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Biosensors and their Applications in Food Safety: A Review

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Abstract

Background: Foodborne pathogens are a growing concern with respect to human illnesses and death. There is an increasing demand for improvements in global food safety. However, it is a challenge to detect and identify these harmful organisms in a rapid, responsive, suitable, and effective way. **Results:** Rapid developments in biosensor designs have contributed to the detection of foodborne pathogens and other microorganisms. Biosensors can automate this process and have the potential to enable fast analyses that are cost and time-effective. Various biosensor techniques are available that can identify foodborne pathogens and other health hazards. **Conclusions:** In this review, biosensor technology is briefly discussed, followed by a summary of foodborne pathogen detection using various transduction systems that exhibit specificity for particular foodborne pathogens. In addition, the recent application of biosensor technology to detect pesticides and heavy metals is briefly addressed.

Keywords: Biosensor, Biotechnology, Food safety, Foodborne pathogens, Rapid measurement

Introduction

Recently, bacterial and microbial diseases have spread worldwide owing to the global trade of agricultural products. Some microorganisms cause diseases that have disastrous effects in humans and can result in widespread health issues. An estimated 2 million deaths annually are attributed to unsafe food, and these deaths are caused by more than 200 diseases ranging from diarrhea to cancer. Therefore, the World Health Organization has promoted food safety as follows: “from farm to plate (and everywhere in between) make food safe” on World Health Day, 2015 (WHO, 2015). The US Centers for Disease Control and Prevention has reported that in the United States, one in six people (i.e., 48 million people in total) get sick per year and 3,000 people die of foodborne diseases, on average. The US Department of Agriculture has estimated that foodborne illnesses cost almost $15.6 billion per year (CDC, 2016a). Some foodborne pathogens are common in food, such as *Campylobacter* spp., *Salmonella* spp., *Listeria monocytogenes,* and *Escherichia coli* O157:H7 (Alocilja and Radke, 2003; Chemburu et al., 2005). Foodborne illnesses caused by these pathogens result in recurring intestinal inflammation, chronic kidney diseases, mental disability, reactive arthritis, blindness, and even death (Hoffmann et al., 2015).

Conventional methods for the detection of microbial contaminants are sensitive and inexpensive, but they require several days to yield results. In contrast, biosensors can rapidly relay results based on a progressive organic reaction. The rapid and sensitive detection of foodborne infections, a major objective of biosensor research, has been successfully achieved (Yang et al., 2008). Biosensor and nano-scale technologies are currently used in many food industries for packaging and pathogen detection in agricultural products and in animals. In comparison with other technologies, such as chromatography and spectroscopy,

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biotechnology offers more cost-effective, rapid, *in-situ*/on-site, and reliable detection methods to control biological hazards owing to the small sizes of biosensor devices and their responsive characteristics.

For a better understanding of current biosensor technology, this review is divided into two sections. In the first section, general concepts related to biosensors are defined, followed by a detailed discussion of the most widely used biosensor types. In the second section, major foodborne pathogens and their biotechnology-based detection methods are summarized. In addition, food safety issues are discussed. Food safety can be defined as the availability and continuous, timely, and permanent provision of foods that meet quality assurance and safety requirements to the entire world population (FAO, 1996).

Biosensor-related definitions

Biotechnology

Biotechnology is a vast discipline that applies knowledge of organisms and cellular components to develop systems for agriculture, medicine, food production, etc. The European Federation of Biotechnology defines biotechnology as "the integration of natural sciences and engineering in order to achieve the application of organisms, cells, parts thereof and molecular analogues for products and services" (Buyukgungor and Gurel, 2009). Throughout the world, biotechnology is used in agriculture by more than 13.3 million farmers to increase yields, reduce insects and pesticides, and reduce environmental hazards (BIO, 2010).

