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Review Article

Nanomaterials Based Monitoring of Food- and Water-Borne Pathogens

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Pathogenic illnesses that are transmitted through food and water sources are admitted as a global problem with significant morbidity and mortality rates. Therefore, the monitoring of food- and water-borne pathogens is a critical aspect of control. The large number of investigations has recently been emphasized analytical techniques to build a strategy for fast, sensitive, and accurate monitoring of food- and water-borne pathogens employing nanomaterials. Irrespective of several efforts in ensuring the food- and water safety, food- and water-borne outbreaks are evident around the world. In pathogen detection and monitoring, electrochemical biosensors based on nanomaterials have gotten a lot of interest. Various types of nanomaterials and electrochemical technological solutions have improved the innovative diagnostics tools to detect the food- and water-borne pathogens. Nanomaterial that includes quantum dots, gold, silver, magnetic, metal oxides, and carbon-based nanomaterials that can be functionalized with biomarkers are commonly used for pathogen detections. Recently, the nanocomposites combined with these functionalized nanomaterials have enhanced the more sensitive, rapid, accurate, and cost-effective biosensors. The proper assessments of pathogens on food and water, along with their quality monitoring, are critical variables in making policy decisions about the infrastructure of food and water distribution networks, the efficient water treatment, and the prevention of food- and water-borne epidemics.

1. Introduction

Several water-based poisons can be lethal to animals if they breath them. Water- and food-borne infections, such as diarrhea, gastrointestinal ailments, and systemic illnesses, are a global issue which are estimated to kill millions of people every year [1, 2]. Children account for almost 1.4 million of these deaths [1]. Diarrheal diseases are the most frequent due to malnutrition in newborns and kids. However, many pathogenic organisms have known to cause food- and water-borne illnesses that include *Campylobacter*, *Clostridium perfringens*, *Escherichia coli* O157:H7, *Helicobacter*

pylori, *Listeria monocytogenes*, *Norovirus*, *Salmonella*, *Shigella* spp., *Staphylococcus aureus*, *Toxoplasma gondii*, and *Vibrio cholera*. These bacterial food- and water-borne pathogens have been reported for major cause of death worldwide [1, 2].

To minimize the occurrence of food-borne disease, identification and monitoring of food- or water-borne microorganisms are essential. Traditional methods of detection of for these pathogens rely on growing them on the agar plates which are exhausting processes and take more than three days to a week, from preliminary observations to confirmation of the pathogens, respectively [3]. However, cultural methods of detection are insufficient, and many pathogens are unculturable. Demands are kept on increasing for more quick process for the detection of food- and water-borne pathogen for prevention of infectious diseases, to assure food safety and to preserve public health.

Water-borne infectious agents are a major cause of diarrhea-related morbidities and mortalities around the world. Many zoonotic illnesses are spread whenever animal/human excreta are not adequately obtained, accumulated, or treated before disposal of wastes to environments like nearby local water bodies. Agriculture-based wastes and storm runoff can spread these organisms across many medium including soils, waters, and aerosols that allow them to settle in places where humans or animals could be exposed and afflicted. Water-borne infectious agents when exposed, breath, touch or consumed by humans or animals, it could cause serious sickness [4]. Illness reported from water-borne toxins and toxigenic microbes are known to spread by direct contacts or consumption of contaminated water as well as aquatic species. Poisoning symptoms are also reported in humans after eating seafood and shellfish that contains water-borne toxins. Toxic substances can build up in salt water, fresh water, and brackish water bodies that result in harmful algal blooms. However, they are known to bioaccumulate in the food webs of the aquatic system, infects the fishes, shore birds, marine mammals, and other species. Exposure via inhalation through respiratory tract depends on the toxin or toxin-producing infectious agents. Inhaling aerosolized harmful algal particles can cause respiratory discomfort and asthma episodes in humans.

2. Food- and Water-Borne Pathogens: Global Scenario

A range of infectious organisms, including bacteria, viruses, protozoa, and helminths, cause waterborne diseases through ingestion, aerosol contact, or contact with contaminated water [5, 6]. Around 780 million people in the globe are inaccessible to clean water, and an estimate of 2.5 billion people are inaccessible to proper sanitizing faculties [7]. The global incidence of food-borne diseases is efficient to measure. According to CDC 2011, an estimate of 1 in 6 Americans (48 million) will become ill, around 128,000 estimates to be hospitalized, and 3,000 death each year from food-borne infections [8, 9].

The pollution of food and drinking water are commonly involved in the outbreak of disease. Early detection of food- and water-borne diseases reduces the number of death and infections. Fast and precise detection methods are necessary for convenient handling. In comparison to other traditional and molecular approaches, nanosensors have higher efficacy. Early detection reduces health risk and improves the overall quality of life.

3. Current Methods of Detection of Food- and Water-Borne Pathogens and Their Limitations

There is currently no consistent approach for collecting and analyzing all pathogenic microorganisms of relevance from food and water samples [10]. For the inhibitors present in the samples of polluted water or food, the most common protocols for sampling, culture-dependent, and zoonotic pathogen detection are posing challenges in the detection methods. The established general protocols for sample collection, culture-independent detection method, and detection of zoonotic pathogens are some of the challenges of the detection methods.

Higher specificities, sensitivities, reproducibility, rapid, automation, and cost-effective are the most significant prerequisites for reliable analysis [11]. The culture-dependent methods are widely applying to identify large number of pathogens in food- and water borne diseases. However, due to other bacterial interference, it affects this methods sensitive and need long time to obtain the results. Further, due to large number of pathogens that is unculturable and culture-based methods produces false negative results as well [3, 12].

Index of pathogens for water quality monitoring has been chosen for both culture and molecular approaches to show the higher percentages of pathogens in the water. Among them, *E. coli* has been widely used because pathogen detection methods are relatively simple and inexpensive. However, the major disadvantage of detecting *E. coli* will not provide information on the pathogen's host origin, and, in some cases, they are not associated with the pathogens in food- and water-like virus and protozoans [13].

Molecular approaches are highly specific to detect the certain species of pathogens and provide additional pathogen phylogenetic information [14]. Alternative indicators that are easily related to the host source can be used with these strategies. This allows for the differentiation of human and animal diseases as well as the tracing of pollution sources [13, 15]. It has been argued that host-origin libraries based on phenotypic approaches could be beneficial for identifying pathogen sources but developing such libraries could be expensive [16]. As a result, molecular approaches appear to be better adapted for assessing health risks.

There are a variety of molecular approaches available now for detecting various infections. They are used to assess food and water microbiological quality, pathogen removal efficiency in drinking and wastewater treatment plants, food, and microbial source-tracking (MST) techniques [17]. Tables 1 and 2 show some examples of detection methods for food- and water-borne pathogens, as well as their

Table 1: Various detection approaches and techniques of food-borne pathogens.

Approaches	Techniques	Advantages	Draw backs	Detection limits	Reference
Molecular-based approaches	Polymerase chain reaction (PCR)	Higher sensitive and more specific. Method can be automated	Need DNA extraction, interface of inhibitors and can detect all cells	Present	[18–20]
	Multiplexed PCR	Sensitive, highly specific, and can detect multiple pathogens in one reaction with automation	Needs more specific primer designs, interface of inhibitors, and detects all type of pathogens		[18–20]
	Real time PCR (RT-PCR)	Highly sensitive, specific, rapid, reliable, and reproductive results with specific time course detection	Most costly, interface of inhibitors, and detects all type of pathogens. Needs a trained technician and false results due to cross-contaminations	Present	[18–20]
	Nucleic-acid sequence-based amplification (NASBA)	Sensitive, specific, and cost-effective method without PCR	Needs culturable pathogens and RNA samples are sensitive to handle	Present	[3, 21]
	Loop mediated isothermal amplification (LAMP)	Highly sensitive, highly specific, cost-effective, and easy to handle and operate	Complicated primer designing technology is needed	Present	[3]
	Oligonucleotide-DNA-based microarray	Highly sensitive, specific, high-throughput screening for multiple detection is possible	Cost is high, needs a trained technician and needs oligonucleotide probes and complicated detection systems	Present	[19–21]
Biosensor based approaches	Optical-based biosensors	Higher sensitivity with real time detection and label-free detection can be integrated	Higher cost	Present	[18, 19, 22]
	Electrochemical-based biosensors	High throughput analysis, automation, and label-free detection can be integrated	Lower specificity, fail to detect if a smaller number of microbes, and multistep analysis	Absent	[18, 19, 22]
	Mass based biosensors	Low cost, user friendly, label-free, and real-time detection is possible	Less specific, lower specificality, time-consuming, and multistep protocols	Present	[18, 19, 22]
Immunological based	Enzyme-linked immunosorbent assay (ELISA)	Very specific, automated, multiple detection systems	Lower sensitive, false results, trained technicians are needed, and labelling is needed	Present	[3, 18, 20]
	Lateral flow immunoassay	Cost-effective, user friendly, reproducible, highly sensitive, and specific	Needs labelling procedures	Absent	[3]

detection limits. Molecular-based approaches that include nucleic acid amplification techniques can provide sensitive and analytical instruments for detection of various types of pathogens including emerging variants. These methods also provide scope for automation and real time analysis of microbial risk assessment [17].

