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The role of smart technologies in wastewater-based epidemiology

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Abstract

This article explores the role of smart technologies in advancing Wastewater-based epidemiology (WBE) for enhanced disease surveillance. Disease surveillance is crucial for monitoring and controlling infectious diseases, and WBE provides a complementary approach by analyzing wastewater to identify and track pathogens. During the COVID-19 pandemic, WBE has been successfully used to detect and monitor *SARS-CoV-2* in various types of wastewater, providing early warning of outbreaks and identifying emerging hotspots. However, WBE faces challenges such as the need for specialized equipment and sensitive methodologies. To overcome these limitations, biosensors have been developed, offering high sensitivity, specificity, and rapid results. Electrochemical biosensors are particularly promising for WBE due to their real-time connectivity, low-cost design, and wireless data collection, despite their limitations. Integration of smart sensors into the Internet of Things (IoT) enables seamless data integration and real-time monitoring. Furthermore, the widespread use of smartphones presents an opportunity to revolutionize smart diagnostics by leveraging their features for data analysis and communication.

Keywords: Disease surveillance, wastewater-based epidemiology, biosensors, smart technologies, internet of things

INTRODUCTION

Disease surveillance is the ongoing, systematic collection, analysis, interpretation, and dissemination of health data. It is a key component of public health efforts to monitor and control infectious diseases[1]. The main goals of disease surveillance are to identify and track the spread of disease, determine the impact of disease on communities, and provide the information needed to design and implement effective prevention and control measures[1-4]. Surveillance can be conducted at various levels, including local, national, and international. It involves the collection of data from a variety of sources, such as medical records, laboratory reports, and reports from healthcare providers and public health agencies. The data are analyzed to identify trends, patterns, and risk factors for diseases, and to inform the development of public health policies and programs[2,5]. There are different types of disease surveillance, including passive surveillance, which relies on the reporting of cases by healthcare providers and laboratories, and active surveillance, which involves actively seeking out and identifying cases through systematic efforts[6,7]. Effective disease surveillance requires strong collaboration and coordination among public health agencies, healthcare providers, and other partners, as well as the use of technology to facilitate the collection, analysis, and dissemination of data. It is an essential tool for protecting public health and preventing the spread of infectious diseases[1,8].

DISEASE SURVEILLANCE THROUGH WASTEWATER

WBE is a public health field that uses the analysis of wastewater to identify and monitor infectious agents such as viruses and bacteria, and to study their occurrence and spread in a given population[7]. Prior to their use with infectious agents, WBE has been used as an innovative tool to monitor human exposure to xenobiotics and chemicals. By analyzing wastewater samples, which contain a wide range of excreted compounds, WBE can provide valuable insights into the collective chemical exposure of a population. It allows for the detection and quantification of various substances, including pharmaceuticals, illicit drugs, and environmental pollutants. WBE offers a non-intrusive and cost-effective approach to monitor trends, identify hotspots of exposure, and inform public health interventions aimed at mitigating potential risks associated with exposure to these substances[9]. The field of WBE has predominantly been developed, standardized, and orchestrated for its application in identifying and quantifying drug use within communities[10-12]. During the recent COVID-19 pandemic, numerous efforts were made to tackle the spread of *SARS-CoV-2* in the population, including the implementation of WBE surveillance systems in many countries[2,13,14]. *SARS-CoV-2* RNA has been detected and monitored in various types of wastewater, including municipal and hospital wastewater[3,15-18], as well as polluted surface water not connected to a sewage system[2,19,20]. Monitoring of *SARS-CoV-2* in wastewater has proven to be an effective complementary tool to track the spread of the virus in communities[2]. It has been used to identify emerging hotspots, estimate the number of infected people and provide early warning of potential outbreaks[21,22]. However, it also has limitations, such as the need for specialized equipment and expertise, and the need for extremely sensitive methodologies[3,18,23].

The ultimate goal of WBE is to provide real-time, on-site data to detect infectious agents in time to provide early warning of infectious disease outbreaks. Current detection and quantification methods either have low sensitivity, such as ELISA assays, or are time-consuming and expensive, such as (RT)-qPCR[24]. To overcome these limitations, biosensors have recently been developed that have the potential to be used for wastewater monitoring with remote access to the data in real time[11,23,25]. Despite undeniable improvements in recent decades, the burden of infectious diseases and antimicrobial resistance remains high. Emerging and re-emerging infectious agents have persisted throughout the twenty-first century, and new trends in globalization and climate change point to a new era of infectious diseases[26]. Real-time monitoring of infectious agents in wastewater and receiving water needs to be further explored.

THE USE OF BIOSENSORS TO QUANTIFY PATHOGENS IN WASTEWATER

Biosensing techniques use smart affinity materials and nanomaterials that can be used to track pathogens and biomarkers in wastewater through biochemical reactions mediated by a biological receptor element[27]. They are increasingly being used for disease detection, as they offer several advantages over traditional methods[11]. One of the main advantages of biosensors for disease detection is their sensitivity and specificity. Biosensors can detect very small amounts of a substance, and they are highly selective, meaning they can distinguish between different substances with high accuracy. This allows them to detect the presence of specific disease-related biomarkers in a sample with a high degree of precision[28]. Another advantage of biosensors is their speed. Many biosensors can provide results in real time, making them useful for rapid diagnostic testing. This can be particularly useful in the early stages of an outbreak when quick action is needed to prevent the spread of a disease. Despite the promising advantages, these technologies are still in their infancy[23,29].