Biosensors

Dr. Leland and C. Clark are considered to be the fathers of biosensors. They established the concept of using a biological sensing element to detect various analytes in 1962 (Nayak et al., 2009). Since then, research based on biosensors has increased consistently worldwide, including studies in miscellaneous areas from food to biotechnology and from medicine to the environment. Biosensors are sensing devices that can be used to analyze and diagnose substances by transforming a biological response into a signal (Velusamy et al., 2010). These devices incorporate a biological sensing element connected to a transducer that converts the response into a measurable signal. Biosensors can be characterized using heterogeneous terminologies that describe their activities, such as canaries, immunosensors, optrodes, biochips, chemical resonant mirrors, glucometers, and biocomputers. Various parameters, such as sensitivity, selectivity, specificity, reproducibility, size, rapidity of diagnostic tests, large-scale manufacturing, and cost, are used to evaluate the performance of a biosensor (Arugula and Aleksandr, 2014).

The epithet "Biosensor" denotes a blend of two building blocks:

a) Bio-element (receptor, which acts as a sensor)
b) Sensing element (transducer, which transmits a signal)

Enzymes, DNA, antigens, living cells, antibodies, RNA, and tissues function as bio-elements. Sensing elements are highly diverse; they include conductance, intensity, phase of electromagnetic radiation, electric current, mass, viscosity, electric potential, temperature, and impedance. The basic concept underlying the function of a biosensor is summarized in Figure 1. A specific bio-element detects a specific analyte. Upon detection, a physico-chemical change occurs on the transducer surface, resulting in a signal that is directly measured or converted into another signal. This analyte-receptor reaction is critical because if the bio-element cannot bind with the specific analyte, a signal will not be transmitted.

To design a biosensor, various requirements must be met. Particular consideration should be given to the recognition type of the bioreceptor and the immobilization method. The selection of bioreceptors should be based on their ability to bind specific target materials and should consider their capacity for immobilization (Singh et al., 2013).

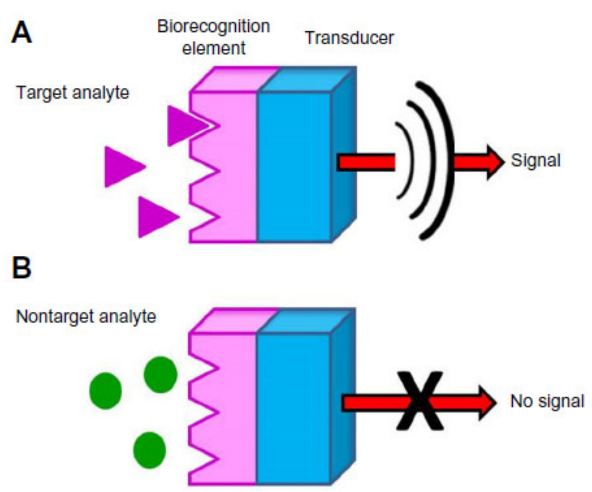

Figure 1. Schematic working model modified from Krejcova et al. (2015).

Immobilization

In order to make a biosensor, biological components need to be properly attached to the transducer. In this process, the activity of the target molecule must not be changed, and this is achieved by a process known as immobilization (Zhao and Jiang, 2010). To immobilize a molecule, the crucial constituents are the target molecule, the matrix, and the coupling procedure. Attachment can occur via interactions ranging from physical adsorption to stable linking bonds. Several methods are used to immobilize molecules. Figure 2 shows various immobilization methods for cells that are based on different techniques.

Types of biosensors

Biosensor types can be classified on the basis of sensing elements or transducers. In the detection of foodborne pathogens, transducers play an important role. In this section, electrochemical, optical, and mass-sensitive biosensors are reviewed owing to their extensive use in many recent applications.

Optical biosensors

The measured output signal of optical-based biosensors is light emission, which allows direct (label-free) detection of foodborne pathogens. When cells bind to receptors or are immobilized on the transducer surface, these sensors are able to detect minute changes. Optical diffraction and electrochemiluminescence are standard technologies for optical biosensors. Using the optical diffraction method, a silicon wafer is coated with proteins via covalent bonds and then exposed to ultraviolet light through a photomask. Under these conditions, antibodies that are exposed to ultraviolet light become inactivated. When the wafer is incubated with an antigen-antibody analyte, only activated antibodies are able to create bonds with the antigen and produce a signal under the laser light source. This signal is measured directly or amplified for improved sensitivity (Kovacs, 1998).