4. Applications of Nanomaterials (NMs) in Monitoring Food- and Water-Borne Pathogens

Nano-based sensors are used in measuring of biological response that converts the response signals for interpretation and analysis. However, the selection of NMs for such sensing applications depends on the properties of the NMs (Table 3).

NMs-based sensors have reported to for higher sensitivity and specific in nature in comparison to that of material-based sensors. Common NMs used in sensor technology are shown in Figure 1.

To maximize the specificity of the biological reaction, the nanosensors can be controlled at a scale equivalent to biological mechanisms. "Nanofabrication" is a key stage in design of experiments before adding the NMs for the application of sensing. Majorly, it includes two crucial steps: The first step needs the fabrication and design of nano-adhesive using integrated circuits, and the second involves the engineering of NMs surface using micro-machining procedures. Chemical bonding, photolithography, surface etching techniques, and thin film etching or growth are four key processes involved in biosensing through nanofabrication.

In the increase of chronic diseases such as diabetes and cancer, there is a need for a broad awareness of early-stage disease detection using biosensors, which provide a quick reaction and high sensitivity in the early stages. The lithography technique is a commonly used fundamental process in

Table 2: Detection methods and limits of detection of water-borne pathogens.

Method	Advantages	Limitations	Detection limits	Reference
Standard PCR	Higher specificity, highly sensitive, and automated systems	Need DNA extraction, interface of inhibitors, and can detect all cells	Present	[23, 24]
Multiplexed PCR	Sensitive, highly specific, and can detect multiple pathogens in one reaction with automation	Needs more specific primer designs, interface of inhibitors, and detects all type of pathogens	Present	[25, 26]
Real-time PCR	Highly sensitive, specific, rapid, reliable, and reproductive results with specific time course detection	Most costly, interface of inhibitors, and detects all type of pathogens. Needs a trained technician and false results due to cross-contaminations	Present	[27–29]
DNA microarray	Highly sensitive, specific, high-throughput screening for multiple detection is possible	Cost is high, needs trained technician and needs oligonucleotide probes and complicated detection systems	Present	[14, 30, 31]
Fluorescent in situ hybridization (FISH)	High selectivity can differentiate viable and nonviable cells	Low sensitivity requires preenrichment and concentration steps for sample processing false-negative results possible high cost	Present	[17, 32]
Next generation sequencing. (NGS)	More specific and higher sensitive, can even characterize the pathogens in biofilm forming infections	Needs DNA extraction procedures, high cost, and complex computing analysis	Present	[33–35]
Immunological techniques	Highly specific and multiple samples can be analyzed	Less sensitive, cross reactivity for high possibility of false results and labelling procedures	Present	[36, 37]

nanofabrication and is used to create nanoscale electrodes. NMs give a larger surface area-to-volume for immobilization of biological agents that can be more sensitivity and specific in biosensing [47].

The usage of enzyme glucose oxidase was used to construct glucose biosensors, and the detection of glucose was increased by the use of Pt NPs on the carbon nanotubes (CNTs). Such biosensors can detect glucose from a variety of sources other than blood. These applications are also useful for immunosensors that are based on antigen-antibody complexes for quick and better detection of antigens [48].

5. Nanomaterial-Based Sensors to Detection of Food- and Water-Borne Pathogens

Many present water quality sensors can be replaced with nanotechnology enabled sensors. Others have stated that the nanosensor can monitor an analyte which should be fast with reversible binding. However, the nano-probe can be selective to detect specific microorganisms/chemical with higher sensitive which do not need for reversibility [49]. For the sake of clarity, the word "nanosensor" refers to any sensor platform that makes use of NMs distinctive optical, electrical, or magnetic capabilities to improve the detection of analyte. A variety of nanosensors are reported for more sensitive detection of pH, infections, and toxins in water that have been proposed [49–52]. Basically, nanosensors consist of three parts, namely, a suitable NM, recognition element, and mechanism for signal processing [53].

The recognition element interacts with the analytes of interest, resulting in a detectable signal that is recorded [52]. The specificity of nanosensor can be obtained by sensing an intrinsic signal obtained either from the analyte or from the recognition elements upon binding. The sensitivity of the nanosensor can be determined optical, electrical, or magnetic properties of the material and their signal processing technologies upon detection of signals upon analyte interaction.

Many nanosensors have extremely low detection limits reported in the literature; however, these detection limits are rarely confirmed under real-world circumstances that represent water quality on the ground. Additionally, due to the significantly small scale of a nanosensor-based detection system, it ensures the efficient detection of biological elements such antigen-antibody, bacteria, and viruses. Sample pretreatment such as purification and concentration may be required for better detection after the deployment of nanosensors.

Microfluidic separation [54, 55] and NMs-based isolation [56] are two fast-evolving technologies for pretreatment, as are more standardized filtering [57] and centrifugation-based methodologies. Many sensor research facilities focus on sample pretreatment, which is not covered in depth here. The types of NMs in nanosensors, the analytes they detect, and the signal transduction method used to monitor analyte recognition can all be classed. For the sake of simplicity, it can be address only nanosensors that use the most widely is signal transduction methods: optical, electrical, and magnetic. The range of NMs used in water-quality nanosensors is summarized in Table 4. There are detailed explanations of the many types of NMs used in nanosensors elsewhere [50, 58–61].

5.1. Optical Signal Transduction. When the target analyte interacts with NMs in an optical sensor, a signal is produced. This method is widely used due to its overall ease of use, a

Table 3: Overview of NMs properties and applications.

