid detection of cholera toxin in water samples. SERS-based immunoassays that employ magnetic

nanoparticles allow for the enumeration of Escherichia coli in water. Optical methods have also been developed for label-free detection of bacteria in various media.

Optical sensors offer fast response times, easy handling, portability for field use, and simultaneous detection capabilities, which are crucial requirements for modern microbial contaminant analysis. Therefore, their application for the early detection of microorganisms in blood is of great interest.

5.3. Mass-Based Nano-Biosensors

Mass-based sensors utilize a highly sensitive mass transducer to effectively detect microorganisms present in contaminated fluid samples. When bacteria come into contact with the sensor surface, they induce a measurable mass change. This mass change can be precisely detected and quantified by the transducer, allowing for the identification and analysis of microbial contamination in various types of fluids.

6. Microbiological Testing Methods

Although traditional culture-based methods provide sufficient bacteria counts to enable pathogen identification, they have very long incubation times that delay treatment considerably. Various methods based on immunoassays or polymerase chain reaction (PCR) are available to accelerate the detection of common bacterial pathogens. PCR-based techniques offer several advantages over culture techniques, including higher sensitivity, and the ability to detect viable but non-culturable cells; the requirements for specialized detection systems, and the fact that dead cells are detected make that assays do not necessarily provide information whether the detected bacteria are still viable. Regions of bacterial DNA are used as targets, including the 16S rRNA gene, alternative housekeeping genes, or genes conferring resistance to specific antibiotics [1]. Immunoassays such as ELISA or lateral flow assays are relatively easy to employ, are cost-effective, and mostly focus on detection of bacterial toxins. However, the requirement of a pre-enrichment of bacterial concentration and the specific link to bacterial toxins, often leads to low sensitivity and is associated with an increased risk of false negative detection. Several bacterial species of clinical interest have been already investigated and materials with bacterial adhesion (such as lectins, lectin-like bacteriophages, antimicrobial peptides or hydrophobic/positively charged materials) have been used as recognition elements on some of the available platforms [10].

The major chemistry of nanoparticle-based optical sensors for pathogenic bacterial detection are also reviewed since nanoparticles have optimized the detection quality of sensor systems. Accordingly the synthesis and essentials of nanotechnology are introduced with detailed engineering using size and morphology of nanoparticles. The purpose of the review is to critically discuss the literature focusing on nanoparticle-based optical sensors and their applications toward pathogenic bacterial identification and detection. Bacterial counts below 10 colony-forming units per millilitre of blood are not sufficient for identifying bacteria using non-DNA based techniques; only bacterial cultures can provide the necessary amount for accurate diagnosis [5].

7. Integration of Nano-Biosensors with Microbiological Tests

Microbiological tests are analytical procedures used to determine the presence of microbial contaminants and identify pathogenic microorganisms from environmental sources [6]. Nano-biosensor technologies advance these techniques by providing enhanced detection capabilities for early identification of microbial contaminants in blood samples. Microbiological tests encompass a range of methods including Gram staining, acid-fast staining, enzyme-based and microscope-based approaches, culture-based and molecular-based analyses, antibiotic sensitivity testing, phage typing, and serological tests [1]. Nano-biosensors complement these conventional assays by facilitating the rapid and sensitive detection of microorganisms, thereby improving the overall efficacy of contamination assessment procedures in blood analysis.

8. Advantages of Nano-Biosensors in Microbial Detection

Nano-biosensors, employing nanoparticles and nanomaterials, offer several advantages for

microbial contaminant detection [1]. Their increased surface-to-volume ratio enables the use of smaller biochemical components, improving sensitivity. These devices maintain high sensitivity comparable to traditional laboratory methods while reducing energy consumption, time, costs, and requiring less complex sample preparation. Miniaturization makes nano-biosensors highly portable, and their materials enable specific bounds. Structure variations influenced by reagents can affect behavior, allowing small mismatches or mutations to modify the sensor's response, potentially enabling species or strain identification with enhanced data analysis and machine learning. A discernible response within seconds is possible due to the sensor's small volume [5].

