Arch Toxicol
DOI 10.1007/s00204-016-1875-8

REVIEW ARTICLE

Biosensors and their applications in detection of organophosphorus pesticides in the environment

Shokoufeh Hassani[1,6] · Saeideh Momtaz[1,2,6] · Faezeh Vakhshiteh[3] · Armin Salek Maghsoudi[1,6] · Mohammad Reza Ganjali[4,5] · Parviz Norouzi[4,5] · Mohammad Abdollahi[1,5,6]

Received: 30 September 2016 / Accepted: 10 October 2016

Abstract This review discusses the past and recent advancements of biosensors focusing on detection of organophosphorus pesticides (OPs) due to their exceptional use during the last decades. Apart from agricultural benefits, OPs also impose adverse toxicological effects on animal and human population. Conventional approaches such as chromatographic techniques used for pesticide detection are associated with several limitations. A biosensor technology is unique due to the detection sensitivity, selectivity, remarkable performance capabilities, simplicity and on-site operation, fabrication and incorporation with nanomaterials. This study also provided specifications of the most OPs biosensors reported until today based on their transducer system. In addition, we highlighted the application of advanced complementary materials and analysis techniques in OPs detection systems. The availability of these new materials associated with new sensing techniques has led to introduction of easy-to-use analytical tools of high sensitivity and specificity in the design and construction of OPs biosensors. In this review, we elaborated the achievements in sensing systems concerning innovative nanomaterials and analytical techniques with emphasis on OPs.

Keywords Organophosphorus pesticides (OPs) · Biosensor detection of OPs · Nanomaterials

Introduction

Pesticides have been used extensively to prevent or decrease damages caused by pests, weeds and illnesses and, hence, benefit agricultural manufacture. Farmers utilize several pesticides for crop protection, pre- and post-harvesting in agriculture sector. It is expected that the use of pesticides supports to save almost 30 % of crop produced worldwide (Nougadère et al. 2011). Pesticides are defined as organic toxic mixtures utilized against a broad range of pests and may get into the food industry via various sources, resulting in health issues to both humans and animals. Researches have revealed that extreme exposure to pesticides can lead to numerous illnesses (Mostafalou and Abdollahi 2013). Fast detection of pesticide is highly essential due to their stability and toxicity. Various analysis approaches have been established for detection of pesticide residues including gas chromatography–mass spectrometry (GC–MS) (García-Valcárcel and Tadeo 2009), liquid chromatography–mass spectrometry (Vuković et al. 2012; Páleníková et al. 2015; Choi et al. 2015), capillary electrophoresis (Guler et al. 2010; Regueiro et al. 2015),

Shokoufeh Hassani and Saeideh Momtaz have participated equally.

✉ Mohammad Abdollahi
Mohammad@TUMS.Ac.Ir;
Mohammad.Abdollahi@UToronto.Ca

1 Pharmaceutical Sciences Research Center, Faculty of Pharmacy, Tehran University of Medical Science, Tehran 1417614411, Iran

2 Medicinal Plants Research Center, Institute of Medicinal Plants, ACECR, Karaj, Iran

3 Nanotechnology Research Centre, Faculty of Pharmacy, Tehran University of Medical Sciences, Tehran, Iran

4 Center of Excellence in Electrochemistry, Faculty of Chemistry, University of Tehran, Tehran, Iran

5 Endocrinology and Metabolism Research Institute, Tehran University of Medical Sciences, Tehran, Iran

6 Toxicology Interest Group, Universal Scientific Education and Research Network (USERN), Tehran University of Medical Sciences, Tehran, Iran

Published online: 19 October 2016

pressurized liquid extraction (Du et al. 2012; Zhao et al. 2015a) and fluorimetry (Pacioni and Veglia 2003). For pesticide extraction procedure, several methodologies are used, such as QuEChERS (Quignot et al. 2012; Martínez-Domínguez et al. 2015; Paz et al. 2015) and liquid–solid extraction (LSE) (Wang et al. 2011b; Łozowicka et al. 2014), which have been reviewed comprehensively in the literature (García-Valcárcel and Tadeo 2009; Kolberg et al. 2011). To detect pesticide residues, GC and LC are frequently employed (Páleníková et al. 2015; Barceló et al. 1995). The mentioned chromatographic methods have been joined to mass spectrometry, such as LC–MS and GC–MS (Coscollà et al. 2013; Luzardo et al. 2015). These methods could perform the quantitative analysis, though they related limitation including difficult procedure, being time-consuming and costly. Hence, the drawbacks restricted their use for on-site applications and fast recognition (Zhao et al. 2014), additionally, being complicated to operate, making them inappropriate for on-site and infield detection (Regueiro et al. 2015).

Today, considerations have been attributed to the development of nanotechnology and nanomaterial as an integrated piece of biosensor technology for detection of pesticides. Nanomaterials as an alternative to old-fashioned techniques have introduced an outstanding approach to developing transportable devices with low cost, simple design and tiny size. Biosensor approaches have shown adequate outcomes for environmental control, food quality screening and toxicity detection (Guler et al. 2010; Ivanov et al. 2002; Boobis et al. 2008). Biosensors-based detection techniques need to work faster and to reduce costs as compared with the conventional systems. In addition, the detection procedures are complicated and make them improper for commercial and industrial applications (Zhao et al. 2015b). Innovative trends in the field of pesticide analysis have introduced aptamers that are alternatives to the conventional antibodies, which offer more robust biosensors for pesticide detection. Other trends such as molecularly imprinted polymers (MIPs) are considered as novel affinity-based detection materials developed for environmental sensors (Sassolas et al. 2012). The artificial neural networks (ANNs) could adequately determine the pesticides present in a sample (Ferentinos et al. 2012). In this review, we elaborated the achievements in sensing systems concerning innovative nanomaterials and analytical techniques with emphasis on organophosphorus pesticides (OPs).

OPs and biological effects

Organophosphorus (OP) compounds are a heterogeneous group of phosphorus compounds composing of chemicals resulting from phosphoric acid family (Kumar et al. 2015). These contain toxic components and counted as the largest class of urban and rural pesticides (Kwong 2002; Dvir et al. 2010). The neurological toxicities of OPs have been established by the regulatory organizations specially for occupational and consumer exposures. World Health Organization (WHO) has announced that the number of pesticide poisoning may reach three million cases and cause over 250,000 deaths (Organization 2006).

OPs have been also misused as chemical warfare agents and known to be the most toxic pesticides to vertebrate animals. OPs are difficult to degrade even at very low concentrations. Slight chemical changes in the molecular structure of OPs cause perceptible variation in the toxicity of one species to others. The bioaccumulation of OPs in the environment leads to the contamination of air, water, soil and agricultural resources. OPs penetrate body mainly through inhalation, ingestion, injection or cutaneous. OPs contamination might occur occupationally in pesticides-manufacturing workers, pesticide applicators, floriculturists and farm workers. Chronic exposure to OPs is associated with the cause of various problems such as verbal and memory difficulties, processing rate, visual-spatial performance and coordination (Mostafalou and Abdollahi 2013). Indeed, OPs are reported to alter human health within embryonic and adult stage and to increase morbidity and mortality in acutely poisoned patients (Rahimi et al. 2006; Rezvanfar et al. 2016). According to the National Academy of Science, infants and the child's diet is considered as the major source of exposure to pesticides. Thus, OPs may contribute to attention-deficit/hyperactivity prevalence in children (Lu et al. 2008; Bouchard et al. 2010). Scientific evidences indicate pesticide exposure significantly increases the chance of developing various cancers. Though, a positive link between job-related exposure to pesticides along with the prevalence of chromosomal damages has remained a controversial subject (Bassil et al. 2007). Chromosomal damages induced by pesticides appear to be cumulative in continuous exposure to complex agrochemical mixtures (Hodjat et al. 2015; Bolognesi 2003).

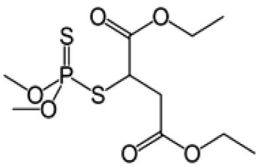
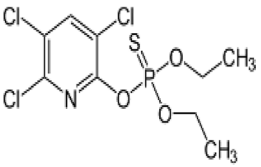
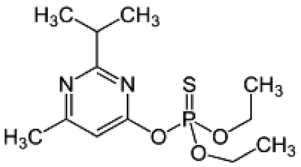
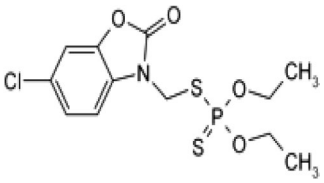
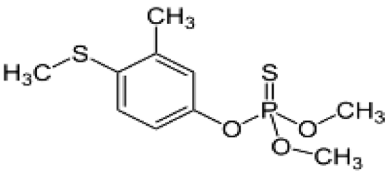
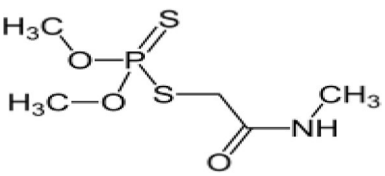
These toxicants act as neurotoxins by adding phosphate to a serine hydroxyl group of acetylcholinesterase (AChE; a carboxyl ester hydrolases) active site in central nervous system, which is responsible to transmit nerve impulses across synapses (Dvir et al. 2010). The phosphorylation reaction forms a covalent bond between OPs and AChE. OPs interrupt signaling at cholinergic synapses by preventing AChE activity via breaking down the ACh. Aggregation of ACh at the synapses leads to overstimulation of ACh receptors (muscarinic and nicotinic) and further blocks the transmission of neurotransmitters, which in turn results in muscular paralysis (Kwong 2002; Hobbiger 1961). Prolonged exposure to OPs can impair the performance of various organs such as defense response, reproductive, nervous, cardiovascular and respiratory systems

(Abdollahi et al. 2004). Functions of OPs might be proportional to the type and quantity of each specific agent. Moreover, given the extent and route of the exposure damage level varies among individuals. Table 1 represents a list of main OPs and their relevance biological effects.