Nanoparticles	Characteristics	Synthetic approaches	Application(s)	Reference
Gold nanoparticles	(i) Redox activities, SERS (ii)SPR (iii) Fluorescent quenching	(i) Solution-based approach	(i) Electronic and electrochemical signal detection (ii) Drug delivery (iii) Cell imaging in molecular diagnostic procedures	[38]
Carbon-based nanostructures	(i) Elastic behavior (ii) Equilibrium structure (iii) Fundamental gaps (iv) Interlayer spacing (v) Lattice constant (vi) Optical properties, viz., electrical and thermal transport	(i) Carbon arc discharge (ii) Laser ablation (iii) Vapor deposition	(i) Tissue engineering, biomedical implants, identification of malignant cells, and delivery of bioactive substances (ii) Development of electromechanical actuators and supercapacitors for robotics and automotives (iii) Fuel cells (H-storage) for electric vehicles and smart gadgets (iv) Development of field emission devices such as gas discharge tubes and lamps, microwave inducing devices, probes, and sensors	[39, 40]
Magnetic nanoparticles	(i) Magnetic eject lead by spinning electronically charged particles and zero coercivity	(i) Co-precipitation (ii) Microemulsion, thermal decomposition (iii) Solvothermal (iv) Sonochemical (v) Microwave-assisted; vapor deposition, combustion synthesis, carbon arc (vi) Laser pyrolysis methods	(i) Drug delivery, NMR imaging, biomolecules separations, in vivo destruction of targeted cells by hyperthermia (ii) Removal of organic and inorganic pollutants (iii) Synthetic pigments for ceramics, porcelain, and paints	[41]
Silicon-based nanomaterials	(i) Optical characteristics (ii) Bright emission (iii) Photostability (iv) Size-dependent and wavelength tunable luminescence and long fluorescence (v) Electronic characteristics (vi) Quantum confinement (vii) Surface functionalization	(i) Pulsed laser ablation (ii) Heating degradation (iii) Ball milling Chemical synthesis (iv) Electrochemical etching	(i) Silicon-based light emission diodes (LED) multicolor (ii) Lithium and solar cells (iii) Microwave mediated filed-electron transistor (iv) Photocatalyst for chemical and industrial application	[42]
Graphene oxides	(i) High strength (ii) Improved electron mobility (iii) Excellent electrical and thermal properties	(i) Approaches of bottom-up and top-down methods	(i) Gas transport, water treatment processes (ii) Multiple-stimuli actuation: humidity, temperature, light, electronic, chemical etc. (iii) Noncorrosive resistance (iv) Lithium cells (v) Supercapacitors	[43]
Dendrimers	(i) Low viscosities (ii) Miscible and highly soluble (iii) Enhanced surface area and encapsulation abilities	(i) Divergent (ii) Convergent methods	(i) Drug delivery (ii) Gene vehicles (iii) Photodynamic therapeutic agents (iv) Water filtration and testing	[44, 45]
Conducting polymers	(i) Electric properties (ii) High conductivity (iii) Microwave absorbing properties (iv) **N**onlinear optical properties (v) Wettability	Chemical methods (i) Electrochemical methods (ii) Emulsion method (iii) Photochemical method (iv) Plasma polymerization (v) Pyrolysis	(i) Electromagnetic shielding materials (ii) LEDs and solar cells (iii) Microwave absorbing materials (iv) Rechargeable batteries (v) Sensors	[46]

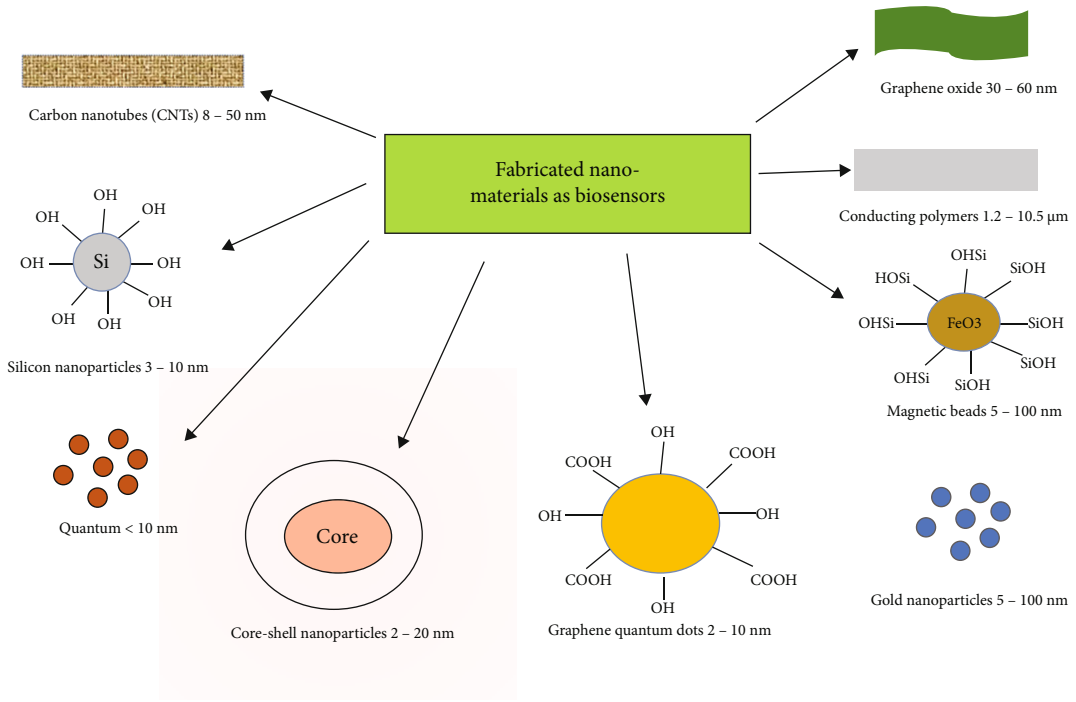

Figure 1: Reported nano- and micro-based fabricated sensors along with their sizes.

quick reading, and practical sensitivity. The most common optical signal transduction techniques are fluorescence and surface plasmon-enabled spectroscopies.

Fluorescence is defined as the measurement of a fluorophore's emission when it returns to its ground state after being excited by light. Quantum dots, metal-based NMs, and up-conversion NMs are among the fluorescent NMs being studied for their sensing uses. Ng et al. [61] have highlighted many of the exciting discoveries in the utilization of fluorescent NMs for sensing applications.

When noble metal-based NMs, such as gold and silver, are activated by light, surface plasmons (e.g., coherently oscillating surface electrons) can form, generating strong electromagnetic fields near the NM surface (within a few nanometers) [62]. The size, shape, identity, and local environment that surrounds the NM all influence the frequency at which the surface electrons resonant, resulting in an absorption band known as the localized surface plasmon resonance (LSPR). The surface-enhanced Raman spectroscopy (SERS) and colorimetric (absorption) approaches are two types of signal transduction that use LSPR.

In the region of the noble metal surface, LSPR generates a stronger electromagnetic field. The Raman cross-sections of target analytes are raised by several magnitudes when they are in this enhanced electromagnetic environment. This augmentation is known as SERS. A SERS spectrum reflects the analyte's distinctive covalent bonds, while the SERS is a vibrational spectroscopic technique. If the signal from this "fingerprint" spectrum is strong enough, it can be used to determine whether an analyte is present in a complex matrix. SERS has demonstrated the ability to identify single molecules in this intrinsic detection mode [63], but often for non-environmentally significant analytes beneath demanding instrumental working circumstances. The implementation of SERS for water-contaminant quantification is hindered by the requirement that the "hot spots" largely responsible for SERS enhancement be less than 5 nm in size, excluding big analytes [60]. This characteristic, combined with the requirement that the analyte binds to the noble metal nanoparticle surface, may make SERS ineffective for intrinsic analyte detection. The alternative, and more extensively used, technique is to use affinity ligands like antibodies and aptamers to enhance the properties of the nanoparticle surface [64]. Because of the method's high sensitivity and multiplex capacity, very sensitive, hand-held Raman spectrometers are becoming more affordable; it is expected that SERS will gradually come to occupy a larger piece of the nanosensor armamentarium [65].

Colorimetric sensing is a simpler kind of LSPR that includes monitoring the aggregation status of NPs. Color variations (usually red to blue for spherical gold NPs; yellow to brown for spherical silver NPs) represent the coupling of surface plasmons on nearby particles when NPs become destabilized. These color changes can be observed visually or with the aid of a spectrophotometer. There have been a lot of aggregation-based tests for water-borne chemicals and microorganisms (Table 4) [59]. Incorporating such assays into minimal paper-based colorimetric assays can make them field-deployable [55].

5.2. Electrical Signal Transduction. The high conductivity and excellent stability of silicon, noble metal–based NMs (Pt, Ag, and Au), carbon-containing nanomaterials (graphene and CNTs), and inorganic two-dimensional nanosheets are used in electrical signal transduction. Chemiresistors, field-effect transistors, and electrochemical sensors are the three types of

Table 4: Nanomaterial based sensor platforms reported for water quality assessment.

