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Identification of pathogenic bacteria by biosensors in water and wastewater

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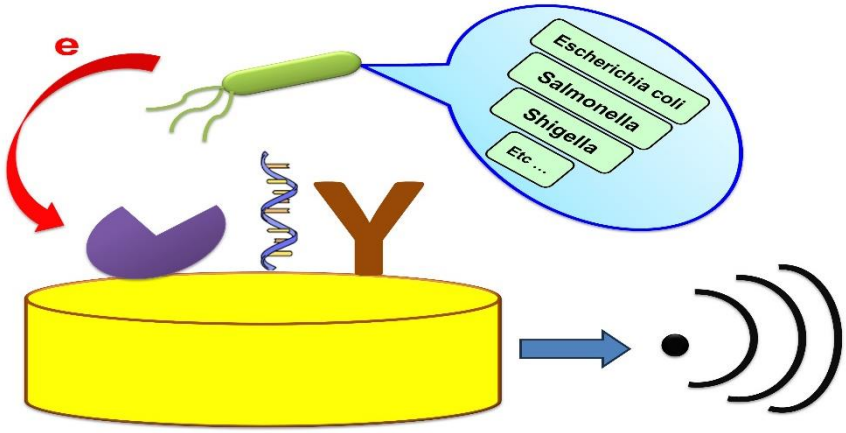
GRAPHICAL ABSTRACT



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Abstract

Pathogenic microorganisms, such as *Escherichia coli, Salmonella, Pseudomonas aeruginosa, Mycobacterium tuberculosis, Staphylococcus aureus, Klebsiella pneumoniae, legionella, Shigella and etc.* can contaminate drinking water and lead to disease and even death. On the other hand, due to the ability of antibiotics to prevent or treat bacterial infections, they have been used as the main method of infection treatment in humans and animals for the past two decades. The irresponsible use of these antibiotics is one of the most important reasons for the emergence of microbial resistance, which has become a global issue. Therefore, timely diagnosis of these pathogens is very important. the use of specialized personnel, machines, and tools in molecular methods such as enzyme-linked immunosorbent assay (ELISA) and polymerase chain reaction (PCR) are expensive, and traditional methods such as plate culture are time-consuming. Today, a variety of biosensors are reported to identify these bacteria, which are fast, accurate, and cost-effective. In this review, we described a number of important pathogenic bacteria and biosensors made to identify these pathogens.

1. Introduction

Pathogenic bacteria cause disease, hospitalization, and death of over 15 million people worldwide each year. These pathogens directly affect human health, the safety of food and drinking water sources. So far, several pathogens have been identified, including *Escherichia coli* (*E. coli*). The Strains of Uropathogenic *Escherichia Coli* (UPEC) are causative agents in urinary tract infections (Mulvey *et al.*, 2000). *Staphylococcus aureus* with the production of several toxins are the most important causes of microbial contamination and food poisoning (Berrettoni *et al.*, 2004). According to previous reports, contamination of water sources with the pathogen *P. aeruginosa* causes hospitalization and death of thousands of people in the United States annually (Anaissie, Penzak and Dignani, 2002). *Salmonella enterica* subspecies *enterica serovar Typhi* (*Salmonella typhi*) causes typhoid fever and severe gastrointestinal issues in humans mainly via contaminated food and water (Mathai *et al.*, 1995; Kidgell *et al.*, 2002; Quaresma *et al.*, 2022). *Shigella* is another important pathogenic bacteria that contaminate water and food, and the agent of Shigellosis is an acute invasive enteric infection that causes severe diarrhea and digestive diseases. Pathogenicity caused by this pathogen is a major challenge in many countries, especially developing countries. Obviously, consuming clean water is one of the ways to prevent the epidemic of this bacteria (Schnupf and Sansonetti, 2019; Bengtsson *et al.*, 2022).