Principles of biosensors

Today, any analytical device that incorporates a biological or biomimetic sensing element that detects specific physicochemical variations and intimately connected to/or integrated within a transducer to produce visible electronic signals, is considered as a biosensor. Simply, a biosensor translates a biochemical signal into an electronic indicator on a small display. Principally, the biological molecule (analyte) interacts with a detection/recognition site, which has been integrated to the electronic components. This interaction triggers a series of changes (pH, mass, electron or specific ions), which are detected, converted and processed by electronics (transducer) to produce measurable electrical signals. The signals subsequently will be monitored automatically. Figure 1 shows a conceptual diagram of biosensing principles. Generally,

Table 1 Common biological effects of OPs

OPs	Chemical structure	Biological effect
Malathion		Alzheimer's disease Muscle dysfunction Cardiotoxicity in zebrafish Increased risk of thyroid cancer[a,b,c,d]
Chlorpyrifos		Lung oxidative damage Immunological abnormalities Increasing IL-1β, IL-1R1 mRNA synthesis[e,f,g]
Diazinon		Hepatotoxicity Cardiotoxicity Impairs glucose homeostasis[h,i,j]
Phosalone		Increase of DNA and RNA damages Downregulation of testicular endocrine activity and antioxidant content[k] Inflammation and oxidative stress in the colon[l]
Fenthion		DNA damage and expression of tumor-related genes Apoptosis in HEPG2 cells[m]
Dimethoate		Reduction of reproductive parameters[n]

Major severe signs and symptoms

Mild: fatigue, headache, blurred vision, dizziness, numbness of the extremities, nausea, vomiting, excessive sweating and salivation, tightness in chest

Table 1 continued

OPs	Chemical structure	Biological effect
Moderate: weakness, difficulty in talking, muscular fasciculations, miosis		
Severe: unconsciousness, flaccid paralysis, moist rales, respiratory difficulty, cardiac arrhythmias and cyanosis[o]		

[a] Yadav et al. (2016)
[b] Karami-Mohajeri et al. (2013)
[c] Simoneschi et al. (2014)
[d] Lerro et al. (2015)
[e] Hassani et al. (2014)
[f] Thrasher et al. (2002)
[g] Wang et al. (2011a)
[h] Kalender et al. (2005)
[i] Razavi et al. (2013)
[j] Pakzad et al. (2013)
[k] Amniattalab and Razi (2015)
[l] Ghasemi-Niri et al.(2016)
[m] Wu et al. (2011)
[n] Jallouli et al. (2015)
[o] Abdollahi et al. (2004)

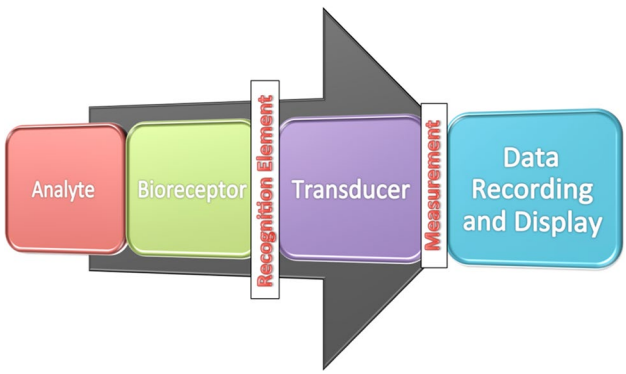


Fig. 1 Conceptual model of biosensing principle

the biosensors are classified based on the type of the biological part (enzymatic or antibody-based biosensors) or on the basis of the transducer systems. A biosensor acts based on the affinity of its components such as antigen/antibody, enzyme/substrate, nucleic acid/complementary sequences, hormone/receptors, microorganisms, cell structure or tissue slices (Fig. 2). Immobilization of the biocomponent plays a key role in biosensor fabrication and depends on various conditions such as pH, temperature, depth and strength of the materials (Kissinger 2005). The immobilization has imperative influence on biorecognition element as it can guarantee stabilization with accurate connectivity and vicinity to the transducer (Rodriguez-Mozaz et al. 2005). The transduction systems might be available in electrochemical, optical, piezoelectric, thermometric, ion-sensitive, magnetic or acoustic forms (Fig. 3). The propriety of the transducer mainly influences the accuracy, refinement and specificity of the biosensors.

Biosensing approaches for OPs detection

Biosensors have a broad spectrum of applications ranging from clinical (general healthcare monitoring, clinical analysis, screening and diagnosis of disease) to the environmental (pollution control and veterinary/agricultural applications) as well as industrial processing and monitoring. Daily use and excessive exposure to OPs spectacles the importance of sensor-based systems regarding two public/environmental health issues more than any time. Nowadays, various conventional and modern techniques are applied to detect OPs residues. The classical approaches, including high-performance liquid chromatography (HPLC), GC, LC, GC–MS or LC–MS/MS, usually provide quantitative information rather than the quality. In addition, some restrictions such as rapid field detection, long procedure, high expenses, the need for technician and operational staffs and limitation in the number of samples analyzed simultaneously are supposed as other drawbacks of these systems. At this point, biosensor-based devices are introduced to improve the current recognition methods by simplifying the complication of preparation procedures to stand requirements such as specificity and sensitivity to analyte, fast response time, approachability, qualitative and quantitative analysis, cost-effectiveness and incorporating bio- and/or chemo-sensing approaches to improve

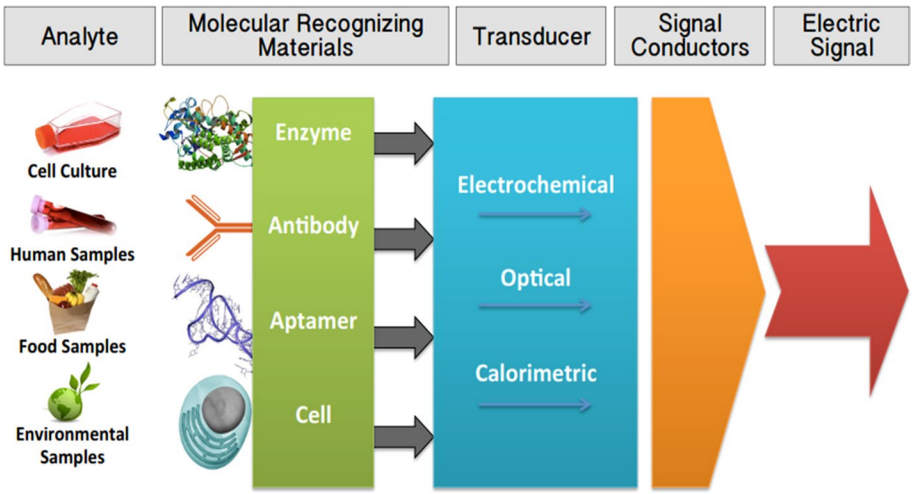


Fig. 2 Typical structure of a biosensor (biorecognition, interface and transduction)

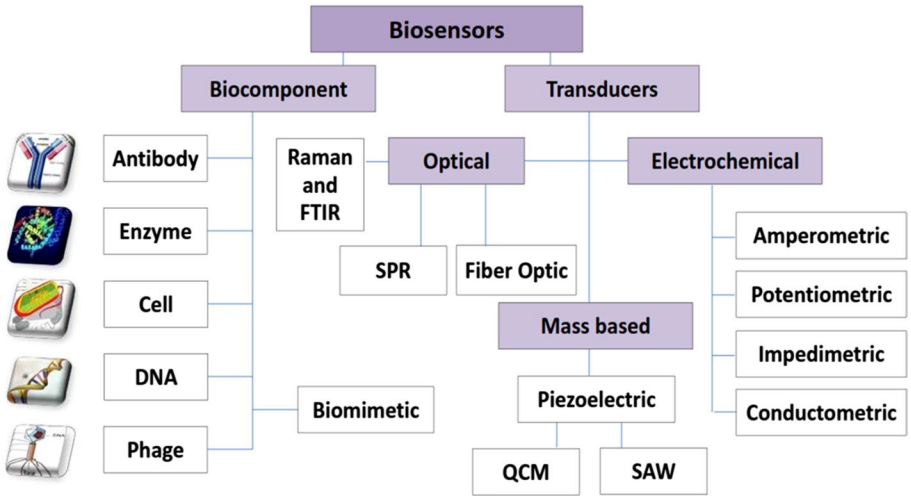


Fig. 3 Classification of biosensors based on transducer systems

processing steps as well as variability in signal transduction systems (Zhao et al. 2015b; Kumar et al. 2015). Table 2 depicts a comparison between characteristics of conventional analytical approaches and biosensing techniques. Environmental samples containing OPs are detectable by means of electrochemical-, optical- and mass-based sensors, of which the former is the most common approach.