Sensing technique	Nanomaterial	Analytes	Reference
Optical methods			
Colorimetric based	Gold and silver NPs	NO_2, NO_3, cocaine, Pb^{II}, Cu^{II}, and Hg^{II}	[75–79]
Fluorescence	Quantum dots	Heavy metals (Cd^{II}, Pb^{II}, Hg^{II}, and Cu^{II})	[80–91]
Surface-enhanced Raman spectroscopy (SERS)	Gold NPs	Pesticides, bacteria, viruses, and protozoa	[92–97]
Electrical methods			
Chemiresistors	Gold nanowires Metal oxide semiconductor Nanowires Polymer nanowires	Halides Volatile organic compounds (VOCs) and NO_2	[98] [99–101] [102–104]
Field-effect transistors	Silicon nanowires (SiNWs) Two-dimensional transition metal dichalcogenides Gold nanoparticle functionalized polymeric FETs Phosphorene (black phosphorus)	Nucleic acids and influenza Glucose, H_2O_2, proteins, Hg^{II}, and pH Hg^{II} IgG protein	[105, 106] [107, 108] [109]
Electrochemical	Graphene Carbon nanotubes Copper nanowire electrodes Polymeric nanocomposite Membranes Reduced graphene oxide/gold nanoparticle nanocomposite	Bacteria Ammonium, CoII, and organophosphate pesticides Nitrate AgI, HgII, and CuII Organophosphate pesticides	[110] [111–113] [114] [115] [116]
Magnetic methods			
Magnetoresistance	Magnetite (Fe_3O_4); maghemite (γ-Fe_2O_3)	*Mycobacterium bovis; Influenza A*	[70, 71, 117]
Hydrodynamic property changes	Magnetite (Fe_3O_4)	Spore detection	[72]
T2-relaxation magnetic resonance	Magnetic beads	*Salmonella enterica* and Newcastle disease virus (as a representative virus); *E. coli* 0157:H7	[73, 118]

electrically based nanosensors [50]. Chemiresistors are electrical circuits that change resistance when an analyte interacts with the sensor surface. The mobility of a charge carrier (i.e., analyte) travelling through channels subjected to an applied electric field controlled by a conductive gate electrode is measured using field-effect transistors (FETs). A change in signal is noticed when an analyte enters the channel. In Cui and Lieber's pioneering work in 2001 [66], the FET-based nanosensor platforms were in development. Electrochemical sensors detect voltage or current changes that occur when the electrons transfer from the sensor surface to a target analyte or intermediate. The addition of recognition elements (antibodies, aptamers) to chemiresistors, FETs, or electrochemical sensors has enabled sensitive detection of aquatic pollutants such as *E. coli* [67] and hepatitis C [68].

5.3. Magnetic Signal Transduction. The signal is generated with the NM in optical sensors interact with the target analyte. The signal is processed, and this method is commonly used because it is easy to use, rapid, and practically sensitive. The optical transduction signal may be fluorescence-based and SPR-enabled technology.

The magnetic NMs can respond to an external magnetic field and their functionalization with analyte specific proteins allows for magnetic isolation of analytes, which can subsequently be detected [69]. The size and chemical identity of NMs determine particle magnetism, which is determined by their final application. Magnetic particles are made from several materials, including metallic iron, iron oxides, cobalt, nickel, and a variety of multi-element compounds. Due to their presumed biocompatibility and lower-cost manufacturing, iron-based NMs (e.g., FeO, Fe_3O_4, and -Fe_2O_3) are of special interest.

Magnetoresistance, hydrodynamic properties, and T2 relaxation nuclear magnetic resonance are three types of magnetic signal detecting methodologies. Magnetoresistance sensors change an electrical resistance when magnetic nanoparticle-labelled analytes bind to them, and they have recently been employed to detect *Mycobacterium bovis* [70] and influenza A [71]. Monitoring nanoparticle relaxation exercises dynamics in a time-dependent magnetic field can reveal changes in hydrodynamic characteristics caused by analyte-induced nanoparticle clustering. This method has been utilized to detect *Bacillus globig*II spores in a field-

Table 5: Comparison of nanotechnology-based food-borne pathogen detection techniques.

Technique	Nanomaterial	Duration	Targets	Sensitivity	Evaluated matrices	Sample pretreatment
Colorimetric (non-LFA)	AuNP	5 min to 5 h	Bacterial cell DNA	10^3 CFU/ml 5 pM–0.44 nM	Pure culture, water	PCR needed for DNA detection
Colorimetric (LFA)	AuNP	15–30 min	Bacterial cell DNA	~10^2–10 ^{6}CFU/ml 1.25 fM–50 pM	Various food samples	IMS, PCR
Fluorescence	QD, CD, graphene, carbon nanotube, lanthanide NP	Assay dependent	Bacterial cell DNA	5–10^3 CFU/ml 10–10^3 CFU/ml	Chicken rinsate, apple juice, milk products	IMS
Chemiluminescence	AuNP, AgNP, platinum NP, QD, MNP, bimetallic	~2 h	Reported for bacterial toxin detection only	Ten times lower than traditional ELISA[b]	**Not reported**	Cation exchanger carboxy methylcellulose chromatography
SPR	AuNP	~1 h	Bacterial cell	10^5 CFU/ml	Pure culture	
LSPR	AuNP	~1 h	Bacterial cell DNA	10^4–10^7 CFU/ml 10 fM	Pure culture	PCR
SERS	AuNP, AgNP	5 min to 2 h	Bacterial cell	Label-free: 10^5–10^6 CFU/ml; labelled: 15–10^2 CFU/ml	Various food matrices and clinical specimens	PCR, IMS
Electrochemical	AuNP, AgNP, MNP	~1 h	Bacterial cell, DNA	1–10^3 CFU/ml	Meat, water, milk	PCR needed for DNA detection
SALDI-MS	AuNP, AgNP, carbon nanotube, titanium NP, graphene	~30 min	Bacterial cell	10^3–10^5 CFU/ml	Pure culture, apple juice	Centrifugation of food matrix
Piezoelectric	AuNP		DNA	2×10^3 CFU/ml	Pure culture	

Measured without sample enrichment.

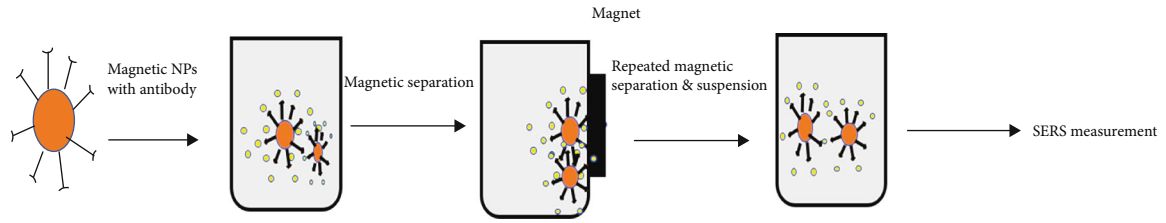

Figure 2: Detection of magnetically separated bacteria using surface-enhanced Raman spectroscopy (SERS). In this test, gold-coated magnetic core NPs functionalized with bacterium-specific antibodies (MnFe3O4@Au-antibody) are used to treat a sample containing bacteria of interest. SERS probes the nanoprobe–bacteria aggregation after it has been magnetically separated and altered with antibody synthesized gold nanorods (Au NR-antibody).

deployable application [72]. The magnetic NPs start to aggregate in presence of an analyte which can be used in magnetic resonance imaging through monitoring of the change in the T2 (e.g., spin-spin) water proton relaxation time. Using this method, it is successful in the detection of *Salmonella enterica* and Newcastle disease virus [73].

6. Conclusion and Future Perspective

Food-borne and water-borne infectious organisms possess a threat for public health hazards, cause of serious illness and death. Therefore, an effective microbiological surveillance, detection of infectious agents and assessment of health risks is required to achieve the safe and disease-free food products and water for drinking.

Traditional methods for detecting food-borne and water-borne pathogens, which rely on growing microorganisms, are selective and specific but time-consuming and laborious. A variety of quick detection methods must be created to address the shortcomings of traditional detection systems. Traditional methods are low sensitive, nonspecific, time-efficient, and dependent methods rather than rapid detection systems. Molecular-based technologies that use the DNA and RNA used the PCR, RTPCR, mPCR, and DNA microarray which are more sensitive and specific but need the skilled labor and high-cost instruments.