Considering the infection and pathogenicity caused by these microorganisms, their timely identification is very important, but the use of specialized personnel, machines, and tools in molecular methods such as enzyme-linked immunosorbent assay (ELISA) (Rajapaksha *et al.*, 2019) and polymerase chain reaction (PCR) are expensive, and traditional methods such as plate culture are time consuming (Sieuwerts *et al.*, 2008;Valones *et al.*, 2009;Does, 2013;Rajapaksha *et al.*, 2019). In recent years, biosensors have overcome the problems and limitations of traditional methods and have attracted a great deal of

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attention in medicine, food and beverage safety, and health owing to their simplicity, high speed, and being inexpensive (Amiri *et al.*, 2018).Some of these biosensors and their details are gathered in Table 1.

2. Biosensors

Biosensors are analytical devices that are used to determine the presence and concentration of a particular analyte in a biological analysis that are generally composed of several basic components required for functionality. Biosensors components include the bioreceptors, transducer, and biosensor reader (Fig. 1) which are described in the following.

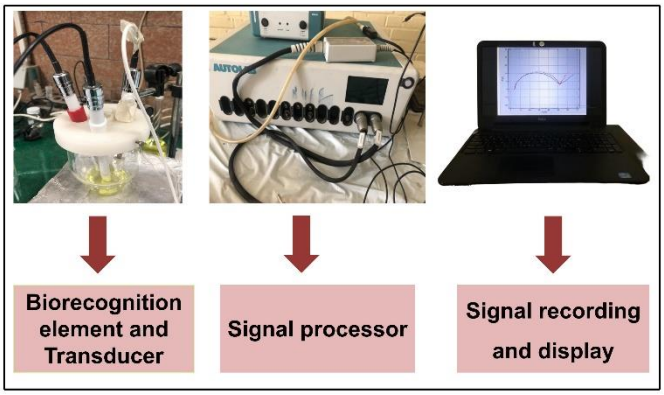

Fig. 1. A three-electrode electrochemical system.

2.1. Bioreceptors

This part performs the act of identifying a specific analyte which is one of the most important parts in the biosensor. Various biological bioreceptors have been used in the construction of biosensors such as DNA (Izadi *et al.*, 2016), RNA aptamer (Wu *et al.*, 2012;Zhang *et al.*, 2018), antibody (Yang, Li and Erf, 2004), enzyme (Kaur *et al.*, 2021;Soy, Sharma and Nigam, 2022), etc., to identify bacterial components.

2.2. Transducers

Transducers are devices that convert energy from one form to another. Biosensors cite the cooperation of receptors that identify target analytes and the transducers that convert this recognition to a detectable signal. (Kaur *et al.*, 2021).

2.3. Biosensor reader

Transducer in the biosensor is directly connected to a biosensor reader that records the results and signals from the transducer and displays them in a user-friendly way, which can be a computer.

2.4. Signal amplifier

Amplification of signals from analyte interaction with bioreceptors is directly related to improving the sensitivity of biosensors designed to identify bacteria. A signal amplification method in different categories of biosensors such as optical, electrochemical, piezoelectric, and thermal biosensors is the use of nanomaterials such as gold nanoparticles in electrochemical and piezoelectric biosensors (Roushani and Shahdost-Fard, 2015;Devi, Sasidharan and Sundramoorthy, 2018;Pohanka, 2018;Fang *et al.*, 2019; Bharti *et al.*, 2020;Yadav, Chhillar and Rana, 2020), silver nanoparticles in optical and electrochemical biosensors (Jiang *et al.*, 2012;Wang *et al.*, 2015), other metal and their oxides nanoparticles, (Muniandy *et al.*, 2019;Pangajam, Theyagarajan and Dinakaran, 2020), and magnetic nanoparticles (Pedrero, Campuzano and Pingarrón, 2012), carbon nanostructures (Ng and Liu, 2009;Jahanbakhshi and Habibi, 2016;Douaki *et al.*, 2020;Pangajam, Theyagarajan and Dinakaran, 2020;Amri, Shukla and Lee, 2021), and quantum dots (Jahanbakhshi and Habibi, 2016;Douaki *et al.*, 2020) (Li *et al.*, 2020;Pangajam, Theyagarajan and Dinakaran, 2020;Choi *et al.*, 2021) in optical and electrochemical biosensors, etc. These nanomaterials can affect the performance of biosensors by providing properties such as creating a high surface-to-volume ratio as a result of creating a broad substrate for the stabilization of other materials and by affecting the electrical or optical properties of the biosensors.