During the past decade, the application of nanostructured biosensor apparatuses in OPs detection has shown a growing pattern. For instance, the detection of OPs via optical-based sensing methods (Viveros et al. 2006; Paliwal et al. 2007; Simonian et al. 2005) or electrochemical immunosensing approaches has been widely reported (Zhang et al. 2013a; Suri et al. 2002). In coming sections, we mainly focus on OPs biosensor classifications, signal transduction mechanisms and related advantages and limitations. In addition, the state of nanomaterials in OPs detection systems is provided. Finally, advanced components, analysis techniques and computational approaches in biosensing systems are introduced.

Classification of biosensors

Electrochemical biosensors

In the simplest definition, an electrochemical biosensor directly converts a biological event to an electronic signal. Despite the diversity in biorecognition elements, enzymes are the predominant substrate in electrochemical detection techniques due to their specific binding capabilities and biocatalytic activity (Grieshaber et al. 2008). Researchers have introduced a different classification for electrochemical biosensors based on signal property, which measures the variation of biological changes in solution by means of potential, charge accumulation, current, conductance

Table 2 Comparison of conventional analytical and biosensing techniques

Conventional analytical techniques		Biosensors	
HPLC; LC; GC; GC–MS; fluorimetry and SPR		Electrochemical; optical; mass based; biocomponent	
Advantages	Disadvantages	Advantages	Disadvantages
Sensitive	Time-consuming	Rapid real-time detection	Limited commercial application
Specific	Expensive	Cost-effective	
	Laboratory monitoring	Portable	
	Trained laboratory personnel	Simple use	
	High-tech equipment	Highly sensitive	
	Extensive sample preparation	Limited sample preparation	
	Not reusable	Reusable	
	More organic solvent consumption	Less organic solvent consumption	
		Specific	

or impedance. Typically, amperometric, potentiometric, impedimetric and conductometric biosensors have been organized. The precision and sensitivity of these systems mainly correlate with the biorecognition element. The sensitivity also depends on the conductivity of the materials. The electrochemical property of the transducer is thoroughly proportional to the electrode materials, surface and dimensions. Electrodes are known to be the cornerstones of the electrochemical devices, which are referred to as reference electrode (maintain stable potency), working or redox electrode (as a transduction element) and/or counter electrode (transfer current to the working electrode) (Zhao et al. 2015b; Grieshaber et al. 2008).

To optimize the efficiency of the sensors, nanomaterials with special structural/functional characteristics offer possibilities to enhance the susceptibility and capturing the power of electricals by modifying the immobilization properties of target biomolecules or by increasing their absorption surface ratio (Patolsky et al. 2006). Electrochemical biosensors appear to be more appropriate to miniaturization with compatible instrumental sensitivity, simplicity, lower cost, and rapidness. However, any disruption or poor conjunction of biomaterials and electrochemical transducers may cause a negative influence on selectivity, sensitivity and strength of these devices. Nonetheless, the contamination of biosensor surface is considered as the main failure (Mehrvar and Abdi 2004).

Amperometric biosensors

Amperometric devices embrace the most common group of biosensors that usually measure the current changes induced by an electro-active chemical reaction between recognition component and analyte. These electro-active types designed to assure the electron transfer flow in the middle of the redox enzymes as well as electrode part and to defeat the tardiness of electron transfer rate in solution (Schuhmann 1995). Typically, the current is maintained at a specific potential (amperometry), or might be measured as voltammetry, defined as controlled differences of the potential (Grieshaber et al. 2008). The main advantage of this transducer is being inexpensive and using disposable electrodes to eliminate the requirement of repeated calibrations (Velasco-Garcia and Mottram 2003).

In the cases of amperometric measurement of OPs, electrochemically active products are measured through various immobilization strategies. Amperometric biosensors generally include ChE-based (ChE inhibitors/indirect approach) and OP hydrolase (OPH)-based biosensors (direct approach). The former was found to be more common with inferior selectivity to OPs due to the enzyme sensitivity to multi-analytes. A classic OPH-based transducer traces the oxidation of the p-nitrophenol generated by the catalytic activity of OPH and hydrolyzes the OP-esters contained nitrophenyl substituent to p-nitrophenol.

Systematically, OPH-based systems detect OPs by utilizing two electrodes; an enzymatic electrode coated with immobilized OPH on a particular surface in direct association with a carbon paste electrode. It has been proposed that ChE immobilization on any suitable physicochemical transducer generates a biosensor. OPs residue could be detected by the immobilizing of AChE and acetylthiocholine (ATC) along with an amperometric transducer. Later, the produced thiocholine undergoes oxidation at the electrode (Pohanka and Skládal 2008). These OP sensors are developed based upon the inhibition of ChE enzymes and principally measure the hydrogen peroxide produced by oxidation of produced choline from ACh hydrolysis by choline oxidase (Verma and Bhardwaj 2015). Since OPH-based examination reacts to OPs as substrates but not inhibitors, OPH methods are considered reversible (Chough et al. 2002).

Amperometric biosensors for OPs detection were established long time ago, and significant improvements in their performance have been perceived. Amperometric devices may afford optimum OPs detection by improving the physicochemical properties of transducers, the quality of ChEs and the use of nanostructured electrode materials (Pohanka et al. 2008). In this manner, genetically modified AChEs with various AChE mutants (Schulze et al. 2003) and immobilization approaches have been broadly developed to certify high enzymatic activity along with the stability of the sensors against OPs. For instance, in the case of ChE-based amperometric, a range of immobilization techniques have been tried with significant sensitivity for OPs/substitutes. In 2006, a biosensor was designed by immobilization of AChE on a carbon nanotube surface to provide an ideal microenvironment to preserve AChE in bioactive form. This system was integrated into a flow injection system to monitor paraoxon. The biosensor showed desirable lifetime stability with no drop in the activity of the enzyme (Liu and Lin 2006). An amperometric biosensor was developed based on AChE immobilized on a gelatin membrane to detect paraoxon by immersing the biosensor in a reaction chamber injecting the OPs compound inside. This gelatin biosensor resulted in the great current sense of paraoxon (Pohanka et al. 2008). Another example of OPH-based system is genetically engineered degrader bacteria, such as *Pseudomonas putida* that catalyzes the hydrolysis of the nitrophenyl substituent of an OP on the surface-expressed OPH with a carbon paste electrode. This biosensor manifested a selective detection of OPs with repetitive/multiple/rapid and online analysis. The detection limit of OPs was reported in part per billion (ppb) (Lei et al. 2005).

Du et al. fabricated an AChE amperometric biosensor to quickly detect triazophos using a multi-walled CNTs–chitosan composite as the working electrode and glutaraldehyde as the cross-linker matrix. AChE was immobilized on the electrode surface. The interaction of AChE with ATC produced thiocholine as a by-product and reached the permanent oxidation point. The inhibitory effect of the OP was measured using the deterioration of the oxidation current of thiocholine that is proportional to the concentrations of triazophos. The detection limit was reported to be in μM range (Du et al. 2007). Earlier in 2002, Chough and coworkers planned an OPH electrode biosensor made of a carbon paste electrode with an attached enzyme-coated nylon net. As reported, it was sensitive against OPs (parathion, EPN, fenitrothion and paraoxon). Significant sensitivity of OPH-based biosensor was caught using mesoporous carbon (MC) and carbon black (CB) to nitrophenol substitute of the analyte paraoxon (Lee et al. 2010).

Potentiometric biosensors

Potentiometric instruments measure the potentials at the working electrode comparing to the reference electrode with a constant or zero current flow. Practically, potentiometer measures the change of the potential differences caused by ions or pH in an electrochemical reaction that correlates to the concentration of analyte. An enzyme catalytic reaction or an antigen/antibody immune reaction is capable of creating such a potential. Concerning OPs detection, sensors are either ion-selective pH (ISE) or pH-sensitive field effect transistors/pH-ISFET. These transducers measure the pH variation based on the acid formed during the hydrolysis reaction (Jaffrezic-Renault 2001). OPH catalyzes hydrolysis of one OP molecule in which 2 protons produced. Measurement of these protons is considered as the principle of potentiometric biosensors (Gäberlein et al. 2000). Commercially available potentiometric sensors such as glass electrodes or metal oxide-based sensors can be miniaturized by means of advanced silicon or thick-film technologies (Koncki 2007).

To determine OPs, the degradation ability of engineered wild-type bacteria has enhanced potentiometric biosensors. To attain clear discrimination between different OPs, dual OPH-immobilized amperometric and potentiometric transducers have been integrated in a flow injection system by means of thin-film techniques. Due to different electrochemical transducer principles, potentiometric biosensor responds to all OPs, while the amperometric device reacts only toward OP–nitrophenol substrates. The system enables fast and selective detection of OPs at low concentration (Wang et al. 2002; Schöning et al. 2003). In 2009, a potentiometric transducer was constructed with a pH electrode modified by immobilizing AChE on methyl cellulose surface, to detect OPs in laboratory and field conditions. Data obtained represented a significant inhibition rate of enzyme with limit sensitivity to OP samples (K'Owino and Sadik 2005).