Optical biosensors are classified into a large number of sub-categories, e.g., reflection, refraction, resonance, dispersion, phosphorescence, infrared absorption, Raman scattering, fluorescence, and chemiluminescence. Among them, surface plasmon resonance (SPR) and fluorescence-based optical biosensors are commonly used for the detection of foodborne pathogens owing to their high sensitivity (Velusamy et al., 2010).

Electrochemical biosensors

The basic principle of electrochemical biosensors is related to their ability to detect specific molecules. They

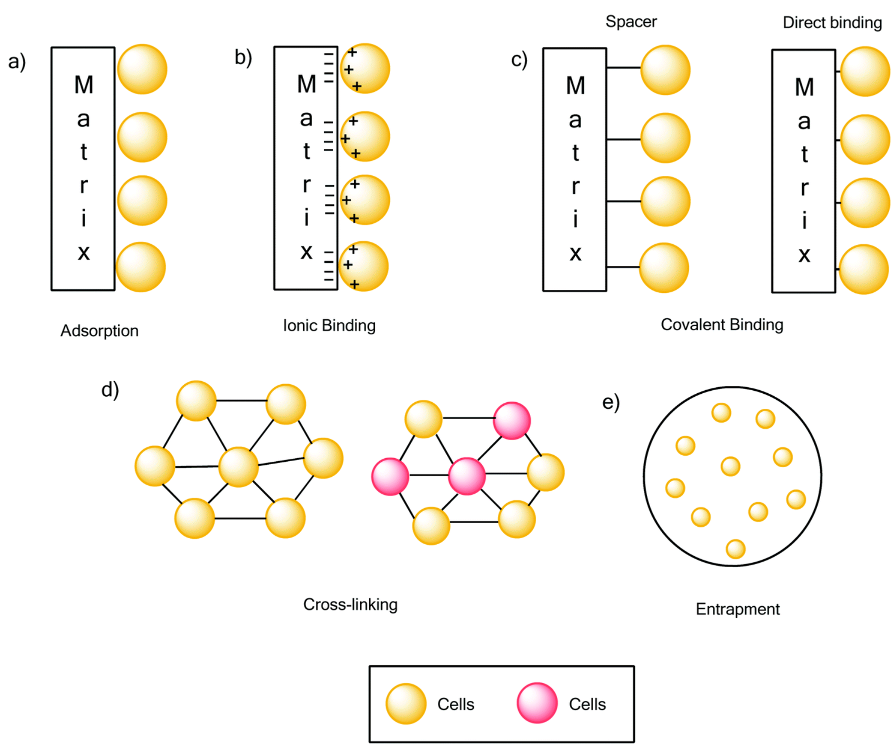

Figure 2. Immobilization models modified by Kisukuri and Andrade (2015).

Table 1. Electrochemical sensing techniques

Characteristics	Electrochemical-based sensing methodology		
	Conductometric	Amperometric	Potentiometric
Parameters	Conductance/resistance	Current	Voltage
Applied Voltage	AC	DC	Ramp voltage
Sensitivity	Low	High	
Dominant Equation	Incremental resistance	Cottrell eqn.	Nernst eqn.
Fabrication	Field effect transistor (FET) + enzyme	FET + enzyme (2 electrodes)	FET + enzyme Oxide electrode

are mainly used to detect DNA-binding drugs, glucose, and hybridized DNA. In this technique, measurable electrons or ions are produced or suppressed by different types of chemical reactions (Kovacs, 1998; Sethi and Lowe, 1990). These biosensors can be classified as amperometric, potentiometric, or conductometric (Velusamy et al., 2010). A general summary of the properties of these three electrochemical biosensors is presented in Table 1.