3. Construction and classification of transducers in biosensors

Biosensors are as a combination of bioreceptors and transducers based on identifiable signals are classified into four general categories, including electrochemical (Arduini *et al.*, 2019), optical (Wu *et al.*, 2012), piezoelectric, and thermal signals (Fig. 2) (Muramatsu *et al.*, 1989;Arreguin-Campos *et al.*, 2023). In these devices, the specific output can be electrical current, resistance potential, fluorescence, piezoelectric temperature changes, or mass changes, based on which biosensors convert the signals from analytes to detectable biological inputs.

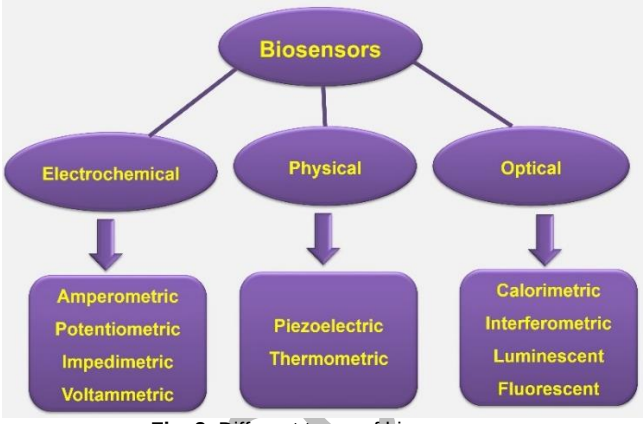

Fig. 2. Different types of biosensors.

4. Pathogenic bacteria and biosensors designed to detect these pathogens

4.1. *Escherichia coli* bacteria and its biosensors

E. coli is a commensal of humans, but also a major pathogen. Consequently, most isolates are innocuous, but some of them cause severe food-borne infections in humans. This gastrointestinal infections can be caused by the transmission of this pathogenic bacterium by contaminated vegetables, such as lettuce, spinach, contaminated water, and raw or poorly pasteurized milk. Members of some pathovars of this bacterium, such as *E. coli O157:H7*, and *E. coli O104:H4*, produce deadly toxins such as Shiga toxin that cause infection and dissemination in live organs (Pandey *et al.*, 2017;Zaraee *et al.*, 2020). Such an infection with enterohaemorrhagic *E. coli O157:H7* can lead to dysentery and, if not diagnosed early and treated quickly, can lead to renal failure and death. Due to the severity of infection by these pathovars of *E. coli*, the diagnosis time and prevention measurements are highly important.

Zaraee et al. designed an optical biosensor for *E. coli* bacteria. This biosensor consists of a modified chip and an optical setup. The chip contains a Si/SiO_2 layered substrate modified with MCP-4 copolymer (copoly DMA-NAS-MAPS). *E. coli* antibody was immobilized on the MCP-4 and bovine serum albumin (BSA) was used as negative control instead of *E. coli* antibody. The prepared chip was then placed under an optical setup, and detection was performed very quickly using the Interferometric Reflectance Imaging Sensor (IRIS) sensitive detection and imaging technique, without the need of complex methods and a skilled user. The Limit of detection (LOD) in this biosensor was reported 2 CFU/mL. The specificity of this biosensor was validated by comparing the response of that to target bacteria *E. coli* and non-target bacteria such as *S. aureus, K. pneumonia, and P. aeruginosa.* The performance of biosensor was investigated in tap water sample (Zaraee *et al.*, 2020).