More recently, researchers increased the sensitivity by applying a fluorescence-based receptor utilizing a pH-sensitive dye combined with OPH on a polystyrene surface matrix. Direct assessment of OPH hydrolysis is attained by screening the emission spectrum alternations of fluor dye in response to changes in pH. Operators were able to detect OP samples at very low concentrations both qualitatively and quantitatively, and also the system provided continual remote monitoring with spectral fluorescent curve (Viveros et al. 2006). A notable limitation of potentiometric tools is that they only monitor low volume and concentration of samples, preferably without any chemical interactions with samples (Grieshaber et al. 2008). In general, lower detection limits are achievable by amperometric devices rather than potentiometric ones.

Impedimetric biosensors

The impedimetric approach investigates the biomolecular interactions to determine variations in capacitance and interfacial electron transfer resistance at the surface of electrode (K'Owino and Sadik 2005). The device allows direct recognition of biomolecules in an easy, rapid, sensitive, label-free and mediator-free manner (Koncki 2007). From one perspective, aptasensors in conjunction with immunosensors are new generations of impedimetric transducers that are dominating the market of pesticide biosensors. Aptasensors measure the impedance changes that are triggered by binding the target sequences, conformational changes or DNA damages. Instead, immunosensors screen the formation of antigen/antibody complex and measure the electron-transferring resistance (Bahadır and Sezgintürk 2016). In a revised version, sensitive field effect transistor (ISFET) biosensor or enzyme field effect transistor (ENFET) was introduced to impedimetric biosensors, which were previously categorized into potentiometric group. The ISFET is a conventional metal/oxide/semiconductor (MOS) field effect transistor combined with an ion-sensitive surface. Interaction between ions and the semiconductor is diffused via a sensor electrode covered with a selectively permeable polymer layer that eventually changes the surface potential (Monošík et al. 2012; Dzyadevych et al. 2006). Extension of the dynamic range and the attenuation of the influence of buffer capacity on biosensors response are attainable by improvement in analytical and working solutions characteristics, supplementary charged membranes or genetically engineered enzymes (Dzyadevych et al. 2003). The formations of false-positive results related to the electrolytes are the main disadvantage of impedance biosensors (Pohanka et al. 2008). It is a promptly developing technique for detection of different OPs occurring at the surface electrode. Nowadays, innovation in recognition material device emerged as a powerful tool regarding OPs electrochemical impedance spectroscopy (EIS) (Justino et al. 2015).

The OP chlorpyrifos (CPF) template-stamped film was manufactured recently, which determines impedimetrically on a pencil graphite electrode (PGE) by electropolymerization of pyrrole (Py) in company with CPF. Measured impedance showed selective and sensitive response to CPF. Furthermore, this fabricated sensor enables to determine CPF in CPF-added artificial samples (Uygun and Dilgin 2013). In an effort to detect OPs, two impedimetric biosensors were structured due to the specificity and catalytic activity of lipase for diazinon, which catalyzes the hydrolysis of ester and modifies triacylglycerol to glycerol and fatty acids. A selected variant of lipase (from microbial or animal sources) was immobilized on functionalized gold electrodes in aqueous medium. According to the reported data, significant accuracy, reproducibility and stability were achieved (Zehani et al. 2014).

Conductometric biosensors

Conductometric devices determine the overall changes of ionic contents of a solution, upon a biochemical interaction. These biosensors can be produced through inexpensive thin-film technology, and differential mode measurements could eliminate undesired interferences (Jaffrezic-Renault and Dzyadevych 2008). However, the conductance measurements have relatively low sensitivity (Monošík et al. 2012). Enzymatic conductometric devices are very common in which the conductivity of a solution between two electrodes alters following the enzymatic reaction. The enzymatic conductometric-based biosensors have exceptional application in OPs identification (Chouteau et al. 2005; Dzyadevych et al. 2005; Dzyadevich et al. 1994).

Optical biosensors

An optical biosensor is a compact analytical device that is able to detect a desired analyte by assembly of a light source, optical transducer system, sensing element and a detector. The optical transducer transmits the light and acts as the substrate for the sensing material that has been immobilized on a suitable optical surface. Thus, the interactions of sensing material with analyte initiate some physiochemical changes that are produced in response to light signals and finally, a detector measures the transduced light as the output. Typical optical systems are based on absorption spectroscopy light, fluorescence, luminescence, reflectance, Raman scattering, refractive index and more complicated approaches such as surface plasmon resonance (SPR) along with evanescent wave. They offer rapid real-time analysis, without sample pre-treatment or large sample volumes. Optical sensors are capable of early recognition of biochemical modifications due to their sensitivity to the minimal levels of analyte achieved by advancement in instrumentation related to spectrofluorimeter (Chaudhury et al. 2003).

Deposition techniques such as screen printing, inkjet printing, thin-film techniques (Langmuir–Blodgett technology and layer by layer) have led to the production of materials with very high precision and reduced thickness, which are essential characteristics for the development of optical biosensors (Dey and Goswami 2011). In this manner, Choi et al. measured the degree of color changes in a fiber-optic system composing of AChE-immobilized Langmuir–Blodgett (LB) film in contaminated water. Due to the inhibitory effect of OPs on AChE, a colorless substrate changed to a yellow product; therefore, the sensing limit decreased

to parts per million (ppm) levels and the response time was about 10 min (min) for OPs detection (Choi et al. 2001).

Fluorescence-based biosensors

Fluorescence-based biosensors detect an analytical signal raised from the fluorescence emission of analytes/sensing molecules that are labeled with fluorescent probes. Briefly, the device spots the emitted light or variation in frequency of electromagnetic radiation subsequent to the absorption and excitation of a fluorophore by light or radiation. The key advantage of such devices mainly comes from the sensitivity of the detection limit even at a single molecule, while the limitation of the false results coming from biological auto-fluorescence and the substantial dependency of fluorescence intensity to the analyte (Schäferling 2006). So far, numerous simple to sophisticated fluorescence-based devices were designed to detect OPs residues on the basis of AChE or OPH enzyme activity and fluorescence polarization immunoassays (FPIA). A published report by Obare and his colleagues comprehensively reviewed fluorescent chemo-sensors for toxic OPs (Obare et al. 2010).

According to published data, sensitivity of OPs detection was increased by application of a fluorescence-based recognition strategy when the pH-sensitive dye fluorescein isothiocyanate (FITC) was included with OPH using poly(methyl methacrylate) beads. Based on the correlation between the levels of immobilized OPH on a nylon microporous membrane and the amount of chromophoric product made by the enzyme, a fiber-optic biosensor was introduced. Significant reproducibility and stability of the enzyme were achieved by this method (Mulchandani et al. 2001). The OPs were detected by a pH-sensitive fluorescence probe to assess the inhibition of the enzyme AChE (Jin et al. 2004). The enzyme dye was immobilized on Au-NPs attached to a fluorescence spectrophotometer. The absence of OP compounds triggers the hydrolysis of ACh by AChE. This reaction leads to a reduction in pH and fluorescence intensity due to the disruption of the fluorophore's conjugation. The sensitivity of OPH–Au-NPs conjugates that were incubated with fluorescent enzyme inhibitor under a normalized ratio of fluorescence intensities was measured versus paraoxon. The fluorescence intensity was dependent on the amount of paraoxon in the solution (Simonian et al. 2005; Obare et al. 2010). Rogers and his group used similar detection system employing the fluorescein isothiocyanate (FITC) immobilized on a quartz fiber. This biosensor was found to be sensitive at nanomolar (nM) levels for paraoxon and some other OP compounds (Rogers et al. 1991).

Long and his coworkers reported a nanosensor toward OPs based on the fluorescence resonance energy transfer (FRET) between up-conversion NPs (UCNPs) and Au-NPs. The recognition mechanism focused on the fact that Au-NPs reduce the fluorescence of UCNPs with the potential to eliminate the interference of background fluorescence. OPs inhibited the activity of AChE, which catalyzes the hydrolysis of ATC into thiocholine (Long et al. 2015). The biosensor showed satisfactory stability with a detection limit of nanogram (ng). More recently, an OP compound (dichlorvos) was detected fast and simple by a fluorescent-based biosensor composing of H_2O_2-sensitive QDs that inhibit AChE (Meng et al. 2013). FPIA technique works based on the application of a monoclonal antibody for the detection of fluorescein-labeled OP derivatives (tracers). Binding of immunogen and tracers approved by determining the strength of emitted polarized light indicating Ab has been bounded. The FPIA technique demonstrated great specification and reproducibility. In addition, the technique is free of any pre-cleanup procedures that offer high-throughput screening for OP contamination (Kolosova et al. 2003, 2004; Xu et al. 2011).