Nanotechnology has been hailed as a game changer in a variety of fields. Despite their increasing popularity, nanotechnologies for detection of pathogens in food and water are still in development, with most pathogen nanosensors or assays still in the proof-of-concept stage. The degree of improvement brought about by nanotechnology, on the other hand, varies. Because of a bulkier architecture and fewer access and reaction centers, certain strategies increase dramatically, while others improve only somewhat. This is notably true for whole-cell detection.

The utilization of nanosensors in food sector that benefits the food safety aspects seems to be a rapid, real time, easy, and cost-effective method to detect the contaminations by pathogens and their toxins. Further, these types of nanosensors can be automated for high throughput and portable for the screening the infectious agents and toxic materials from the variety of food and water samples.

Furthermore, a variety of biosensor-based approaches have the potential to address the demand for downsizing as well as low-cost analytical instruments. Biosensor-based approaches are simple to use and do not necessitate the use of trained staff.

It is also feasible to employ a combination of many fast methods to detect a specific food-borne disease, as using only one method may not be enough to confirm the discovered infection. To establish the most effective and accurate detection approach for food-borne pathogens, more research into the effects of diverse combinations of fast methods is needed.

Researchers will be able to construct highly sensitive, selective, and unobtrusive nanosensors for evaluating food-borne microorganisms at an affordable cost thanks to considerable research advancements in nanotechnology for nanomaterial exploration and the development of novel processes in the future. Biosensor-based approaches are simple to use and do not necessitate the use of trained staff.

Abbreviations

ELISA: Enzyme-linked immunosorbent assay
SERS: Surface-enhanced Raman spectroscopy
FISH: Fluorescent in situ hybridization
LFA: Laser flash analyzer
SPR: Surface plasmon resonance
LSPR: Localized surface plasmon resonance
IMS: Integrated medical systems
PCR: Polymerase chain reaction
NMR: Nuclear magnetic resonance
SALDI-MS: Surface-assisted laser desorption/ionized mass spectroscopy
VBNC: Viable but non-culturable
MST: Microbial source tracking
rGO: Reduced graphene oxide
OP: Organophosphorus pesticides
GCE: Glassy carbon electrode
ATCL: Acetylthiocholine chloride
SDBS: Sodium dodecylbenzene sulphonate
MFnS: Magneto-fluorescent nanosensors
CFU: Colony-forming unit
FET's: Field-effect transistors
VOC's: Volatile organic compounds
SiNWs: Silicon nanowires
LAMP: Loop-mediated isothermal amplification
NASBA: Nucleic acid sequence-based amplification
NGS: Next generation sequencing

Conflicts of Interest

There is no conflict of interest.

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References

[1] World Health Organization (WHO), "Water Sanitation and Health," February 2015, http://www.who.int/water_sanitation_health/diseases.

[2] G. Bitton, *Microbiology of Drinking Water Production and Distribution*, John Wiley & Sons, Inc., Hoboken, NJ, USA, 1st edition, 2014.

[3] X. Zhao, C. W. Lin, J. Wang, and D. H. Oh, "Advances in rapid detection methods for foodborne pathogens," *Journal of Microbiology and Biotechnology*, vol. 24, no. 3, pp. 297–312, 2014.

[4] K. Rhoden, J. Alonso, M. Carmona, M. Pham, A. N. Barnes, and O. Health, "Twenty years of waterborne and related disease reports in Florida, USA," *One Health*, vol. 13, 2021.

[5] F. S. Alhamlan, A. A. Al-Qahtani, and M. N. Al-Ahdal, "Recommended advanced techniques for waterborne pathogen detection in developing countries," *The Journal of Infection in Developing Countries*, vol. 9, no. 2, pp. 128–135, 2015.

[6] H. Leclerc, L. Schwartzbrod, and E. Dei-Cas, "Microbial agents associated with waterborne diseases," *Critical Reviews in Microbiology*, vol. 28, no. 4, pp. 371–409, 2002.

[7] Centers for Disease Control and Prevention (CDC), "Global water, sanitation, and hygiene (WASH)," February 2015, http://www.cdc.gov/healthywater/global/.

[8] S. P. Oliver, B. M. Jayarao, and R. A. Almeida, "Foodborne pathogens in milk and the dairy farm environment: food safety and public health implications," *Foodbourne Pathogens & Disease*, vol. 2, no. 2, pp. 115–129, 2005.

[9] Centers for Disease Control and Prevention (CDC), "CDC estimates of food borne illness in the United States," 2011, June2014, http://www.cdc.gov/foodborneburden/PDFs/FACTSHEET_A_FINDINGS_upd.

[10] T. M. Straub and D. P. Chandler, "Towards a unified system for detecting waterborne pathogens," *Journal of Microbiological Methods*, vol. 53, no. 2, pp. 185–197, 2003.

[11] T. Kostic, B. Stessl, M. Wagner, and A. Sessitsch, "Microarray analysis reveals the actual specificity of enrichment media used for food safety assessment," *Journal of Food Protection*, vol. 74, no. 6, pp. 1030–1034, 2011.

[12] J. W. Law, N. S. Ab Mutalib, K. G. Chan, and L. H. Lee, "Rapid methods for the detection of foodborne bacterial pathogens: principles, applications, advantages, and limitations," *Frontiers in Microbiology*, vol. 5, p. 770, 2015.

[13] S. L. McLellan and A. M. Eren, "Discovering new indicators of fecal pollution," *Trends in Microbiology*, vol. 22, no. 12, pp. 697–706, 2014.

[14] K. Gilbride, "Molecular methods for the detection of waterborne pathogensIn Waterborne Pathogens, Detection Methods and Applications," Elsevier B.V, London, UK, 2014.

[15] J. P. Cabral, "Water microbiology. Bacterial pathogens and water," *International Journal of Environmental Research and Public Health*, vol. 7, no. 10, pp. 3657–3703, 2010.

[16] P. K. Pandey, P. H. Kass, M. L. Soupir, S. Biswas, and V. P. Singh, "Contamination of water resources by pathogenic bacteria," *AMB Express*, vol. 4, no. 1, p. 51, 2014.

[17] R. Girones, M. A. Ferrus, J. L. Alonso et al., "Molecular detection of pathogens in water - the pros and cons of molecular techniques," *Water Research*, vol. 44, no. 15, pp. 4325–4339, 2010.

[18] G. Zhang, "Foodborne pathogenic bacteria detection: an evaluation of current and developing methods," *The Meducator*, vol. 1, no. 24, p. 15, 2013.

[19] P. K. Mandal, A. K. Biswas, K. Choi, and U. K. Pal, "Methods for rapid detection of foodborne pathogens: an overview," *American Journal of Food Technology*, vol. 6, no. 2, pp. 87–102, 2011.

[20] S. H. Park, M. Aydin, A. Khatiwara et al., "Current and emerging technologies for rapid detection and characterization of _Salmonella_ in poultry and poultry products," *Food Microbiology*, vol. 38, no. 250, pp. 250–262, 2014.

[21] A. Lauri and P. O. Mariani, "Potentials and limitations of molecular diagnostic methods in food safety," *Genes & Nutrition*, vol. 4, no. 1, pp. 1–12, 2009.

[22] D. Ivnitski, I. Abdel-Hamid, P. Atanasov, and E. Wilkins, "Biosensors for detection of pathogenic bacteria," *Biosensors & Bioelectronics*, vol. 14, no. 7, pp. 599–624, 1999.

[23] A. K. Bej, M. H. Mahbubani, J. L. Dicesare, and R. M. Atlas, "Polymerase chain reaction-gene probe detection of microorganisms by using filter-concentrated samples," *Applied and Environmental Microbiology*, vol. 57, no. 12, pp. 3529–3534, 1991.

[24] H. Y. Tsen, C. K. Lin, and W. R. Chi, "Development and use of 16S rRNA gene targeted PCR primers for the identification of Escherichia coli cells in water," *Journal of Applied Microbiology*, vol. 85, no. 3, pp. 554–560, 1998.

[25] H. Fan, Q. Wu, and X. Kou, "Co-detection of five species of water-borne bacteria by multiplex PCR," *Life Sciences Journal*, vol. 5, pp. 47–54, 2008.