Pourmadadi *et al.* designed an aptasensor using glassy carbon electrodes (GCE) modified with graphene oxide (GO) and gold nanoparticles to detect *E. coli* lipopolysaccharides (LPS) type O55:B5 based on voltammetry method. The electrode demonstrated desirable selectivity and the LOD of this biosensor was obtained 30 fg/mL. To design this biosensor, Mg/CQD (carbon quantum dot) was used as the redox-active medium to reduce the electrochemical potential in LPS detection. The specificity of this biosensor was confirmed by comparing the signal response of the nanoprobe electrode to LPS compared to the non-target analytes of glucose, albumin, and fetal bovine serum (Pourmadadi *et al.*, 2019).

4.2. Shigella dysenteriae and its biosensors

Shigella is a gram-negative bacterium without spores and a major cause of dysentery. This bacterium was named after its discoverer Kiyoshi Shiga, who was a Japanese bacteriologist. There are four subtypes of this bacterial species, and all of them are capable of damaging the epithelial cell lining of the large intestine. The type of dysenteriae can cause long and widespread epidemics, resulting

infection being more severe, possessing a longer duration than other Shigella species, and often associated with mortality. Successful infection of this pathogen can require less than one hundred cells. The symptoms of *Shigella* are nausea, pain, and abdominal cramps. This bacterium is similar to *E. coli* (infact a subspecies of *E. coli* possessing species status due to particular infection phenotypes) and *Salmonella* and only causes pathogenesis in humans and primates. Dairy products, and contaminated milk and water samples can be the main sources of this bacterium (Mukama *et al.*, 2017).

Table 1. Different types of biosensors for identifying pathogenic bacteria.

Metod	Biorecognition element	Target analyte	Linear dynamic range	LOD	Reference
Electrochemical	Biorecognition element free	*E. coli*	$10^{3.2}$~10^{6} CFU/mL	$10^{3.2}$ CFU/mL	(Lin *et al., 2022)*
Electrochemical	Carbohydrate	*E. coli*	1.3 × 10 ^{1}~1.3 × 10^{6} CFU/mL	2 CFU/mL	(Hargol Zadeh, Kashanian and Nazari, 2023)
Electrochemical	Anti-E. coli antibody	*E. coli*	-	53 CFU	(Malhotra *et al.*, 2022)
Electrochemical	DNA Biosensor	*E. coli*	1 × 10^{-10} to 1 × 10^{-5} µM	1.95 × 10^{-15} µM	(Yuhana Ariffin *et al.*, 2020)
Electrochemical	Biochar-based immunosensor	*E. coli O157:H7*	10^{4} to 10^{7} CFU/mL	4 log CFU/mL	(Sobhan *et al.*, 2022)
Electrochemical	Antigen−antibody-based	*H. pylori*	0.1 to 12.8 ng/mL	0.3 μA^{-1} ng /mL	(Saxena *et al.*, 2022)
Colorimetric	Aptamer	*Salmonella typhimurium*	10 to 10 ^{7} CFU/mL	7 CFU/mL	(Wei *et al.*, 2022)
Colorimetric	Aptamer	*Salmonella typhimurium*	-	3.2× 10^{3} CFU/mL	(Li *et al.*, 2023)
Fluorescence	Aptamer-functionalized horseradish peroxidase	*Shigella*	2.3 × 10^{2} to 2.3 × 10^{7} CFU/mL	32 CFU/mL	(Song *et al.*, 2023)
Fluorescence	Aptamer-Based	*Shigella sonnei*	10^{3} to 10^{7} Cells/mL	10^{3}–10^{7} Cells/ mL	(Song *et al.*, 2017)
Fluorescence	Aptamer	*Salmonella typhimurium*	30 to 3 × 10^{4} CFU/mL	13 CFU/ mL	(Liu *et al.*, 2022)
Fluorescence	Nanoprobe-Based FRET	*Shigella*	1.2 × 10^{2} to 1.2 × 10^{8} CFU/mL	30 CFU/mL	(Chen *et al.*, 2022)
Optical	Oligonucleotide-Gold Nanoparticles	*Salmonella spp*	-	<10 CFU/mL	(Quintela *et al.*, 2019)
Optical	Monoclonal antibodies	*Escherichia coli K12*	-	10^{4} Cells/ mL	(Massad-Ivanir, Shtenberg and Segal, 2013)
Termal biosensore	Copper chip holder	*E. coli*		10^{3} CFU/mL	(Arreguin-Campos *et al.*, 2023)