Mass-sensitive biosensors

Mass-sensitive biosensors are utilized less frequently than optical and electrochemical biosensors (Su and Li, 2005). Also known as piezoelectric biosensors, they use piezoelectric crystals that are highly sensitive and can detect small changes in mass. When an alternating electrical current with a fixed frequency is applied, piezoelectric crystals vibrate at a specific frequency. This frequency is dependent on the mass of the crystal in addition to the fixed electrical frequency. Chemical reactions affect the frequency of oscillations, which is measured as an output signal (Velusamy et al., 2010). Two major types of mass-sensitive biosensors are a) bulk wave devices and b) surface acoustic wave devices.

Biosensors for microorganism detection to ensure food safety

Foodborne pathogens compromise food safety at all steps from handling to manufacturing, distribution, and consumption. Food safety as a scientific discipline considers food handling, preparation, and storage for the prevention of foodborne illnesses and associated outbreaks. Biological hazards are primarily caused by pathogenic microorganisms that may not change the organoleptic properties of food, but can cause serious health injuries to consumers. Foodborne diseases caused by pathogens have long-term effects on social and economic conditions by resulting in a loss of productivity (Plata, 2003). Common foodborne pathogens that are major concerns are *Campylobacter* spp., *L. monocytogenes*, *E. coli*, and *Salmonella* spp. (Hara-Kudo et al., 2012; Korsak et al., 2015; Crim et al., 2015; Torso et al., 2015).

Various conventional and traditional methods are used to detect foodborne pathogens. The enzyme-linked immunosorbent assay is one of the most widely used methods for detecting pathogens in food as well as in tissues of humans and other animals (Nowak et al., 2007; Deng et al., 2008; Cabrera et al., 2009; Yeni et al., 2014; Zhao et al., 2014; Zhang et al., 2014; Wladir et al., 2015). Although this technique enables the accurate detection of foodborne pathogens, it is time-consuming and expensive.

Salmonella spp.

Salmonellosis is one of the most common foodborne diseases caused by *Salmonella* in both humans and animals (Wang et al., 2011). An estimated 93.8 million human infections and 155,000 deaths occur annually worldwide (Hendriksen et al., 2011). Symptoms include diarrhea, fever, and abdominal pain lasting 4 to 7 days (CDC, 2016). Therefore, the detection of *Salmonella* in a sensitive and rapid manner is particularly important for food safety.

In 1880, Karl Eberth first discovered *Salmonella* in both the Peyer's patches and spleens of typhoid patients (Eberth, 1880). These gram-negative bacteria are naturally found in the gastrointestinal tracts of warm-blooded animals, including humans (Nowak et al., 2007; Lu et al., 2009). In 1884, Georg Theodor Gaffky successfully grew *Salmonella* in pure culture (Hardy, 1999). Moreover, *Salmonella* spp. can survive outside of their natural habitat, e.g., in water and food products (White et al., 2002). *Salmonella* detection by SPR-based assays with antibodies as the recognition element has been described in many studies (Bokken et al., 2003; Oh et al., 2004; Mazumdar et al., 2007; Dudak and Boyaci, 2009; Mazumdar et al., 2010; Singh et al., 2015; Vaisocherová-Lísalová et al., 2016).

In addition, P-7 SPR-based optical fiber sensors have been reported for the detection of *Salmonella* (Romanov et al., 2011). Recently, new DNA-based SPR biosensors have been proposed to detect *Salmonella* based on the *invA* gene (Rahn et al., 1992; Daum et al., 2002; Jeong et al., 2011; Zhang et al., 2012). In another study, wireless magnetoelastic biosensors were used for the rapid, sensitive, and direct detection of *Salmonella* on eggshells (Chai et al., 2012). García et al. (2012) described the development of disposable DNA electrochemical bioplatforms for selective *Salmonella* detection, even in the presence of other pathogens.