8.1. Sensitivity and Specificity

The efficacy of nano-biosensors (NBS) in detecting low concentrations of microbial contaminants in blood is governed by their sensitivity and selectivity [11]. The necessity for data acquisition in NBS arises from the search for transducer elements capable of sensing and enhancing specific molecular interactions within a mixture of numerous non-target species. The performance characteristics of an NBS assay are frequently represented by the limit of detection (LOD), analytically defined as the smallest amount of particular analyte measured in a matrix that can be reliably distinguished from the blank, and sensitivity—quantitatively described by the calibration curve's steepness, indicating the efficiency with which the sensor transduces analyte concentration variations into measurable signals. Selectivity denotes the ability to discriminate the target bacterial analyte from others, a property dictated entirely by the recognition element; in principle, no cross-reactivity with nontarget analytes occurs. The reported sensitivity of NBSs ranges from nanomolar to femtomolar levels, and efforts also focus on improving specificity, which has enhanced measurement quality and the ability to discriminate closely related species, strains, and even serotypes [1].

8.2. Rapid Response Time

The screening of microbes in a sample necessitates sensitivity at very low concentrations—typically below the detection threshold of standard methods—and a rapid response time. Conventional microbiological tests are time-intensive, often requiring several hours before completion. Sensors assist microscopists during the initial examination, providing early warnings that enable prompt identification of the causative micro-organisms. Due to their affordability and portability, they are well-suited for rapid, on-site analyses. It is particularly crucial to detect contamination events as swiftly as possible to mitigate their effects [11] [12].

8.3. Portability and Ease of Use

The portability and user-friendliness of nano-biosensors play a decisive role in their widespread application. Portable devices facilitate not only on-site analysis but also enable personnel without specialized training to gain reliable results. Biosensors, in this regard, reduced their size while preserving sensitivity and specificity [13]. Portable devices are preferred over stationary instruments, as they can be employed anywhere and maintain their performance while being transported. Because handheld biosensors can take advantage of the electronic platform of smartphones, relatively low-cost yet sophisticated portable biosensors can be fabricated. Nanomaterials that feature inherent flexibility present numerous benefits regarding the development of portable biosensors owing to their ability to maintain electronic, mechanical, and optical properties under various bending and stretching conditions.

The preparation of the sample for the biosensing platform has a critical role in biosensor portability. The sample exhibited may be less portable than the various sensing platforms if sample preparation involves the use of non-portable laboratory equipment and reagents. Incorporating microfluidics with biosensor platforms is a suitable strategy for enhancing biosensor portability. Microfluidic biosensors facilitate the processing of the sample prior to the biosensor's operation in a single, compact, and portable device. These biosensors can concentrate an analyte wherein the concentration of metabolites in human breath remains below the detection limits of

most conventional assays. Paper-based biosensors are suitable for–point-of-care testing because of their compatibility with colorimetric, fluorescence, chemiluminescence, and electrochemical detection. Specific analytes such as viral RNA have been detected directly from clinical samples without any pre-processing. Furthermore, uric acid has been measured in whole blood with a small volume of reagents and a short reaction time. Despite the numerous advantages, some microfluidic platforms require external pumps and other equipment to operate, consequently limiting the biosensor's overall portability.

9. Challenges in Implementation

The successful implementation of nano-biosensor technology into mainstream clinical practice requires a multi-component system. This system consists of the biosensors, on-board sample processing, and a readout system integrated into a single affordable platform. Although biosensors facilitating the early detection of blood contamination have improved sensitivity (other methods provide results at a later stage when it is more difficult to treat the patient), further advancement is necessary. Extant devices may falter or become non-functional when exposed to false-positive specimens or environmental insults, such as rise in temperature. The cost of nano-biosensor production is often prohibitive of widespread use. For example, paper-based substrates are highly advantageous but they tend to have poor analytical characteristics when compared to solid polymer (e.g., polyester, PET, PMMA, PC, and COC) substrates. Additionally, nano-biosensors can be incompatible with already poor infrastructure due to sample storage requirements and reduced shelf-life. Finally, government regulations often restrict the application of certain reagents and procedures; therefore some nano-biosensor platforms become compromised for large-scale deployment [14]. A successful multi-component nano-biosensor system needs to simultaneously address all of the above specifications [1]. Integration of these components into a unified nano-biosensor platform will facilitate effective point-of-use (POU), point of care (POC), or in-field testing.