Zarei et al. designed an aptasensor using gold nanoparticle-modified glassy carbon electrode (GCE) for *Shigella dysenteriae*. After aptamer immobilization on the surface of gold nanoparticles, residual free gold nanoparticles were blocked with 6-mercapto-1-hexanol. Detection of *Shigella dysenteriae* was done by determining electrical surface resistance changes in different concentrations of *Shigella dysenteriae* in the presence of hexacyanoferrate as a chemical probe. The LOD of this work was reported 10 CFU/mL, and the prepared aptasensor successfully detected *Shigella dysenteriae*. Selectivity of this biosensor was examined and the aptasensor did not show a significant response against other pathogenic bacteria (Zarei, Soleimanian-Zad and Ensafi, 2018).

4.3. *Staphylococcus aureus (SEA)* and its biosensors

Staphylococcus aureus is a threat to food safety and health, which can produce a variety of neurotoxins and cytotoxins (Jia *et al.*, 2013; Rasooly *et al.*, 2019). Currently, 24 subtypes of this bacterium have been reported, among which *Staphylococcal Enterotoxin A* (SEA) cause to water and food poisoning worldwide (Desouza *et al.*, 2009). Consumption of fifty ounces of contaminated water or food such as meat, eggs, milk, and dairy products (per 70 kg body weight) can cause food poisoning, toxic shock, and exacerbate various diseases caused by toxin ingestion (Zhang *et al.*, 2020). In addition to food poisoning, the species of this bacterium cause diseases such as post-surgery infections, purulent skin lesions, pneumonia, etc (Davydova *et al.*, 2016). In 2020, Zhang et al. designed a label-free fluorescence aptasensor to identify staphylococcal Enterotoxin A, abbreviated SEA, using functionalized aptamer with silver nanoclusters. In this biosensor, DNA sequences were modified to increase the fluorescence intensity with the sequence of C6GC6. Polypyrrole nanoparticles (PPyNPs) were used to fabricate this biosensor which silver nanoclusters and DNA were adsorbed through fragment accumulation within PPyNPs; therefore, energy transfer took place directly from silver nanoclusters as donors to PPyNPs as energy receptors. The LOD in this work was reported 0.3393 ng/mL. Selectivity of the biosensor was examined with three nontarget bacteria including *S. aureus* enterotoxins such as staphylococcal enterotoxin B (SEB), staphylococcal enterotoxin C1 (SEC1), and staphylococcal enterotoxin D (SED) (Zhang *et al.*, 2020). In 2020, Bagheri et al. also designed an iron ion fluorescence- whole cell-based aptasensor to detect the *Staphylococcus aureus* using fluorescence resonance energy transfer (FRET) between green CQDs and AuNPs. The CQDs and gold nanoparticles act as donors and energy receptors, respectively. The reported biosensor, detected *Staphylococcus aureus* up to 10 CFU/mL. Specificity of this biosensor was validated by comparing the response to the target bacteria *Staphylococcus aureus* versus non-target *bacteria E. coli, Salmonella typhimurium, and Pseudomonas aeruginosa*.(Pebdeni, Hosseini and Ganjali, 2020).