Nucleic acid aptamers are single-stranded DNA or RNA molecules with unique structural forms and binding affinities for specific targets. An aptamer-based electrochemical biosensor for rapid *Salmonella* detection has been developed (Ma et al., 2014). Additional electrochemical biosensing strategies for *Salmonella* detection are based on the use of a screen-printed carbon electrode formed from nanoparticles (Noguera et al., 2011) or carbon nanotubes (Zelada-Guillen et al., 2010), resulting in a disposable immunosensor (Afonso et al., 2013). A phase-based magnetoelastic biosensor was established to detect *Salmonella* directly on spinach leaves (Park et al., 2013).

Escherichia coli

E. coli O157:H7 is a serious pathogen that causes celiac diseases and presents an alarming challenge to human health. It was first observed in 1982 in the USA and has since been identified worldwide as a major foodborne pathogen (Riley et al., 1983; Wells et al., 1983). The German bacteriologist Theodor Escherich first detected *E. coli* in 1885 in the human colon and identified it as being responsible for infant diarrhea and gastroenteritis (Feng et al., 2002). *E. coli* is a gram-negative bacterium that is naturally found in the intestinal tracts of humans, other warm-blooded animals, and food products (Darnton et al., 2007). Strains of *E. coli* can cause urinary tract infections, respiratory illness, and bloodstream infections (CDC, 2014). They are also responsible for severe diarrhea with bleeding and kidney damage resulting from inflammation in the small intestine (Lin et al., 2010).

A modified SPR apparatus for the cost-effective, label-free, real-time, and specific detection of *E. coli* in less than 20 min has been developed (Tawil et al., 2012). A biosensor based on specific antibody-antigen interactions, which is termed an immunosensor, was also constructed for *E. coli* detection (Ivnitski et al., 1999; Iqbal et al., 2000; Leonard et al., 2003). Additionally, evanescent wave detection, a label-free optical fiber sensor technique that works on the basis of a change in light absorbance at 280 nm in the presence of the target analyte, has been used successfully for *E. coli* detection (Bharadwaj et al., 2011).

A DNA sequence-specific electrochemical biosensor has been developed for the amperometric detection of *E. coli* using a Fe_2O_3 core/Au shell nanoparticle (Li et al., 2011). Additionally, a new type of electrochemical DNA biosensor based on magnetic beads that detect the *uidA* gene, which encodes the enzyme β-D-glucuronidase produced by *E. coli*, has been developed (Geng et al., 2011). Impedimetric sensing based on covalently-linked antibodies on a conducting polyaniline film surface is also possible using the antibody-antigen binding method and this approach is label-free, rapid, and inexpensive (Setterington and Alocilja, 2011; Chowdhury et al., 2012).

Three different electrodes that were modified by carboxylic multi-walled carbon nanotubes, glutaraldehyde, and 3-aminopropyltriethoxysilane, respectively, were fabricated to generate functional porous pseudo-carbon paste electrodes for the detection of *E. coli* (Lijian et al., 2012). In another study, an immunosensor for the ultra-sensitive detection of *E. coli* O157:H7 on biofunctional magnetic beads was reported to determine the bacterial cell concentration in a nanoporous alumina membrane (Chan et al., 2013). *E. coli* O157:H7 can also be detected using biosensors that employ a ferrocene-antimicrobial peptide conjugate on a gold surface based on impedance (Li et al., 2014).

Listeria monocytogenes

L. monocytogenes causes listeriosis when it infects the blood, central nervous tissue, or a placenta/fetus. According to the Public Health Agency of Canada in 2016, pregnant women and their unborn/newborn children, adults aged 65 years and older, and people with weakened immune systems are at the highest risk of serious illness by *Listeria* (PHAC, 2016).

A biosensor constructed based on immobilization of the cell wall-binding domain of bacteriophage-encoded peptidoglycan hydrolases (endolysins) on a gold screen-printed electrode was applied to *Listeria* detection. This technology uses electrochemical impedance spectroscopy for the rapid detection of *Listeria* cells (Tolba et al., 2012). Additionally, a new electrochemical DNA biosensor was assembled using gold nanoparticles and an electrochemically reduced graphene composite modified by a carbon ionic liquid electrode as the platform (Sun et al., 2012).