SPR-based biosensors

The SPR instruments are applicable in multidisciplinary areas from life science to the environmental safety. When a light beam imposes on a metal film at a specific angle, the surface plasmons absorb the light and in turn resonate. SPR happens once a polarized light hit a metal film at the boundary of medium, with various refractive indices (often a metal and a dielectric). In SPR technique, a beam of light with a specific wavelength and at a particular incident angle (SPR angle) is focused on a film through a glass prism. The evanescent field wave from total internal reflection (TIR) is able to stimulate a collective fluctuation of free electrons (known as surface plasmons), which are transmitted along the metal surface and the subsequent reflections could be detected. The intensity of the light rays reflected at different angles exhibits a molecular interaction on or next to the metal film or causes a structural alteration in the molecules attached to the film. By application of proper non-magnetic materials, surface plasmon wave is p-polarized. As a result of electromagnetic and surface propagating characteristic, created evanescent wave will be improved (Grieshaber et al. 2008; Pattnaik 2005). SPR is suitable for analyzing the label-free interactions such as protein adsorption on self-assembled monolayers, antibody–antigen interaction, DNA and RNA attachment and receptor–ligand contacts in immunosensing. SPR allows analyzing the endpoint results besides the kinetic monitoring of the entire process.

In 2006, Mauriz and coworkers used a portable SPR immunosensor for real-time detection of CPF. The system achieved by developing an immunoassay based on binding inhibition method in combination with a commercial β-SPR sensor system (Mauriz et al. 2006c). The SPR biosensor showed a high sensitivity for detection of CPF in

ng concentration without requirements of pre-extraction or cleanup. In another study, an electrochemical configuration and SPR were used to optically measure the reaction kinetics of OPs in the presence of electric fields. The toxic OPs analogs were detected by a detector composed of SPR and potentiometric techniques. A modified polyamidoamine (PAMAM) carbazole/Cu^{2+} dendrimer was used as an active sensing element to trap the OPs. The carbazole groups served as cross-linkers in dendrimers to form a conjugated network with ultrathin film and to generate the potentiometric response. The SPR/potentiometric setup demonstrated a real-time dual detection of OPs analogs with remarkable low detection limit Taranekar et al. (2006). Metal NPs (Au and Ag) are identified with optical localized surface plasmon resonance (LSPR) properties. The electrons of metal NPs are able to make a collective oscillation where their frequency and the incident of electromagnetic radiation are harmonized (Jokar et al. 2016a). This LSPR property allows the red Au-NPs solution change to blue, and the yellow Ag-NPs solution shifting to brown that are optically measurable. A sensor was developed using LSPR of Au-NPs that were covalently coupled to AChE against paraoxon. It was found that the AChE-modified LSPR sensors have the linear inhibition response with 0.234 ppb detection limit for paraoxon (Lin et al. 2006).

Waveguide-based biosensors

Waveguide-based techniques benefit from the advantages of the evanescent field detection principle. Often, the guiding mechanism is based on TIR in a material with high permittivity/refractive index (core) surrounded by a low-index material (cladding), where the TIR phenomenon confines the light in the high-index material. In this regard, planar and fiber-optic instruments are typically used. The utilization of fluorescent labels in planar optical waveguides increases sensitivity and specificity, as well as ease of labeling, while detection within the evanescent field minimizes the difficulties of background auto-fluorescence. Waveguide-based devices have the ability to confine light in nanoscale low-refractive-index material using TIR that are not easily accessible with other optical biosensors (Barrios 2009; Mukundan et al. 2009). An outstanding exploration toward waveguide-based biosensors was provided by Mukundan et al. (2009). A large number of studies have investigated waveguide biosensors to detect biological toxins, but only few attempts have been conducted regarding OPs detection. In 2006, a direct fiber-optic biosensor was fabricated by conjugating OPH enzyme with a fluorophore dye anchored to the optical waveguide of portable fluorimeter analyte to detect paraoxon and neurotoxin diisopropyl fluorophosphate (DFP). The system provided micromole (μM) limit detection of OPs with continual remote monitoring (Viveros et al. 2006).

Mass-based biosensors

Mass-based biosensors sensitively measure the alterations in resonance frequency straightforward related to the mass variations.

Piezoelectric biosensors

In a piezoelectric biosensor, piezoelectric materials that vibrate under the influence of an electrical field are paired with a bioelement. Commonly, piezoelectric ceramics and single-crystal materials are used to construct piezoelectric sensors. The ceramic materials such as lead zirconate titanate ceramic (PZT) are more sensitive than the crystal types, but this sensitivity decreases over time mostly in correlation with the increase in temperature. The single-crystal materials (gallium phosphate, quartz, tourmaline, polymers, silicon, lead magnesium niobate–lead titanate (PMN-PT)) exhibit long-term stability (Ramadan et al. 2014). Generally, when pressure is applied to a polarized crystal, the resulting mechanical deformation leads to an electrical charge. The alternating potential changes the frequency within the crystal, which is highly related to the mass, effective viscosity and conductivity of the absorbed material. Piezoelectric transducers sorted as useful label-free detectors for real-time monitoring. The simplicity of piezoelectric quartz crystal sensors made them proper for the depiction of biomolecular events. In these sensors, the quartz crystal is coated with a biological recognition element, the binding of analyte–receptor that one has been immobilized on the surface and the other is free, or vice versa in a solution or gas phase, will change the resonance frequency and give a binding signal. Piezoelectric transducers have disadvantages such as excessive interference which makes them less specific, sensitive and causes some challenging calibration problems (Marrazza 2014). Piezoelectric transducers have been widely applied based on inhibition of AChE and immunosensing methods to increase the sensitivity against OPs.

Data show that there is an increased interest to develop quartz crystal biosensors for OPs detection (Karousos et al. 2002). A quartz crystal microbalance piezoelectric biosensor was developed to determine OPs and carbamate pesticides (Abad et al. 1998). The inhibitory potential of OPs versus the activity of AChE is the key basis of this assay. The exposure of the immobilized AChE to a solution of the histological substrate, 3-indolyl acetate, forms

an insoluble product that precipitates on the crystal surface. Accumulation of the insoluble products led to the changes of mass and frequency at the crystal surface. The extent of the enzymatic reaction can be estimated in real time by measuring the frequency changes. The presence of OPs and carbamate pesticides is detected by a reduction in frequency changes resulting from analytes inhibitory effects. Detection limit of 10^{-8} M was observed for paraoxon. In 2005, a sensitive quartz crystal piezoelectric sensor has been developed for detection of ChE inhibitors. The inhibitor was immobilized on a self-assembled monolayer on the gold surface of the sensor in a flow-through arrangement. The binding of high molecular weight ChE to immobilized inhibitor was monitored with a piezoelectric quartz crystal nanobalance. The concentration of free inhibitor in the sample showed a direct connection to the mass changes. The detection limit for different OPs falls to 10^{-10} mol in 25 min (Halamek et al. 2005). The enzyme immobilization directed to design a study for detection of OPs with quartz crystal microbalance-precipitation sensor. Hence, the precipitation of AChE reaction product on the surface of a QCM-precipitation sensor was measured. Significant sensitivity and binding efficiency were achieved for OPs and carbamate pesticide with lower detection limits about 10^{-9} M (Kim et al. 2007). To prove the strong binding affinity of nanomaterials, Shang et al. built a piezoelectric biosensor by utilizing macromolecular polymer and carboxyl multi-wall CNTs (MWNTs-COOH) coated with AChE on the Ag-coated quartz crystal electrodes. This system determined the OPs residue in radishes after the application of phoxim and CPF. They found a rapid detection of pesticide residues with limit detection rate of μM (Shang et al. 2011).

Funari et al. (2013) designed an immunosensor for detection of parathion using Ab solution activated by ultrashort UV laser pulses anchored by photonic immobilization technique (PIT) to the Au electrode of QCM. Since the parathion is a light compound, its complexion with bovine serum albumin (BSA) makes it heavier and more proper for piezoelectric detection. The results indicated the effectiveness of the sensor to detect light analytes. A piezoimmunosensor (QCM sensor) was fabricated toward the detection of carbaryl and 3, 5, 6-trichloro-2-pyridinol (TCP) (a metabolite of CPF). They used monoclonal antibodies in a competitive conjugate-immobilized immunoassay manner. The system provided 150 repeated assays with significant sensitivity and specificity. Therefore, this immunosensor was approved for detection of carbaryl and TCP in fruits and vegetables at European regulatory levels (Velusamy et al. 2010). More information and criteria of piezoelectric biosensors for OPs detection have been illustrated by Marrazza (2014).

Magnetoelastic-based biosensors

Magnetoelastic (ME) devices are composed of amorphous ferromagnetic ribbons or wires that are considered analog to piezoelectric acoustic wave sensors. Once magnetostrictive materials (iron, nickel, molybdenum and boron) are exposed to a magnetic field, they would express magnetic fluxes, which can be monitored by a pickup coil from the distance, thus allows having wireless devices. The fundamental of the ME implicates a variation in sensor resonance frequency due to the mass loading of the sensor. In ME, the desired analyte is bound to biorecognition element that immobilized on the surface of the ribbon-like ME sensor—in response to changes in mass (Velusamy et al. 2010; Guntupalli et al. 2007). ME biosensors support contactless and remote query operation that has attracted many practical uses of the sensor platform for detection of a verity of biochemical agents, pathogens and bacteria. A group of researchers designed a wireless magnetoelastic biosensor composing of a pH-sensitive coating polymer and OPH enzyme. The ME system directly detected OPs, when the viscoelasticity changed due to the swelling/shrinking of the polymer, once is exposed to the pesticides. The system sensed paraoxon and parathion at very low concentrations (Zourob et al. 2007). Theoretical overview, instrumentation and applications of ME sensors were discussed in a review by Grimes et al. (2011).