4.4. *Pseudomonas aeruginosa* and its biosensors

Pseudomonas aeruginosa is a gram-negative environmental bacterium present in soil and water. It is also present on the surface of plants and animals (Cuttelod, Seddon and Neubert, 2011). Nevertheless, *P. aeruginosa* can cause serious infections in patients with weakened immune systems, organ transplants, skin burns, and cystic fibrosis (Gao *et al.*, 2018). In addition, *P. aeruginosa* can efficiently colonize artificial devices and is a major cause of infection in ventilator-associated pneumonia, (El Solh *et al.*, 2008). Therefore, to ensure the importance of nutrition and protect common health, it is extremely vital to develop rapid and practical methods to detect *Pseudomonas aeruginosa* (Gao *et al.*, 2018). Ran Gao et al. designed a fluorescence-supported fluorescence aptasensor with graphene oxide quantum dots (GOQDs) for rapid detection of *Pseudomonas aeruginosa*. In the absence of *Pseudomonas aeruginosa*, the complementary strand with the fluorescent 5-carboxyfluorescein-labeled complementary DNA (FAM-cDNA) was hybridized with the part of aptamer sequence, and the fluorescent FAM was quenched by GOQDs. By adding the target bacterium, the aptamer detected the biological element (analyte) and bound to a specific aeruginosa. As a result, it was repelled by GOQDs (desorption), so the fluorescence of FAM was restored. The LOD was 100 CFU/mL, and the detection time was 2 hours. In addition, selectivity of the aptasensor was examined and successful results toward was demonstrated compare to other pathogenic bacteria (Gao *et al.*, 2018).

4.5. *Mycobacterium tuberculosis* and its biosensors

Mycobacterium tuberculosis (MTb) is a major cause of infection and causing chronic and acute tuberculosis that is seriously life-threatening. The cure requires long-term treatment with a low likelihood of eradicating the infection (Diouani *et al.*, 2017; Zhang *et al.*, 2018). Research has shown that water and wastewater contamination with *mycobacterium tuberculosis* is one of the ways of environmental transmission of this pathogen to humans. So early and rapid detection of *Mycobacterium tuberculosis* (MTb) is an important factor in the rapid diagnosis and control of tuberculosis. ESAT-6 (6-kDa early secreted antigenic target) is a 6-kDa primary antigen secreted by this bacterium in the first stage of MTB infection. Therefore, the identification of ESAT-6 is considered to be of great importance in the initial diagnosis of tuberculosis (Zhang *et al.*, 2018).

Li et al. designed an aptasensor for ESAT-6 using a nanofiber hybrid material composed of a reduced graphene oxide metal-organic framework (rGO-MOF). This rGO-MOF was placed on a glassy carbon electrode, and toluidine blue (TB) was used as the electroactive compound. Platinum/Au core/shell (PtNPs @ AuNPs) were used to concentrate the thiolated aptamer (EBA) on the modified electrode and increase sensitivity to the ESAT-6 response. The LOD was 3.3 × 10^{-5} ng/mL (Li *et al.*, 2018). In another approach, Diouani et al. designed an

unlabeled immunoelectrochemical biosensor for the diagnosis of ESAT-6. In this work, an anti-ESAT-6 monoclonal antibody was used as a bioreceptor, and $[Fe(CN)_6]^{-3/-4}$ was used as a redox probe. Finally, the LOD of 7 ng/mL was obtained in this work (Diouani *et al.*, 2017). Also, Sypabekova et al. designed another aptasensor using the gold solid support and a thiolated linker of OP (O_2) O- $(CH_2CH_2O)_6$, that the LOD was obtained 4.1 fM (Nikonovas *et al.*, 2020).