9.1. Technical Limitations

Numerous studies have reported micro-organisms that have developed their resistance towards current drugs. Microbial contamination has been a worldwide issue. One of the main factors of microbial contamination is blood. A blood product, blood component or a blood derivative (such as a blood transfusion, blood donation, intravenous drug delivery and plasma derivatives) is associated with the transmission of communicable pathogens. The microorganism transmission is by any of the modes of entry of the microorganism through a person's body, such as the skin, mucous membranes of the eyes, mouth and nose; structures including the gastrointestinal tract and respiratory tract; or through the genitourinary tract.

Micro-organisms can be transmitted through blood through various routes, as listed below: • Skin to skin contact. • Contact with surfaces and inanimate objects. • Droplets of airborne (<5μm in size) or respiratory (>5μm in size) secretions. • Blood/blood products or body fluid transference. • Contaminated sharps.

The issue on microbial contamination did not receive immediate attention. However, with numerous outbreaks of deadly diseases that were reported to be transmitted through blood (such as severe acute respiratory syndrome, Ebola virus and HINI virus), the issue has triggered a rapid attempt from all related authorities to come out with a solution before it becomes another severe and deadly worldwide epidemic.

An exciting advancement in the field of wireless medicine and surgery and battery health systems is the development of nano-bio sensors attached or implanted within human beings and animal tissue, where nano-tech-based components are utilized. At the core of every nano-bio sensor lies a biological component that is capable of recognizing a target analyte in the close vicinity of the sensor surface [1]. Some examples of biological components are tethered antibodies and aptamers. The biological component is coated on the surface of the sensor. Once the target analyte binds to

the biological component, the sensor produces a response (electrical or optical). These sensors are then connected to a data processing system that converts the signal produced by the sensors into a measurable value.

9.2. Regulatory Hurdles

Blood represents a sterile tissue comprising a complex mixture of cells suspended in a protein-enriched aqueous fluid known as plasma. A key challenge arises when microorganisms contaminate this vital physiological fluid through infections or handling procedures. Nano-biosensors have been integrated with microbiological tests for early detection of microbial contaminants in blood with improved accuracy and speed while maintaining high reliability. Microbial contamination in blood manifests as microbial samples-derived materials originating from bacteria, proteins, fungi, and extracellular vesicles present in the bloodstream or blood culture and related samples. Microbial samples are usually recognized as single molecular or cellular specimens with specific biological, chemical, and physical properties [15]. Microbial contamination in blood culture sample results from systemic microbial infections, microbial samples entry during clinical procedures, or improper handling of blood samples during phlebotomy.

Employment of nano-biosensors in microbial detection remains an incipient approach that requires precise implementation to ensure several pertinent issues do not compromise the significance of this application. Nano-biosensors contribute size, surface charge, and zeta potential properties that render them valuable in diverse applications such as therapeutic delivery and cellular labeling. Yet, a clear appreciation of their implementation in microbe detection within blood samples is critical to prevent detrimental genomic and proteomic outcomes from such contamination.

9.3. Cost Considerations

Continuous efforts are underway to develop low-cost detection methods. Point-of-care biosensors (POCBs) can operate on low power and provide easy access for early detection of diseases without the need for complicated sample preparation and handling. Impedance spectroscopy is a widely adopted electrical detection approach in biosensors. In impedance-based biosensing, ions dissolved in the solution of interest accumulate to form an electrical double layer (EDL) that shields the electric field and changes the capacitance at the sensor surface, resulting in deterioration of sensor performance at low frequencies, which are the frequencies of interest for impedance spectroscopy. The EDL also limits the detection within a small distance from the electrodes, which in turn increases the sample volume for testing, lowering the sensitivity of the biosensor. Thus, the EDL effect poses a significant challenge for the development of electrical impedance-based biosensors. A biosensor design with integrated nanogaps between electrodes is demonstrated with the goal of overcoming the EDL effect and improving sensing performance [16]. The nanogap electrodes are placed in a coplanar, face-to-face arrangement to enable low-frequency molecular detection. The sensor uses a low-frequency measurement technique that eliminates the double-layer shielding and confines the electrical field within the nanogaps. Such a field is able to penetrate through the entirety of the EDL, enabling detection of biomolecules of interest even at very low frequencies. The sensor consequently exhibits a significantly higher sensitivity compared to traditional planar electrodes of the same gap spacing. This work also investigates the potential deployment of biosensors for point-of-care diagnostics in developing countries, considering technological, economic, and regulatory aspects [17].