Immunosensors-based biosensors for OPs detection

Immunosensors are known as affinity ligand-based biosensors that record immunochemical interactions between immobilized antibodies (Ab)/antigens (Ag) on the transducer surface and can provide concentration-dependent signals. The unique specificity of Ab against the specific binding site of analyte or Ag lays the foundation of immune transducers. The specificity, regenerability, stability and sensitivity of the Ab mainly affect sensors efficacy and reliability. Immobilization of antibody on the solid matrix gives the possibility of repeated use. Hence, it is necessary to dissociate the Ag–enzyme conjugate from the immobilized Ab matrix after each use in order to maintain the activity and specificity of the device (Kandimalla et al. 2004).

Immunosensors can be categorized based on the applied detection principle. In addition, they can be categorized based on application of labels; thus, immunosensors are divided into labeled and label-free types. The labeled type includes enzymes, nanoparticles and fluorescent or electrochemiluminescent probes to quantify the amount

of bounded Ab or analyte. Labeled systems consist of a sandwich and competitive biosensors. In sandwich model upon the formation of Ab–analyte (Ag) complex, the second labeled Ab is bound, respectively. In competitive form, non-labeled analyte competes with a labeled one for a limited number of Ab-binding sites. Obviously, label-free type detects the conjugation of Ab on a transducer surface without any labels. This type of free labeled sensors either directly responds to interaction between the immobilized Ab with a target molecule (Ag), or indirectly by inhibition of immobilized Ab on the surface of a transducer in the presence of target Ag (Monošík et al. 2012; Jiang et al. 2008). Labeled systems are more sensitive, whereas real-time monitoring and simplicity of label-free formats has made them more attractive.

The literature shows a great deal of advances that have been made in design and fabrication of immunosensors for OPs detection. Furthermore, the mutual application of nanomaterials as demonstrated in other types of biosensors results in promising outcomes. Immune devices are ideal for identification of a single pesticide or a small group of identical pesticides (Mallat et al. 2001). Generally, enzyme-based systems measure the total toxicity of toxicants, while immunosensors have been empowered by specificity and discriminatory features. Examples of these types of biosensors have been reported extensively (Kandimalla et al. 2004; Liu et al. 2013; Lu et al. 2011; Zhang et al. 2013b).

Some researchers have taken the advantages of expanding the surface area using nanoparticles, which leads to capturing of further Abs. A nanoparticle immunosensor was made based on the binding affinity of anti-AChE to the phosphorylated AChE (which formed in response to OPs) with significant sensitivity and minimal detection limits (Liu et al. 2008). Similarly, a disposable NPs-based electrochemical immunosensor was set for detection of OP-butyrylcholinesterase (OP-BChE). Zirconia NPs (ZrO_2NPs) was used to selectively capture the OP moiety of OP-BChE adducts in plasma sample and QDs-tagged anti-BChE-Abs for amplified quantification. The developed instrument demonstrated a sensitive response along with acceptable reproducibility (Liu et al. 2013). In a very same experiment, a NP-based fluorescence immunochromatographic test strip (FITS) was designed for detection of the OP–AChE adduct by the use of sandwich-like immunoreactions in QDs–anti-AChE–OP–AChE–ZrO_2 complex. Data were collected by recording the fluorescence intensity of captured QDs during the experiment, and high sensitivity was observed (Zhang et al. 2013a). To show the correlation between the degree of Ag/Ab dissociation and the accuracy of immunosensors, Kandimalla et al. developed a transducer for ethyl parathion (EP) using EP-Ab and different dissociating agents. They found that almost 50 % of dissociation would occur. In addition, some degree of Ab denaturation was observed. Conversely, a mixture of dimethyl sulfoxide (DMSO) and glycine–hydrochloric acid (Gly–HCl) buffer showed the full dissociation besides the Ab remained highly active and reproducible for EP (Kandimalla et al. 2004). Despite the potential of immunosensors for OPs detection, preservation of the quantity and the activity of immobilized materials upon the immobilization procedures as well as the proper positioning on the sensing interface; play crucial roles in biosensor design. Furthermore, there are other limitations such as biomolecule deactivation, leaking, high diffusion resistance of the substrate/biocomponent and the lack of validated protocols for sample matrices (Jiang et al. 2008; Makaraviciute and Ramanaviciene 2013).

DNA-based biosensors

DNA biosensors rely on immobilization of a single-stranded (ss) DNA probe directly on the surface of the transducer to measure specific binding with DNA usually by electrical, thermal or optical signal transduction. Electrochemical DNA biosensors have been used more frequently than other types. Electrochemical DNA biosensors typically follow three common steps as follows: formation of the DNA recognition layer, actual hybridization event and transformation of the hybridization into an electrical signal. These devices directly couple signal transduction to sequence recognition (Teles and Fonseca 2008; Vercoutere and Akeson 2002). DNA biosensors were developed for detection of genetic and infectious diseases as well as DNA damages and mutations. DNA transducers offer a fast and low-cost substitute to traditional methods. Unlike enzyme or antibodies, nucleic acid recognition elements can be readily synthesized and regenerated for multiple uses. The redox behavior of damaged DNA is precisely controlled by any alteration in its physicochemical and structural properties, which has been taken to detect DNA damage (Wang 2000; Hlavata et al. 2012).

Nowicka et al. prepared an electrochemical DNA hybridization biosensor to detect the level of single mismatches in the probe–target ssDNA sequences caused by some OPs and other pesticides. By coupling ferrocene moiety to streptavidin connected to biotinylated DNA, the voltammetric transduction was obtained. The mass-related frequency transduction was employed restraining the sensory DNA on Au-coated quartz crystal piezoresonators oscillating. These pesticides caused DNA unwinding; thus, the ferrocene oxidation current was reduced in voltammetric experiments. This method proposed a rapid comparative determination of DNA damage caused by OPs (Nowicka et al. 2010).

Apta-biosensors

Overall look indicates aptasensors as a subcategory of nucleic acid-based instruments. The combination of nucleic acids and electrochemical/optical biosensors introduces a new generation of biosensors, which is named aptasensors to rapidly screen the molecular interactions between the surfaces-linked DNA and target samples (Mehrvar and Abdi 2004). Aptamer has been referred to as the artificial ssDNA or RNA oligonucleotides which are selected from randomized oligonucleotide libraries by systematic evolution of ligands by exponential enrichment (SELEX). Aptamers bind to non-nucleic acid targets such as proteins, cells, viruses, bacteria, as well as small molecules including organic dyes, metal ions, amino acids with high affinity and specificity (Sassolas et al. 2012; Yan et al. 2011). Aptamers are comparable to monoclonal antibodies based on their binding affinity; in addition, they exhibit numerous convenient aspects as compared to traditional antibodies (Table 5). They possess prolonged shelf life, attainable cross-reactivity, small size, chemical stability and are lucrative. Aptamers offer prominent flexibility in their structure design, which may result in introducing novel biosensors with improved detection limits, high sensitivity and selectivity (Verma and Bhardwaj 2015; Song et al. 2008). Aptamers are more resistant to denaturation and degradation. Moreover, they can be modified with functional groups or tags, providing harmonized immobilization on biochips with highly ordered receptor layers (Stadtherr et al. 2005). Aptamers facilitate the reproducibility of the target binding to ensure an impeccable regeneration of aptamer-derived sensors (Strehlitz et al. 2008).

Recently, the combination of aptamers with novel nanomaterials has reached a new platform. Although nucleic acid aptamers have fascinated extreme interest with inclusive extents in biomolecules detection, in the case of OPs detection the expected position was not reached. Only few experiments have been performed in this regard. An aptasensing system was designed using polymer–Au-NPs–DNA composite microspheres exposed to malathion, which ultimately allowed the direct detection of this OP compound with limitation rate of microgram and the possibility of on-site analyte detection (Fei et al. 2015). Recently, phorate (an OP) was detected employing a specific aptamer and gold nanoparticles as the optical sensors. In the presence of phorate, the aptamer experienced conformation and caused the aggregation of the Au-NPs, which finally results in a change in the color of solution. Their findings proposed a selective and rapid recognition of phorate with the detection limit of nanomole (nM) (Bala et al. 2016).