Integrated biosensors such as impedimetric biosensors, which combine impedance and biological recognition technology, have gained widespread utilization and could be used for on-site detection (K'Owino and Sadik, 2005). Monoclonal antibodies immobilized on an Au electrode have been used in combination with electrochemical impedance spectroscopy to detect *L. monocytogenes* (Radhakrishnan et al., 2013). An inexpensive biosensor was developed by modifying screen-printed carbon electrode strips that were initially designed for glucose monitoring in diabetes using specific antibodies against *L. monocytogenes* in combination with secondary antibodies enzymatically labeled with gold nanoparticles (Davis et al., 2013). In a recent study, hybridization reactions with a covalently immobilized DNA probe were used to develop a paper-based microfluidic device for the detection of *L. monocytogenes* that yielded high sensitivity and reliability (Liu and Zhang, 2015).

Recently, a new method that is referred to as immunomagnetic separation was developed to effectively isolate pathogens from food matrices using magnetic pellets to functionalize antibodies against target pathogens (Varshney et al., 2005). A similar technique was reported that is based on magnetic nanoparticles with a diameter of 30 nm functionalized with anti-*L. monocytogenes* antibodies via biotin-streptavidin bonds to generate immunomagnetic nanoparticles that were shown to capture *L. monocytogenes* during a 2-h immunoreaction (Damira et al., 2012).

Campylobacter spp.

Campylobacter spp. are often found in the gastrointestinal tracts of poultry, cattle, swine, wild birds, and pet animals (Nachamkin and Blaser, 2000). *Campylobacter* can infect humans via the consumption of infected meats. Bacteria belonging to the genus *Campylobacter* typically attack the digestive system, resulting in campylobacteriosis, which has symptoms including diarrhea, cramping, abdominal pain, and fever. Approximately 2 million cases of infections caused by *Campylobacter* are reported annually, among which 5-6% of cases are gastroenteritis (Medscape, 2015). Compared with the *Campylobacter* incidence between 2006 and 2008, the infection rate increased by 9% in 2014 (CDC, 2016). Therefore, there is an obvious need to develop rapid and effective methods for the detection and identification of *Campylobacter* spp.

Optical SPR biosensors are highly sensitive for *Campylobacter* detection when specific antibodies against the target *Campylobacter* populations are used (Wei et al., 2007). Aptamer research is continuously generating interest within the field of biosensor research. A DNA aptamer-magnetic bead and quantum dot sandwich assay was developed using aptamer-sensors against $MgCl_2$-extracted surface proteins from *Campylobacter* spp. (Bruno et al., 2009). To detect *Campylobacter* spp. in a short time period, e.g., within 24 h, an organic deep-blue light-emitting diode was constructed based on DNA biochip and showed high sensitivity with real meat samples (Manzano et al., 2015).

Biosensors for pesticide detection

Highly toxic and poisonous pesticides, insecticides, and herbicides have been widely used for decades in the agricultural industry (Alavanja et al., 2004). For example, pesticides are commonly applied to crop fields, including potatoes, corn, wheat, and rice. In the long term, repeated exposure to certain pesticides can cause allergies, breathing difficulties, or cancer (Criswell and Campbell, 2013), and their high toxicity can affect environmental properties (Givaudan et al., 2014). In comparison with those in the year 2000, pesticide sales were almost $20 billion higher in 2011 (Matthews et al., 2014). Accordingly, analyses of pesticides are becoming increasingly important. In general, gas chromatography or high-performance liquid chromatography is used to detect the presence of pesticides, but these methods are time-consuming and labor-intensive. Biosensors may be an effective alternative approach for rapid and responsive pesticide detection.