[26] K. B. Omar and T. G. Barnard, "Detection of diarrhoeagenic Escherichia coli in clinical and environmental water sources in South Africa using single-step 11-gene m-PCR," *World Journal of Microbiology and Biotechnology*, vol. 30, no. 10, pp. 2663–2671, 2014.

[27] A. F. Maheux, D. K. Boudreau, M. A. Bisson et al., "Molecular method for detection of total coliforms in drinking water samples," *Applied and Environmental Microbiology*, vol. 80, no. 14, pp. 4074–4084, 2014.

[28] B. Taskin, A. G. Gozen, and M. Duran, "Selective quantification of viable Escherichia coli bacteria in biosolids by quantitative PCR with propidium monoazide," *Applied and Environmental Microbiology*, vol. 77, no. 13, pp. 4329–4335, 2011.

[29] B. Li and J. Q. Chen, "Real-time PCR methodology for selective detection of viable Escherichia coli O157:H7 cells by targeting Z3276 as a genetic marker," *Applied and Environmental Microbiology*, vol. 78, no. 15, pp. 5297–5304, 2012.

[30] J. Zhou, "Microarrays for bacterial detection and microbial community analysis," *Current Opinion in Microbiology*, vol. 6, no. 3, pp. 288–294, 2003.

[31] W. J. Wilson, C. L. Strout, T. Z. DeSantis, J. L. Stilwell, A. V. Carrano, and G. L. Andersen, "Sequence-specific identification of 18 pathogenic microorganisms using microarray technology," *Molecular and Cellular Probes*, vol. 16, no. 2, pp. 119–127, 2002.

[32] R. Amann and B. M. Fuchs, "Single-cell identification in microbial communities by improved fluorescence _in situ_ hybridization techniques," *Nature Reviews. Microbiology*, vol. 6, no. 5, pp. 339–348, 2008.

[33] T. G. Aw and J. B. Rose, "Detection of pathogens in water: from phylochips to qPCR to pyrosequencing," *Current Opinion in Biotechnology*, vol. 23, no. 3, pp. 422–430, 2012.

[34] J. F. Siqueira, A. F. Fouad, and I. N. Rôças, "Pyrosequencing as a tool for better understanding of human microbiomes," *Journal of Oral Microbiology*, vol. 4, no. 1, 2012.

[35] A. M. Ibekwe, M. Leddy, and S. E. Murinda, "Potential human pathogenic bacteria in a mixed urban watershed as revealed by pyrosequencing," *PLoS One*, vol. 8, no. 11, article e79490, 2013.

[36] L. P. Mansfield and S. J. Forsythe, "The detection of salmonella using a combined immunomagnetic separation and ELISA end-detection procedure," *Letters in Applied Microbiology*, vol. 31, no. 4, pp. 279–283, 2000.

[37] H. Peng and L. A. Shelef, "Automated rapid screening of foods for the presence of salmonellae," *Journal of Food Protection*, vol. 62, no. 11, pp. 1341–1345, 1999.

[38] Y. C. Yeh, B. Creran, and V. M. Rotello, "Gold nanoparticles: preparation, properties, and applications in bio-nanotechnology," *Nanoscale*, vol. 4, no. 6, pp. 1871–1880, 2012.

[39] R. H. Baughman, A. A. Zakhidov, and W. A. D. Heer, "Carbon nanotubes-the route toward applications," *Science*, vol. 297, no. 5582, pp. 787–792, 2002.

[40] A. Eatemadi, H. Daraee, H. Karimkhanloo et al., "Carbon nanotubes: properties, synthesis, purification, and medical applications," *Nanoscale Research Letters*, vol. 9, no. 1, p. 393, 2014.

[41] A. Akbarzadeh, M. Samiei, and S. Davaran, "Magnetic nanoparticles: preparation, physical properties, and applications in biomedicine," *Nanoscale Research Letters*, vol. 7, no. 1, p. 144, 2012.

[42] C. Huan and S. Shu-Qing, "Silicon nanoparticles: preparation, properties, and applications," *Chinese Physics B*, vol. 23, no. 8, article 88102, 2014.

[43] A. T. Smith, A. M. LaChance, S. Zeng, B. Liu, and L. Sun, "Synthesis, properties, and applications of graphene oxide/reduced graphene oxide and their nanocomposites," *Nano Materials Science*, vol. 1, no. 1, pp. 31–47, 2019.

[44] B. Klajnert and M. Bryszewska, "Dendrimers: properties and applications," *Acta Biochimica Polonica*, vol. 48, no. 1, pp. 199–208, 2001.

[45] E. Abbasi, S. F. Aval, A. Akbarzadeh et al., "Dendrimers: synthesis, applications, and properties," *Nanoscale Research Letters*, vol. 9, no. 1, p. 247, 2014.

[46] R. Kumar, S. Singh, and B. C. Yadav, "Conducting polymers: synthesis, properties and applications," *International*

Advanced Research Journal in Science, Engineering and Technology, vol. 2, pp. 110–124, 2015.

[47] P. V. Gerwen, W. Laureyn, W. Laureys et al., "Nanoscaled interdigitated electrode arrays for biochemical sensors," *Sensors and Actuators B: Chemical*, vol. 49, no. 1-2, pp. 73–80, 1998.

[48] S. C. Pak, W. Penrose, and P. J. Hesketh, "An ultrathin platinum film sensor to measure biomolecular binding," *Biosensors & Bioelectronics*, vol. 16, no. 6, pp. 371–379, 2001.

[49] S. M. Rodrigues, P. Demokritou, N. Dokoozlian et al., "Nanotechnology for sustainable food production: promising opportunities and scientific challenges," *Environmental Science. Nano*, vol. 4, no. 4, pp. 767–781, 2017.

[50] G. T. Chandran, X. W. Li, A. Ogata, and R. M. Penner, "Electrically transduced sensors based on nanomaterials (2012-2016)," *Analytical Chemistry*, vol. 89, no. 1, pp. 249–275, 2017.

[51] Z. Farka, T. Juriik, D. Kovaar, L. Trnkova, and P. Sklaadal, "Nanoparticle-based immunochemical biosensors and assays: recent advances and challenges," *Chemical Reviews*, vol. 117, no. 15, pp. 9973–10042, 2017.

[52] D. C. Vanegas, C. L. Gomes, N. D. Cavallaro, D. Giraldo-Escobar, and E. S. McLamore, "Emerging biorecognition and transduction schemes for rapid detection of pathogenic bacteria in food," *Comprehensive Reviews in Food Science and Food Safety*, vol. 16, no. 6, pp. 1188–1205, 2017.

[53] P. J. Vikesland and K. R. Wigginton, "Nanomaterial enabled biosensors for pathogen monitoring — a review," *Environmental Science & Technology*, vol. 44, no. 10, pp. 3656–3669, 2010.

[54] R. Pol, F. Céspedes, D. Gabriel, and M. Baeza, "Microfluidic lab-on-a-chip platforms for environmental monitoring," *Trends in Analytical Chemistry*, vol. 95, pp. 62–68, 2017.

[55] G. Sriram, M. P. Bhat, P. Patil et al., "Paper-based microfluidic analytical devices for colorimetric detection of toxic ions: a review," *Trends in Analytical Chemistry*, vol. 93, pp. 212–227, 2017.

[56] T. Shelby, S. Sulthana, J. McAfee, T. Banerjee, and S. Santra, "Foodborne pathogen screening using magneto-fluorescent nanosensor: rapid detection of E. coli O157:H7," *Journal of Visualized Experiments*, vol. 127, no. 127, article e55821, 2017.

[57] R. van den Hurk and S. Evoy, "A review of membrane-based biosensors for pathogen detection," *Sensor*, vol. 15, no. 6, pp. 14045–14078, 2015.

[58] T. R. Fadel, D. F. Farrell, L. E. Friedersdorf et al., "Toward the responsible development and commercialization of sensor nanotechnologies," *ACS Sensor*, vol. 1, no. 3, pp. 207–216, 2016.