4.6. *Salmonella bacteria* and its biosensors

Salmonella is a gram-negative bacterium that is an important food pathogen for humans and animals. Annually, this bacterium causes more than 1 billion infections worldwide and causes over 155,000 deaths due to the consumption of food contaminated with this pathogen (He *et al.*, 2023). *Salmonella* is found in meat, eggs, milk, fruit juice, and poultry (Dill, Stanker and Young, 1999). Among the all serotypes of *Salmonella*, one of the important serotypes that associated with human disease is *S-Typhimurium*. The consumption of water contaminated with this bacteria can lead to immune deficiencies and other symptoms such as fever, gastrointestinal disorders, diarrhea, and even death within a short time (Park *et al.*, 2015). Therefore, rapid and reliable diagnosis of this pathogen is very important (Lee *et al.*, 2015). In 2016, Sheikhzadeh et al. designed an unlabeled biosensor, in which a gold disk-shaped electrode was polished with a micropad and alumina powder 0.1, 0.3, 0.05, and then the clean gold disk was modified by the copolymer to covalently stabilize the aptamer on the surface. The aptasensor identified *Salmonella typhimurium* with high specificity and a LOD in 3 CFU/mL at a short time (Sheikhzadeh *et al.*, 2016).

4.7. Pathogenic bacteria (total bacteria) and its biosensors

Pathogenic bacteria and contamination of various environments with these bacteria are serious threats to the health of humans and living organisms. They contaminate water, food, and pharmaceutical products, leading to pathogenicity and even death in humans (Lâm *et al.*, 2010). Therefore, it is essential to discover a fast, sensitive, and reliable method for timely diagnosis and screening. There are several methods, including colony counting as the gold standard, ELISA, and PCR that all of which are expensive and require a skilled user. In the development of suitable on-site bacterial identification methods, colorimetric methods have attracted a lot of attention due to easy operation and visual detection without the need of tools and expertise (Zhu *et al.*, 2016;Alamer *et al.*, 2018). Thao Nguyen Le et al. reported a calorimetric method for the identification of bacteria using chitosan-coated magnetic nanoparticles(CS-MNPs), in which the surface of the MNP was coated with chitosan to produce CS-MNP. Chitosan has a positive charge (+) and that it can electrostatically attach to a negatively charged bacterial cell membrane with a very high affinity. In this work, the 2-2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt (ABTS) solution was used as colorimetric probe. CS-MNP exhibits peroxidase-like catalytic activity by producing a dense green color in the absence of bacteria. However, due to the presence of bacteria in the environment and the electrostatic interaction of bacteria, it was attached to the chitosan surface coated on MNP, which created a barrier to ABTS access to chitosan, thus reducing peroxidase-like activity of CS-MNP. The presence of bacteria was determined by a decrease in calorimetric activity. The LOD for this sensing method was at 10^4 CFU/mL and bacteria could be identified with the naked eye. This sensor was tested in the presense of *Staphylococcus aureus* and *E. coli* (Le, Tran and Kim, 2020).

4.8. Biofilm and its biosensors

Bacterial biofilm consists of one or more bacterial species encapsulated within self-produced extracellular polymeric substances (EPSs) that adhere to wetted surfaces (Becerro, Paredes and Arana) (Funari and Shen, 2022;Werwinski *et al.*, 2022;Römling, 2023). Due to high antibiotic resistance, bacterial biofilm is considered to cause many diseases, especially in the clinical setting (Subramanian *et al.*, 2020;Ameer *et al.*, 2023). Biofilms can cause many problems including biological, environmental, infectious, biofouling, or spoilage. As a result, there is a need to monitor the formation of biofilms in different environments. In recent years, biosensors have received attention including the identification of bacteria and the supervision of biofilm formation in many environmental and medical fields (Saccomano, Jewell and Cash, 2021;Funari and Shen, 2022). Fig.3 shows the steps of biofilm formation and its cycle. Liu et al. reported an interdigital microelectrode integrated biosensor chip to monitor the formation process of *Salmonella* and *E. coli* biofilms. Using electrochemical impedance spectroscopy, they showed that changes in the impedance spectroscopy of biofilms occur with the time of cultivation and the changes in the process of decreasing and increasing of the capacity of biofilm are proportional to the process of biofilm formation (Liu *et al.*, 2018). Brochman et al. reported a microfluidic sensor to assess biofilm formation. In this study, they used different bacterial strains and complex biofilms. The results of electrochemical monitoring showed the high dynamics of biofilms to chemical treatment strategies (Bruchmann *et al.*, 2015). Rakhimbekova et al. reported the possibility of using optical and fiber-based sensors to identify and analyze bacterial biofilms. In this study, measuring the refractive index with an optical backscatter reflectometer determined the initial concentration of the biofilm by the crystal violet adhesion method (Rakhimbekova *et al.*, 2022).