Organophosphorus is a commonly used pesticide, despite its negative impacts on the environment and human health. It is necessary to develop methods to accurately analyze these pesticides. Enzymatic biosensors have been widely studied for this purpose owing to their stability, sensitivity, and accuracy. Optical, calorimetric, electrochemical, and piezoelectric biosensors have been developed based on enzyme inhibition to measure pesticides (Arduini and Amine, 2014).

Among the various types of enzyme that are used in

Table 2. Biosensors for the detection of organophosphorus pesticides

Enzyme	Target analyte	Substrate type	Nanomaterials	Detection limit	Samples	Ref (Year)
AChE	Paraoxon	Glassy-carbon electrode	CNT, Au/cr-Gs	0.4 pM, 0.1 pM		Liu and Lin, 2006a; Wang et al., 2011
AChE	Monocrotophos	SPE	PBNCs/rGO	0.1 ng mL^{-1}	Cucumber	Zhang et al., 2012a
AChE	Malathion, Chlorpyrifos, Monocrotophos, Endosulfan	Au electrode	Fe_3O_4/MWCNT	0.1 nM, 0.1 nM, 1 nM, 10 nM	Milk and water	Chauhan and Pundir, 2011
AChE + CHO	Methyl parathion	SPE	CNT	0.05 μM		Lin et al., 2004
AChE + CHO	Dichlorovos	Liquid phase	CdTe QDs	4.49 nM	Apple	Meng et al., 2013
OPH	Paraoxon	Glassy-carbon electrode	CNT, MC/CB	0.15 μM, 12 μM		Deo et al., 2005; Lee et al., 2010
OPH	Methyl parathion	Glassy-carbon electrode, SPE	CdTe/Au/ MWCNT, Fe_3O_4/Au	1 ng mL^{-1}, 0.1 ng mL^{-1}		Du et al., 2010a; Zhao et al., 2013
	Methyl parathion	Au electrode	ZrO_2	3 ng mL^{-1}		Liu and Lin, 2005b
	Methyl parathion	Glassy-carbon electrode	Graphene/ZrO_2	0.1 ng mL^{-1}	Garlic	Du et al., 2011b;
	Paraoxon-ethyl	Glassy-carbon electrode	Au/ZrO_2/SiO_2	0.5 ng mL^{-1}		Yang et al., 2012
3,5,6-trichloro-2-pyridinol	3,5,6-trichloro-2-pyridinol	Test strip	Au, CdS@ZnS QDs	0.47 ng mL^{-1}, 1.0 ng mL^{-1}	Human saliva, rat plasma	Zhang et al., 2013b; Zou et al., 2010
2,6-dichloroben zamide	2,6-dichloroben zamide	Microarray substrates	Au	20 ng mL^{-1}	Water	Han et al., 2003
AChE activity	Paraoxon	SPE/flow injection system	CNT	2 pM	Rat saliva	Wang et al., 2008; Du et al., 2009c
OP-AChE	Paraoxon	SPE	CdS@ZnS QDs, ZrO_2	8 pM, 0.15 ng mL^{-1}, 0.02 nM	Human plasma, rat plasma	Liu et al., 2008; Wang et al., 2008; Du et al., 2011d
OP-AChE	Chlorpyrifos	Test strip/SPE	CNT	0.02 nM	Human RBCs	Du et al., 2012e
OP-BChE	Diisopropyl fluorophosphate	SPE	ZrO_2	0.03 nM	Human plasma	Lu et al., 2011
OP-BChE	Paraoxon	SPE	Fe_3O_4@TiO_2 QDs	0.01 nM	Human plasma	Zhang et al., 2013

biosensors, cholinesterases, organophosphorus hydrolases, and ureases are commonly used to construct electrochemical biosensors for pesticide detection. Zhang et al. (2014) summarized the most common enzymes used for biosensors to detect pesticides (Table 2). Additionally, Yada (2015) discussed common enzymatic biosensors for the detection of pesticides and herbicides.