10. Case Studies of Nano-Biosensors in Clinical Settings

Nanoarray sensors applied to breath analysis successfully detected and discriminated different disease conditions with an accuracy of 86%. This performance exploited the unique ‘‘breath prints’’ produced by each disease. In biomedical sciences, nanotechnology has been applied for early detection of bacteria, prevention of biofilm formation, and management of bacterial resistance. Nanoparticles represented by gold, copper oxide, silver, nitric oxide and magnesium

inhibit biofilm formation. Table 1 reports several examples of nanoparticles with intrinsic antibacterial powers (further enhanced when combined with antibiotics) based on the progressive release of metal ions, generation of reactive oxygen species (ROS), and different types of membrane disruption. These inorganic nanoparticles have also been used as drug carriers for antibiotics and for rapid and accurate detection of bacteria. Gold and silver nanoparticles are employed as integral elements in nano-biosensors that leverage the localized surface plasmon resonance to achieve utmost sensing performance in terms of sensitivity and detection limit [1].

11. Comparative Analysis of Traditional Methods vs. Nano-Biosensors

Microbial contamination of blood is a significant threat in healthcare settings worldwide [1]. The presence of microbes in blood can cause severe illnesses and, if untreated, often result in death. Therefore, early-stage detection of microbes and their byproducts is of great concern for medical practitioners as well as public/health departments. Several nanotechnology projects currently focus on the development of ultrasensitive nano-biosensors for extremely rapid detection of microbes in blood. Coupling traditional microbiological testing methods with nano-biosensors enhances early detection accuracy. Several detection technologies that meet these criteria are available. Nano-biosensors detect types and approximate amounts of microbial contamination by observing changes in impedance, fluorescence, or ultrasounds. They utilize electrochemical, optical, and mass-based methods. Microbiological testing methods are commonly divided into five types, which can be combined to develop integrated processes for early detection in contaminated blood products.

Microbial contamination of blood is a worldwide threat. The presence in blood of microbial agents—bacteria and/or fungi—and their byproducts gives rise to acute illnesses that often leads to death if left untreated; blood-borne pathogenic agents account for more than fourteen million deaths annually, based on World Health Organization estimates. Early-stage detection of bacteria and their byproducts are therefore a significant concern for medical practitioners, public health departments, and the military. Several nanotechnology-enabled projects are focused on the development of ultrasensitive nano-biosensors capable of very rapidly detecting microbes in blood. Such ultrasensitive nano-biosensors, coupled with associated conventional microbiological tests, enhance early microbial contaminant-detection accuracy. Several detection technologies exist with the potential to meet these requirements. Nano-biosensors can detect the type of microbial contamination present and provide an approximate indication of its magnitude by monitoring perturbations in the electrical complex impedance, fluorescence emission, or ultrasonics signal. They are generally based on electrochemical, optical, and mass-sensitive principles. Microbiological-testing methods generally fall into five categories. Combinations of techniques from different categories can be integrated into new procedures for rapid early microbial-detection in contaminated blood products.

12. Future Trends in Nano-Biosensor Technology

Nano-biosensors are undergoing significant development, with efforts focusing on enhanced reusability, portability, and sensitivity, as well as commercial and economic viability [1]. Additional work aims to expand the range of detectable analytes, reduce response times, and simplify instrumentation and readout procedures. The integration of novel nanostructured materials, including hybrid materials, holds promise for improved sensor platforms. More rigorous research is required to address issues such as selectivity and reproducibility, which are crucial for achieving practical, routine applications. These trends suggest that nano-biosensor technology will become increasingly effective in early detection of microbes in blood samples.

13. Conclusion

Microbial contamination of blood is a significant concern for maintaining the health of transfusion recipients. Ultimately, the presence of microorganisms in blood can lead to many diseases depending on the type of bacteria or virus found. These microorganisms can produce endotoxins

that cause various symptoms and diseases of the body. With the available detection methods, accurate detection remains difficult because microorganisms are so small. Therefore, combining nano-biosensors with microbiological tests for the early detection of microbial contaminants in blood can improve the accuracy of detection results.

Nano-biosensors are devices that can detect biological molecules, including bacteria and viruses, by utilizing changes in physical, chemical, or biological properties. Three types—electrochemical, optical, and mass nano-biosensors—have been recently developed. Despite the demonstrated potential of integrated nano-biosensors for early detection, further work is necessary to establish a more effective approach for accurately detecting these biological contaminants. Early detection of microorganisms in blood can save many lives.

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