[59] C. Wang and C. X. Yu, "Detection of chemical pollutants in water using gold nanoparticles as sensors: a review," *Reviews in Analytical Chemistry*, vol. 32, no. 1, pp. 1–14, 2013.

[60] M. J. Banholzer, J. E. Millstone, L. D. Qin, and C. A. Mirkin, "Rationally designed nanostructures for surface-enhanced Raman spectroscopy," *Chemical Society Reviews*, vol. 37, no. 5, pp. 885–897, 2008.

[61] S. M. Ng, M. Koneswaran, and R. Narayanaswamy, "A review on fluorescent inorganic nanoparticles for optical sensing applications," *RSC Advances*, vol. 6, no. 26, pp. 21624–21661, 2016.

[62] H. Wei, S. M. H. Abtahi, and P. J. Vikesland, "Plasmonic colorimetric and SERS sensors for environmental analysis," *Environmental Science. Nano*, vol. 2, no. 2, pp. 120–135, 2015.

[63] K. Kneipp, Y. Wang, R. R. Dasari, and M. S. Feld, "Approach to single molecule detection using surface-enhanced resonance Raman-scattering (SERRS) — a study using rhodamine 6G on colloidal silver," *Applied Spectroscopy*, vol. 49, no. 6, pp. 780–784, 1995.

[64] R. A. Alvarez-Puebla and L. M. Liz-Marzan, "Traps and cages for universal SERS detection," *Chemical Society Reviews*, vol. 41, no. 1, pp. 43–51, 2012.

[65] S. Giannoukos, B. Brkic, S. Taylor, A. Marshall, and G. F. Verbeck, "Chemical sniffing instrumentation for security applications," *Chemical Reviews*, vol. 116, no. 14, pp. 8146–8172, 2016.

[66] Y. Cui, Q. Wei, H. Park, and C. M. Lieber, "Nanowire nanosensors for highly sensitive and selective detection of biological and chemical species," *Science*, vol. 293, no. 5533, pp. 1289–1292, 2001.

[67] H. M. So, D. W. Park, E. K. Jeon et al., "Detection and titer estimation of Escherichia coli using aptamer- functionalized single-walled carbon-nanotube field-effect transistors," *Small*, vol. 4, no. 2, pp. 197–201, 2008.

[68] J. Peterson, G. Green, K. Iida et al., "Detection of hepatitis C core antigen in the antibody negative 'window' phase of hepatitis C infection," *Vox Sanguinis*, vol. 78, no. 2, pp. 80–85, 2000.

[69] J. Kudr, Y. Haddad, L. Richtera et al., "Magnetic nanoparticles: from design and synthesis to real world applications," *Nanomaterials*, vol. 7, no. 9, p. 243, 2017.

[70] T. G. Barroso, R. C. Martins, E. Fernandes, S. Cardoso, J. Rivas, and P. P. Freitas, "Detection of BCG bacteria using a magnetoresistive biosensor: a step towards a fully electronic platform for tuberculosis point-of-care detection," *Biosensors & Bioelectronics*, vol. 100, pp. 259–265, 2018.

[71] V. D. Krishna, K. Wu, A. M. Perez, and J. P. Wang, "Giant magnetoresistance based biosensor for detection of influenza A virus," *Frontiers in Microbiology*, vol. 7, p. 400, 2016.

[72] T. Z. G. de la Torre, R. Ke, A. Mezger, P. Svedlindh, M. Strømme, and M. Nilsson, "Sensitive detection of spores using volume-amplified magnetic nanobeads," *Small*, vol. 8, no. 14, pp. 2174–2177, 2012.

[73] Y. Chen, Y. Xianyu, Y. Wang et al., "One-step detection of pathogens and viruses: combining magnetic relaxation switching and magnetic separation," *ACS Nano*, vol. 9, no. 3, pp. 3184–3191, 2015.

[74] I. S. Muratova, K. N. Mikhelson, Y. E. Ermolenko, A. Offenhausser, and Y. Mourzina, "Chemiresistors based on ultrathin gold nanowires for sensing halides, pyridine and dopamine," *Sensors and Actuators B: Chemical*, vol. 232, pp. 420–427, 2016.

[75] A. R. Gao, N. Lu, Y. Wang et al., "Enhanced sensing of nucleic acids with silicon nanowires field effect transistor biosensors," *Nano Letters*, vol. 12, no. 10, pp. 5262–5268, 2012.

[76] F. X. Shen, J. Wang, Z. Xu et al., "Rapid flu diagnosis using silicon nanowire sensor," *Nano Letters*, vol. 12, no. 7, pp. 3722–3730, 2012.

[77] S. Jiang, R. Cheng, R. Ng, Y. Huang, and X. F. Duan, "Highly sensitive detection of mercury (II) ions with few-layer molybdenum disulfide," *Nano Research*, vol. 8, no. 1, pp. 257–262, 2015.

[78] D. Sarkar, W. Liu, X. Xie, A. C. Anselmo, S. Mitragotri, and K. Banerjee, "MoS2 field-effect transistor for next-generation label-free biosensors," *ACS Nano*, vol. 8, no. 4, pp. 3992–4003, 2014.

[79] O. Knopfmacher, M. L. Hammock, A. L. Appleton et al., "Highly stable organic polymer field-effect transistor sensor for selective detection in the marine environment," *Nature Communications*, vol. 5, no. 1, p. 2954, 2014.

[80] M. S. Mannoor, H. Tao, J. D. Clayton et al., "Graphene-based wireless bacteria detection on tooth enamel," *Nature Communications*, vol. 3, no. 1, p. 763, 2012.

[81] A. M. Stortini, L. M. Moretto, A. Mardegan, M. Ongaro, and P. Ugo, "Arrays of copper nanowire electrodes: preparation, characterization and application as nitrate sensor," *Sensors and Actuators B: Chemical*, vol. 207, pp. 186–192, 2015.

[82] X. G. Li, J. L. Zhang, and M. R. Huang, "Chemical response of nano composite membranes of electroactive poly diamino naphthalene nanoparticles to heavy metal ions," *Journal of Physical Chemistry C*, vol. 118, no. 22, pp. 11990–11999, 2014.

[83] Y. Yang, A. M. Asiri, D. Du, and Y. Lin, "Acetylcholinesterase biosensor based on a gold nanoparticle–poly pyrrole–reduced graphene oxide nano composite modified electrode for the amperometric detection of organophosphorus pesticides," *Analyst*, vol. 139, no. 12, pp. 3055–3060, 2014.

[84] K. Wu, T. Klein, V. D. Krishna, D. Su, A. M. Perez, and J. P. Wang, "Portable GMR handheld platform for the detection of influenza A virus," *ACS Sensor*, vol. 2, no. 11, pp. 1594–1601, 2017.

[85] T. Banerjee, S. Sulthana, T. Shelby et al., "Multiparametric magneto-fluorescent nanosensors for the ultrasensitive detection of Escherichia coli O157:H7," *ACS Infectious Diseases*, vol. 2, no. 10, pp. 667–673, 2016.

[86] E. Scallan, R. M. Hoekstra, F. J. Angulo et al., "Foodborne illness acquired in the United States major pathogens," *Emerging Infectious Diseases*, vol. 17, no. 1, pp. 7–15, 2011.

[87] R. Comparelli, M. L. Curri, P. D. Cozzoli, and M. Striccoli, *In Nanotechnologies for the Life Sciences: Nanomaterials for Biosensors*, C. S. S. R. Kumar, Ed., Wiley-VCH, Weinheim, 2007.

[88] W. L. Daniel, M. S. Han, J.-S. Lee, and C. A. Mirkin, "Colorimetric nitrite and nitrate detection with gold nanoparticle probes and kinetic end points," *Journal of the American Chemical Society*, vol. 131, no. 18, pp. 6362-6363, 2009.

[89] J. Liu and Y. Lu, "Fast colorimetric sensing of adenosine and cocaine based on a general sensor design involving aptamers and nanoparticles," *Angewandte Chemie, International Edition*, vol. 118, no. 1, pp. 96–100, 2006.