AChE (acetylcholinesterase); BChE (butyrylcholinesterase); CNT (carbon nanotubes); MC/CB (mesoporous carbon/carbon black); MWCNT (multi-walled carbon nanotubes); OP (organophosphorus); OPH (organophosphorus hydrolyase); PBNCs (Prussian blue nanocubes); QDs (quantum dots); RBCs (red blood cells); rGO (reduced graphene oxide); SPE (screen-printed electrode).

Biosensors for heavy metals detection

Owing to their high toxicity, heavy metals are harmful to human and animal health. They accumulate in organisms and can cause metabolic alterations in animals, particularly those that graze near industrial areas and consume contaminated water. Health issues caused by heavy metals include the inhibition of hormonal activity, cardiovascular and respiratory problems, irritation, infertility, malfunctioning of principal organs, and even death.

The spread of heavy metal ions from industrial processes to the environment is a serious public health threat. Generally, heavy metals are denser than iron, e.g., cadmium, mercury (Hg), and lead (Pb), and they are non-biodegradable. They often come from vehicle emissions, chemical fertilizers, or lead-acid batteries (Gammoudi et al., 2010). To protect human health and the environment, urgent steps are needed for the remediation of these heavy metals from food products. However, large-scale methodologies for heavy metals detection based on spectrometry and chromatography are costly, time-consuming, and require expertise (Bagal-Kestwal et al., 2008). A portable, rapid, and inexpensive detection method for heavy metals that can be used for on-site screening is necessary, and biosensors may be appropriate for this purpose.

Microbial biosensors have a sufficiently high sensitivity for the detection of heavy metal ions at a low cost. For example, microbial fluorescence-based biosensor devices (Tao et al., 2013; Amaro et al., 2014) use reporter genes that react only when biochemical interactions occur between cellular reporters and inducer molecules. A combination of a chemostat-like microfluidic platform and microbial biosensors facilitates molecular analyte detection on a chip (Kim et al., 2015). For the rapid detection of heavy metal ions, a DNA optical biosensor combined with evanescent wave analysis can enable *in-situ* detection (Long et al., 2013).

To rapidly identify selective sub-nanomolar Pb^{2+} ions in liquefied solutions, a luminescent G-quadruplex-based sensing device was developed (He et al., 2013). Additionally, for the *in-situ* detection of heavy metal ions, various methods have been used, e.g., amperometric (Wang et al., 2013), acoustic (Gammoudi et al., 2014), and electrochemical sensors (Sbartai et al., 2012) as well as inhibition-based biosensors (Ghica et al., 2013; Amine et al., 2014).

Graphene oxide is environmentally friendly and economic. To detect Hg^{2+} ions, a simple and highly responsive graphene oxide-based fluorescent sensor has been developed in which graphene oxide functions as a fluorophore. The molecular recognition probe binds to Hg^{2+} ions via a DNA aptamer (Li et al., 2013). β-Carotene, which is naturally found in palm kernels, can be used as a biological reporter in biopolymer-based biosensors to detect heavy metals such as aluminum (Wong and Wong, 2015). To detect heavy metals such as cadmium-chelate conjugates, an on-chip label-free sensing device was designed that enables the high-throughput detection of concentrations as low as 5 parts per billion (Yan et al., 2016). Various biosensor techniques to detect heavy metals have been described by Mehta et al. (2016).

Conclusions

Increasing efforts have been made to develop techniques for the detection of foodborne pathogens, residues, and pesticides as well as heavy metals. There are many technical obstacles against the preparation of sensitive biosensors that have the necessary properties for specific target detection in a short time period. Improvements in bio-technology can facilitate the manufacturing of effective biosensors. Published studies and literature reviews indicate that conventional methods show favorable sensitivity and are inexpensive, but are unable to provide instant results. A wide range of signal transducers has recently been developed to detect foodborne pathogens, pesticides, and heavy metals. Detection results vary depending on the properties of the transducers and the biological elements that are used as analytes. Ensuring food safety is vital, and yet it presents a great challenge. Biosensor technologies have a good potential for the determination of deleterious substances in foods and can provide on-site/*in-situ* detection.

Conflict of interest

The authors have no conflicting financial or other interests.

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