In order to detect pesticides, two separate studies attempted to detect acetamiprid using aptasensors. Initially in 2014, an aptasensor was introduced by combining the nanozyme activity of Au-NPs and acetamiprid-specific S-18 aptamer. The activity of nanozyme was inhibited by a target-specific aptamer molecule, which was able to inactivate the surface of nanozyme. In the presence of such a target, aptamer molecules are detached from the Au-NPs surface, leading to the reactivation of Au-NPs nanozyme. This reversible nanozyme activation/inhibition strategy resulted in highly rapid, specific and sensitive detection of acetamiprid with a detection limit of about ppm (Weerathunge et al. 2014). Fei et al. 2015 successfully detected the femtomole level of acetamiprid via label-free direct impedimetric aptasensor. Table 3 provides analytical characteristics of OPs biosensors in commercial samples, and AChE-based biosensors for OPs detection are listed in Table 4.

Advanced complementary elements for OPs detection

Nanomaterials

Nowadays, nanotechnology and nanomaterials are intertwined in the construction of almost every bioelectronics or biosensor devices due to their exceptional physicochemical, electrical, optical and mechanical properties. Nanomaterials have overcome the obstacles of low sensitivity, selectivity and analytical interference of old methods by controlling the size, shape and composite (Marx et al. 2004). Along with the existing practices, nanomaterials including carbon nanotubes (CNTs) (multi-wall CNTs and single-wall CNTs), metal nanoparticles (MNPs) [gold (Au) and silver (Ag)], graphene and graphene-based nanocomposites, nanocrystal coordination polymers, quantum dots (QDs) and magnetic NPs have had the opportunity to be used in various OPs biodetection systems (Laschi et al. 2008) (Table 5).

Different NPs display diverse characteristics in various sensing systems as they might be used as signal transducers to mediate current flow or might be used as recognition agents or electroactive tags to detect analyte (Zhang et al. 2014b). However, they all share common roles such as to truncate both sample preparation and experimental durations, to increase the active surface areas of electrodes, to serve as multi-functional platforms for biomolecule immobilization and to accelerate electron transfer between electrodes and labeling biomolecules (Xiao et al. 2016).

Until now, numerous NPs-based biosensors for OPs detection were developed. The excellent optical absorption properties of metal NPs such as biocompatibility, conductivity and catalytic properties make them appropriate for electrochemical and piezoelectric biosensors (Li et al. 2010). The tubular and multi-dimensional configuration of CNTs and graphene-based nanocomposites provides the

Table 3 Analytical characteristics of OPs biosensors in commercial samples

OPs	Sensing mechanism	Limit of detection
Malathion	Electrochemical (amperometry)	10^{-10} M,
	Immunosensor (amperometric)	0.17 ppm[a,b]
Chlorpyrifos	Label-free immunosensors SPR	45–64 ng/L
	Immunosensor (amperometric)	0.0016 ppm[c,d,e,f,g,h]
Diazinon	Colorimetric	17.903 nM[i]
Phosalone	Chemiluminescence	3.1×10^{-8} g/mL[j]
Fenthion	Optical surface-enhanced Raman spectroscopy	0.4 mg/L[k]
	Chemiluminescence	2.5×10^{-9} g/mL[l]
	MIPs	1.83×10^{-11} mol/L[m]
Dimethoate	Electrochemical (amperometric)	2.6×10^{-10} mol/L[n]
Paraoxon	Immunosensor (amperometry)	12 ng/ml[o]
Paraoxon/methyl parathion/parathion	Cell-based biosensor: microbial (amperometric)	0.28, 0.26,0.29 ppb[p]
Parathion	Electrochemical (MIPs)	0.003 mg kg^{-1}[q]
Phorate, profenofos, isocarbophos, omethoate	Fluorometric FRET, aptamer-type DNA	19.2, 13.4, 17.2, 23.4 nM, 0.8–2.5 μM[r,s]
Chlorfenvinphos	Quartz crystal microbalance (piezoelectric)	1×10^{-10} M[t]

[a] Gahlaut et al. (2012)
[b] Prabhakar et al. (2007)
[c] Mauriz et al. (2006c)
[d] Mauriz et al. (2006a)
[e] Mauriz et al. (2006b)
[f] Mauriz et al. (2007)
[g] Mauriz et al. (2006d)
[h] Prabhakar et al. (2007)
[i] Jokar et al. (2016a)
[j] Zhi-tao et al. (2010)
[k] Li et al. (2014)
[l] Li and Liu (2007)
[m] Li et al. (2015)
[n] Hui-li (2005)
[o] Hu et al. (2003)
[p] Lei et al. (2005)
[q] Lee and Henthorn (2012)
[r] Zhang et al. (2014a)
[s] Wang et al. (2012)
[t] Halamek et al. (2005)

maximum interfacial contact area between the analyte and transducer; additionally, the electron transfer kinetics, conductivity and the current potential are enhanced (Ramnani et al. 2016).

Graphene-based materials have been frequently used for electrochemical detection of OPs (Zhang et al. 2014b). The magnetic NPs could improve the methods of purifying and concentrating the analytes even in a mixture solution with a superior detection limits and are able to simplify sample preparation. Magnetic NPs usually provide immobilization supports and facilitate immunomagnetic separations in various bioassays (Hayat et al. 2013). QDs or semiconducting nanocrystals are considered as one of the latest generation nanomaterials with outstanding photophysical properties. They preserve physical flexibility, tininess and robustness. In addition, they possess light- and size-dependent emission characteristics, thereby allowing analytes to be tagged and contribute in energy transfer systems, which make them more appropriate for field detections (Rowland et al. 2016; Bülbül et al. 2015).

Table 4 AChE-based biosensors for OPs detection

Target analyte	Transduction	Limit of detection
Malathion	Electrochemical (potentiometric)	0.1 mg/L[a]
	Electrochemical cyclic voltammetry	0.03 ng/mL[b]
Diazinon	Photothermal	32.86 µM[c]
Dimethoate	Electrochemical (amperometric)	2 nM[d]
Paraoxon	Piezoelectric (quartz crystal microbalance)	500 µM[e]
	Electrochemical (potentiometric)	0.02 µg/L[f]
Dichlorvos	Electrochemical (amperometric)	10^{-10} M g
Methyl parathion	Optical	5.2 µg/L[h]
	Electrochemical (amperometric)	0.05 µM[i]

[a] Ristori et al. (1996)
[b] Du et al. (2008)
[c] Pogačnik and Franko (1999)
[d] Du et al. (2010)
[e] Abad et al. (1998)
[f] Marty et al. (1993)
[g] Vakurov et al. (2004)
[h] Andreou and Clonis (2002)
[i] Lin et al. (2004)

Molecularly imprinted polymers (MIPs)

MIPs are synthetic, stable polymers with the recognition properties of the biological systems. MIPs contain specific binding pores that are matched with complementary functional groups (Haupt 2001). This unique versatile characteristic of MIPs compensates the lack of stability and the current limits of the signal transduction mechanisms of conventional biorecognition molecules (Jenkins et al. 2001). Normally, imprinting polymers are fabricated by attaching the template (guest) molecule to the functional monomer(s) via covalent or non-covalent bond to form a pre-polymerization complex. This complex is fixed in a highly cross-linked polymer matrix via further polymerizations in the presence of a progen solvent. Therefore, inflexible cavities are formed that are compatible with the template in size, shape and position of the functional group. By elimination of the template molecule, the polymer would be available to be used as a recognition material. The optimum selectivity of MIPs is attained by the right selection of the functional monomer to form reversible interactions with the template; cross-linking agents to ensure proper orientations of functional groups around the template; and progen to dissolve template, monomers and cross-linkers (Lee and Henthorn 2012). MIPs have been reported with several applications in medicine, diagnostics, proteomics, environmental analysis, drug delivery as well as biosensors. To date, MIPs have been employed to a number of electrochemical, piezoelectric and optical sensing systems to detect OPs.

Zhao et al. could detect the methyl parathion, electrochemically, using a molecularly imprinted polymer–ionic liquid–graphene composite film coated with glassy carbon electrode (Zhao et al. 2013). The sensor displayed high selectivity and stability toward methyl parathion with the detection limit of 6 nM (Rowland et al. 2016). Several studies developed electrochemical tools using MIPs to detect OPs (Yang et al. 2009). Optical-based studies attempted to enhance the efficacy of MIPs by introducing the fluorescent or luminescent components. In 1999, such technique was able to detect the product of the hydrolysis of the nerve agent soman via the combination of molecular imprinting and sensitized lanthanide luminescence (Jenkins et al. 1999). Later, Jenkins et al.

Table 5 Comparison of antibodies and aptamers in biosensor

Features	Antibodies	Aptamers
Time needed for synthesis	Several months	Several weeks
Stability and storage	Poor; easily desaturated and undergo irreversible denaturation; losing structure; temperature sensitive	Repeated desaturation without loss of structure and function; not temperature sensitive
	Suitable for refrigerating and freezing	No freezing or refrigeration needed
Synthesis and production	Manufactured in vivo and in animals	Manufactured in vitro (no animal used)
	Expensive and complex reactors required	Chemically synthesized
Binding affinity (KD) and specificity	High affinity (nM to pM)	High affinity (nM to pM)
	High specificity	Major potential for specificity
Shelf life	Limited	Unlimited (several years if frozen)
Pharmacokinetic parameters	Difficult to modify	Alternate based upon the intended and use
Activity method	Batch to batch	Uniform activity

(2001) developed another direct imprinting system integrating MIPs and fluorescent to detect OPs. The addition of this optical element enhances the chemical affinity, as binding of the target analyte appeals a specific spectrum of the bioreceptor molecule. Besides the increase of OPs concentration, the fluorescent intensity of the spectra raised. The detection limits for these MIPs sensors were less than 10 parts per trillion (ppt) with long linear dynamic ranges (ppt to ppm) and response times of less than 15 min (Jenkins et al. 2001).