[90] L. Beqa, A. K. Singh, S. A. Khan, D. Senapati, S. R. Arumugam, and P. C. Ray, "Gold nanoparticle-based simple colorimetric and ultrasensitive dynamic light scattering assay for the selective detection of Pb (II) from paints, plastics, and water samples," *ACS Applied Materials & Interfaces*, vol. 3, pp. 668–673, 2011.

[91] Z. Zhang, Z. Chen, C. Qu, and L. Chen, "Highly sensitive visual detection of copper ions based on the shape-dependent LSPR spectroscopy of gold nanorods," *Langmuir*, vol. 30, no. 12, pp. 3625–3630, 2014.

[92] D. Vilela, M. C. González, and A. Escarpa, "Sensing colorimetric approaches based on gold and silver nanoparticles aggregation: chemical creativity behind the assay. A review," *Analytica Chimica Acta*, vol. 751, pp. 24–43, 2012.

[93] M. Algarra, B. B. Campos, B. Alonso et al., "Thiolated DAB dendrimers and CdSe quantum dots nanocomposites for Cd(II) or Pb(II) sensing," *Talanta*, vol. 88, pp. 403–407, 2012.

[94] M. Li, X. Zhou, S. Guo, and N. Wu, "Detection of lead (II) with a "turn-on" fluorescent biosensor based on energy transfer from CdSe/ZnS quantum dots to graphene oxide," *Biosensors & Bioelectronics*, vol. 43, pp. 69–74, 2013.

[95] W. Luan, H. Yang, Z. Wan, B. Yuan, X. Yu, and S. T. Tu, "Mercaptopropionic acid capped CdSe/ZnS quantum dots as fluorescence probe for lead (II)," *Journal of Nanoparticle Research*, vol. 14, no. 3, pp. 1–8, 2012.

[96] T.-W. Sung and Y.-L. Lo, "Highly sensitive and selective sensor based on silica-coated CdSe/ZnS nanoparticles for Cu^{2+} ion detection," *Sensors and Actuators B: Chemical*, vol. 165, no. 1, pp. 119–125, 2012.

[97] M. R. Chao, Y. Z. Chang, and J. L. Chen, "Hydrophilic ionic liquid-passivated CdTe quantum dots for mercury iondetection," *Biosensors & Bioelectronics*, vol. 42, pp. 397–402, 2013.

[98] T. T. Gan, Y. J. Zhang, N. J. Zhao et al., "Hydrothermal synthetic mercaptopropionic acid stabled CdTe quantum dots as fluorescent probes for detection of Ag^{+}," *Spectrochim Acta A*, vol. 99, pp. 62–68, 2012.

[99] R. Gui, X. An, H. Su, W. Shen, Z. Chen, and X. Wang, "A near-infrared-emitting CdTe/CdS core/shell quantum dots-based off-on fluorescence sensor for highly selective and sensitive detection of Cd2+," *Talanta*, vol. 94, pp. 257–262, 2012.

[100] X.-Q. Liu, Q. Liu, S. H. Cao et al., "Directional surface plasmon-coupled emission of CdTe quantum dots and its application in Hg (II) sensing," *Analytical Methods*, vol. 4, no. 12, p. 3956, 2012.

[101] H. Wu, J. Liang, and H. Han, "A novel method for the determination of Pb2+ based on the quenching of the fluorescence of CdTe quantum dots," *Microchimica Acta*, vol. 161, no. 1-2, pp. 81–86, 2008.

[102] Y. Q. Wang, Y. Liu, X. W. He, W. Y. Li, and Y. K. Zhang, "Highly sensitive synchronous fluorescence determination of mercury (II) based on the denatured ovalbumin coated CdTe QDs," *Talanta*, vol. 99, pp. 69–74, 2012.

[103] M. Koneswaran and R. Narayanaswamy, "RETRACTED: l-cysteine-capped ZnS quantum dots based fluorescence sensor for Cu^{2+} ion," *Sensors and Actuators B: Chemical*, vol. 139, no. 1, pp. 104–109, 2009.

[104] J. Ke, X. Li, Y. Shi, Q. Zhao, and X. Jiang, "A facile and highly sensitive probe for Hg (II) based on metal-induced aggregation of ZnSe/ZnS quantum dots," *Nanoscale*, vol. 4, no. 16, pp. 4996–5001, 2012.

[105] C. Zhang, L. Wang, Z. Tu et al., "Organophosphorus pesticides detection using broad-specific single-stranded DNA based fluorescence polarization aptamer assay," *Biosensors & Bioelectronics*, vol. 55, pp. 216–219, 2014.

[106] K. R. Ackermann, T. Henkel, and J. Popp, "Quantitative online detection of low-concentrated drugs via a SERS microfluidic system," *ChemPhysChem*, vol. 8, no. 18, pp. 2665–2670, 2007.

[107] K. Hadjigeorgiou, E. Kastanos, and C. Pitris, "Multi-bacteria multi-antibiotic testing using surface enhanced Raman spectroscopy (SERS) for urinary tract infection (UTI) diagnosis," *In Clinical and Biomedical Spectroscopy and ImagingIII*, V. Deckert and N. Ramanujam, Eds., p. 87980L, 2013.

[108] R. A. Halvorson and P. J. Vikesland, "Surface-enhanced Raman spectroscopy (SERS) for environmental analyses,"

Environmental Science & Technology, vol. 44, no. 20, pp. 7749–7755, 2010.

[109] R. M. Jarvis and R. Goodacre, "Characterisation and identification of bacteria using SERS," *Chemical Society Reviews*, vol. 37, no. 5, pp. 931–936, 2008.

[110] H. Zhou, D. Yang, N. P. Ivleva, N. E. Mircescu, R. Niessner, and C. Haisch, "SERS detection of bacteria in water by in situ coating with Ag nanoparticles," *Analytical Chemistry*, vol. 86, no. 3, pp. 1525–1533, 2014.

[111] S. Y. Cho, H. W. Yoo, J. Y. Kim et al., "High-resolution p-type metal oxide semiconductor nanowire array as an ultrasensitive sensor for volatile organic compounds," *Nano Letters*, vol. 16, no. 7, pp. 4508–4515, 2016.

[112] J. H. Kim, A. Katoch, S. H. Kim, and S. S. Kim, "Chemiresistive sensing behavior of SnO2 (n)–Cu2O (p) core–shell nanowires," *ACS Applied Materials & Interfaces*, vol. 7, no. 28, pp. 15351–15358, 2015.

[113] J. F. Fennell, S. F. Liu, J. M. Azzarelli et al., "Nanowire chemical/biological sensors: status and a roadmap for the future," *Angewandte Chemie, International Edition*, vol. 55, no. 4, pp. 1266–1281, 2016.

[114] L. R. Kindra, C. J. Eggers, A. T. Liu et al., "Lithographically patterned pedot nanowires for the detection of iron (III) with nanomolar sensitivity," *Analytical Chemistry*, vol. 87, no. 22, pp. 11492–11500, 2015.

[115] O. S. Kwon, S. J. Park, H. Yoon, and J. Jang, "Highly sensitive and selective chemiresistive sensors based on multidimensional polypyrrole nanotubes," *Chemical Communications*, vol. 48, no. 85, pp. 10526–10528, 2012.

[116] S. Chen and G. Sun, "High sensitivity ammonia sensor using a hierarchical polyaniline/poly (ethylene-co-glycidyl methacrylate) nanofibrous composite membrane," *ACS Applied Materials & Interfaces*, vol. 5, no. 14, pp. 6473–6477, 2013.

[117] A. J. Bandodkar, I. Jeerapan, J. M. You, R. Nunez-Flores, and J. Wang, "Highly stretchable fully printed CNT-based electrochemical sensors and biofuel cells: combining intrinsic and design-induced stretchability," *NanoLetters*, vol. 16, no. 1, pp. 721–727, 2016.

[118] P. P. Gou, N. D. Kraut, I. M. Feigel, and A. Star, "Rigid versus flexible ligands on carbon nanotubes for the enhanced sensitivity of cobalt ions," *Macromolecules*, vol. 46, no. 4, pp. 1376–1383, 2013.