Matthias Fischer et al. reported a robust fiber-optic biofilm sensor for online monitoring of large biofilms in natural aquatic environments based on natural fluorescence detection of biofilm microorganisms. The working principle of this device is based on the natural fluorescence detection of biofilm-forming microorganisms. The results of marine bacterial strains showed a linear signal response characteristic with a detection of 4 x 10^3 cells/cm^2 (Fischer, Wahl and Friedrichs, 2012).

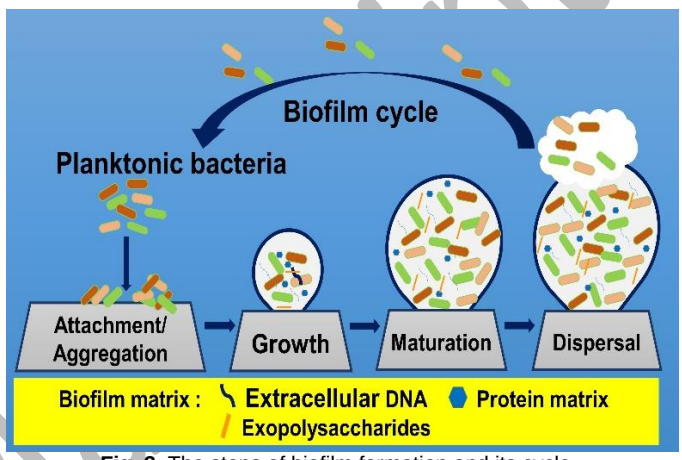

Fig. 3. The steps of biofilm formation and its cycle.

5. An overview of the advantages and disadvantages of these biosensors

Biosensors offer advantages in comparison with other bacterial detection methods, such as ELISA, PCR, or standard culture medium methods, which show that these devices have the potential to overcome the limitations of previous methods. Bactrial biosensors with high sensitivity provide the possibility of detecting very small amounts of analyte and with their high selectivity, they can identify the target analyte in complex environments. The response of these systems is fast and provides the possibility of early diagnosis. These devices have very small dimensions that make them easy to transport and they also need a small amount of sample. The performance of some of these devices may be affected by pH, temperature, or magnetic field that limited the bacterial biosensor performances. Using biosensors in some complex environments such as contaminated water is a challenge and their accuracy and sensitivity may be affected by interference. Many of these sensors are not recoverable and have a short lifespan.

6. Conclusions

In this study, some of the important pathogenic bacteria in water, their associated diseases, and their role in creating life-threatening conditions, and some fabricated biosensors for their detection quickly and accurately were investigated. These biosensors were designed with different methods such as optical, electrochemical, etc. All of these biosensors succeeded in selective identifying the target bacteria in a short time. Given the high accuracy, speed of detection, and cost-effectiveness of biosensors in identifying pathogens, seem to have a clear vision for fast detection.

Author Contributions

Sakineh Hargol Zadeh: Conceptualization, investigation, and writing the original draft.
Soheila Kashanian: Supervisor.
Maryam Nazari: Data curation and visualization.

Conflict of Interest

The authors declare no conflict of interest.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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