There are a variety of biosensors available for disease detection, including those that use enzymes, piezoelectric elements, DNA, and other biological molecules to detect the presence of specific substances[30]. Some of the biosensing types include enzyme-based sensors, which are made with proteins that catalyze chemical reactions, to detect the presence of specific substances. The enzymes are usually immobilized on a surface, such as a microelectrode or a nanoparticle, and the reaction they catalyze is used to generate a signal that can be measured[31]. Antibody-based sensors use antibodies that recognize and bind to specific substances[32]. Another technique is DNA-based sensors, which use DNA or RNA molecules. The DNA or RNA molecules are designed to specifically bind to the target substance. Electrochemical sensors use an electrode to detect the presence of specific substances. The electrode is typically coated with a material that is sensitive to the presence of the target substance, and the reaction of the target substance with the electrode is used to generate a signal that can be measured. Optical sensors use light to detect the presence of specific substances. The light may be generated by a laser or other light source, and the interaction of the light with the target substance can be measured[25,33].

Among biosensing techniques for infectious agent detection, electrochemical biosensors are the most feasible options. The advantages of electrochemical biosensors include the fact that no sample preparation is required, they can be used in a variety of matrices, enable rapid detection, boast low-cost sensor design, support multiplexable capabilities and facilitate wireless data collection[34]. Electrochemical biosensors also enable not only detection but also estimation of the amount of target analyte. Investigation and identification of highly sensitive biorecognition elements, including antibodies, aptamers and imprinted polymers, are needed. Aptamers have several advantages and are particularly promising for novel viruses for which no antibodies are known[25]. Given the typically low concentrations of viruses such as *SARS-CoV-2* in wastewater[3], particularly during periods of limited community infection rates, the precision of electrochemical biosensors for detection poses a challenge. Notably, the necessity for higher viral loads for effective detection suggests that real-time monitoring might not yield further insights beyond data collected from active hospitalizations. Importantly, the critical window for *SARS-CoV-2* detection precedes outbreaks, when wastewater viral levels are minimal. Given the current lack of a robust approach for substantial sample concentration, ongoing research and development are imperative to establish a method for significant sample concentration before quantification, especially for complex matrices such as wastewater with a high abundance of inhibitory substances[3,34,35].

TOWARDS SMART, DATA-DRIVEN DISEASE SURVEILLANCE

The development of smart sensors for WBE has become increasingly important in recent years. To effectively monitor and track the spread of infectious agents, these sensors must be designed with high sensitivity and specificity to avoid false-negative and false-positive results. In addition, the ability of these sensors to connect to other smart systems and end users/decision makers via the Internet is critical for seamless data integration and real-time monitoring[33]. The use of digital technologies such as machine learning, deep learning, big data analytics, artificial neural networks and artificial intelligence is critical to the success of a smart WBE. The concept of the IoT plays a key role in connecting and exchanging data between smart devices and systems, making them smarter, more reportable, controllable, and manageable. By leveraging the power of IoT, smart WBE sensors can be seamlessly integrated into Industry 4.0, Analytics 4.0 and Healthcare 4.0, paving the way for real-time connectivity, data sharing, analytics, and optimization. This integration leads to the generation of smart data, which in turn serves as a valuable resource for intelligent decision-making in disease monitoring and control[36].

The widespread adoption of smartphone technology has the potential to revolutionize the field of smart diagnostics. Smartphones are an incredibly versatile tool with a wide range of features that make them an ideal platform for healthcare applications[37,38]. They can be used as miniature computers for data analysis, imaging and communication, all essential components of smart diagnostics. In addition, the availability of high-speed wireless connectivity and data-sharing modes enables real-time communication between the smartphone and other smart devices, making it an indispensable tool for smart diagnostics[39]. It is worth noting that the high penetration of smartphones around the world - more than 90% of the world's population using smartphones - makes them an accessible and cost-effective technology for smart diagnostics. This provides an opportunity to develop novel approaches that harness the power of smartphone technology to facilitate smart diagnostics, especially in resource-limited settings[40,41].

Biosensors to be used in WBE must meet additional criteria beyond real-time connectivity, sensitivity, and specificity. Ten criteria for diagnostic devices/tests based on the World Health Organization ASSURED criteria have been proposed, known as REASSURED (Real-time connectivity, Ease of specimen collection, Affordable, Sensitive, Specific, User-Friendly, Rapid and Robust, Environmentally friendly, Deliverable to end-users)[42]. Microfluidic and nanofluidic technologies have recently emerged as miniaturized platforms with capabilities of molecular-scale sensitivity on low-cost and rapidly fabricated devices[e][43-45]. Despite their potential, these platforms have not yet been adopted in clinical diagnostics and disease surveillance[46], but they represent a promising future in disease surveillance.

DECLARATIONS

Authors' contributions

The author contributed solely to the article.

Availability of data and materials

Not applicable.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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