Özkütük et al. (2013) invented an instrument to detect paraoxon based on the modification of paraoxon-imprinted QCM film on a quartz crystal, taking the advantages of piezoelectric approach along with high sensitivity and analytical performance of QCM detection. The same QCM technique was used to develop a biosensor by employing a thin film of a molecularly imprinted sol–gel polymer with specific binding sites for parathion. The films were subjected on glassy carbon electrodes and were used to detect parathion in aqueous solutions, while coated QCM was utilized for gas-phase binding. The imprinted films showed high selectivity toward parathion. The binding was mainly affected by the type of functional monomer used for imprinting (Marx et al. 2004). Zhu et al. reported high accuracy and minimal detection limit rate of monocrotophos, mevinphos, phosphamidon and omethoate in water and soil samples. They used a simple MIPs system based on molecularly imprinted solid-phase extraction (MISPE) process using a monocrotophos-imprinted polymer (Zhu et al. 2005).

Recently, a sensor device incorporating novel restricted access materials (RAM) to MIPs was developed using malathion as template molecule and glycidyl methacrylate (GMA) as pro-hydrophilic co-monomer. Initially, RAM-MIPs were used as the adsorbent enclosed in solid-phase extraction column to detect several OPs, which exhibited significant selectivity toward OPs. Next, they used the RAM-MIPs solid-phase extraction coupled with GC to determine OPs from honey sample. Data analysis showed a low detection limit (0.0005–0.0019 $\mu g\ mL^{-1}$) with significant reproducibility and recovery (He et al. 2015).

Advanced analysis techniques

Artificial neural networks (ANNs)

Virtual screening is defined as prediction tools to identify binding of a large database of ligands to one receptor (Jokar et al. 2016a; Kitchen et al. 2004). ANN is a biologically motivated computational program. ANNs database is collected through determination of patterns and relationships in data and thus learn (or are trained) via experiences not from the programming. Therefore, ANNs work based on the input and output (Agatonovic-Kustrin and Beresford 2000). The use of ANNs methodologies have been proven to be very expedient in case of complicated nonlinear chemical (logarithmic) and biological processes. To detect OPs residue, ANNs help for classification or pattern recognition, prediction and modeling (Ferentinos et al. 2012; Agatonovic-Kustrin and Beresford 2000).

ANNs have been used in biosensor-based detection of a series of OPs such as azinphos-methyloxon, Dipterex, dichlorvos and omethoate (Alonso et al. 2010, 2012; Li et al. 2007). A cell-based biosensor was constructed in combination with ANNs technique to classify different pesticide groups (pyrethroids, carbamates and OPs). These ANN systems provided a high-quantity, rapid and high-capacity detection (Ferentinos et al. 2012). Based on the fact that the activity of ChE is inhibited by various substrates such as OPs and carbamate pesticides, a variety of ANNs have been established (Alonso et al. 2010, 2012; Bachmann et al. 2000; Dong et al. 2012). For instance, two ANNs were used to accompany three different amperometric enzyme-based biosensors to discrete mixtures of chlorpyrifos oxon (CPO) and chlorfenvinphos (CFV) pesticides. Biosensors were also built using the wild-type and genetically modified AChE. In both ANN systems, a satisfactory separation of OPs was observed (Istamboulie et al. 2009). The decomposition of OPs by oxidants under ultraviolet radiation and subsequent changes of the intensity of chemiluminescence (CL) emission were used to form an optical flow CL system with ANN calibration to determine OPs residues. Results indicated that OPs were successfully distinguished in vegetable samples (Li and Liu 2007).

Modern computational approaches

Computational approaches allow to screen and/or rank bioreceptor structure and to predict the interaction outcomes. These simulations have the privileges of being free of charge, ultrasensitivity as well as selectivity based on computational calculations. In this respect, several algorithms have been settled to predict the receptor–ligand interaction in which computational docking and molecular dynamics (MD) are quite well known. Computational modeling (e.g., AutoDock software) predicts the optimal conformations and the quaternary structure of complexes formed by targeting two or more biological macromolecules. MD is a computational molecular microscopic method that simulates the quantity and quality of the interaction and thus investigates the conformational changes and binding conditions to completely clarify the interaction mechanism (Jokar et al. 2016a, b). A new trend in computational interaction analysis has been made by Sharma et al. to evaluate the quality of the interruptions made in the metabolic pathways by OPs in humans. They monitored the inhibitory

property of some proteins as exposed to OPs (Sharma et al. 2011). Computational techniques are beneficial to the studies that redesign the essential enzymes for OPs hydrolysis. These methods help to catalyze non-cognate chemical transformations of the enzymes to reactivate their untapped catalytic potential (Khare et al. 2012). More importantly, computational studies assist to determine OPs structures and their different mode of actions in reactions (Rathnayake and Northrup 2016).

A rapid diazinon detection apta-nanosensor was assembled incorporating phenomenal computational approaches. The best sequence of high-affinity diazinon–ssDNA was isolated through SELEX experiment among a number of random aptamers. Initially, docking was used as virtual screening and static step to select more frequent conformation of each aptamer. Subsequently, MD as a flexible technique simulated the quantity and quality of aptamer–diazinon interaction. MD specifically indicated the conformational flexibility and bonding interactions between diazinon–aptamer complexes. Computational screening showed G-quadruplex DNA aptamer (DF20) as the best candidate for diazinon biosensing. In this regard, a SPR-Ag-NPs colorimetric aptasensor was designed. The aptasensor enables the detection of diazinon in the range of 0.141-0.65 nM (Jokar et al. 2016a).

Conclusions

To summarize, biosensors offer considerable promise to perform assays in a faster, simpler, cheaper and more sensitive manner compared with the traditional techniques for environmental control and monitoring various samples. Over the past decades, an intense activity aimed to develop various types of biosensors. MIPs- and apta-based sensors provide innovative stability, specificity and selectivity for OPs detection; hence, it is not irrational that such systems dominate the future world of biosensors. These approaches leave behind the limitations of enzyme and immunosensors in terms of non-specificity and instability. Pioneering efforts have been made to couple nanotechnology, bioelectronics and computational analysis to improve the application of compatible microfabrication and to generate more cost-effective biosensors. Nanomaterials improved the concept of flexibility, stability, optical transparency and compatibility with microfabrication techniques to high levels. They will improve the electrochemical response of the electro-active analytes and thus facilitate multi-analysis and designation of portable on-site detection sensors. In spite of the huge development of biosensors instrumentation during the last two decades, the use of biosensors in environmental field is still restricted compared to medical applications. Additional attempts should be made to manufacture more reliable devices that will accelerate the detection of minor-scale pesticides in both laboratory and field conditions.

Author's contribution SH and SM contributed to the work by doing data collections and drafting the article. FV assisted in introduction, drawing of the figures and the language editing. ASM contributed in data collection and table preparation. MRG and PN made enough consultation during the study. MA conceived and supervised whole study. All agreed to be accountable for the accuracy and scientific authenticity of the manuscript.

Acknowledgments Authors thank the Pharmaceutical Sciences Research Center of Tehran University of Medical Sciences (TUMS) and Iran National Science Foundation (INSF) for supporting the PhD program of the first author and the Postdoctoral program of the second author.

References

Abad J, Pariente F, Hernandez L, Abruna H, Lorenzo E (1998) Determination of organophosphorus and carbamate pesticides using a piezoelectric biosensor. Anal Chem 70(14):2848–2855

Abdollahi M, Ranjbar A, Shadnia S, Nikfar S, Rezaiee A (2004) Pesticides and oxidative stress: a review. Med Sci Monit 10(6):RA141–RA147

Agatonovic-Kustrin S, Beresford R (2000) Basic concepts of artificial neural network (ANN) modeling and its application in pharmaceutical research. J Pharm Biomed Anal 22(5):717–727

Alonso GA, Istamboulie G, Ramírez-García A, Noguer T, Marty J-L, Muñoz R (2010) Artificial neural network implementation in single low-cost chip for the detection of insecticides by modeling of screen-printed enzymatic sensors response. Comput Electron Agric 74(2):223–229

Alonso GA, Istamboulie G, Noguer T, Marty J-L, Muñoz R (2012) Rapid determination of pesticide mixtures using disposable biosensors based on genetically modified enzymes and artificial neural networks. Sens Actuators B Chem 164(1):22–28

Amniattalab A, Razi M (2015) Effect of phosalone on testicular tissue and in vitro fertilizing potential. Int J Fertil Steril 9(1):93

Andreou VG, Clonis YD (2002) A portable fiber-optic pesticide biosensor based on immobilized cholinesterase and sol–gel entrapped bromcresol purple for in-field use. Biosens Bioelectron 17(1):61–69

Bachmann TT, Leca B, Vilatte F, Marty J-L, Fournier D, Schmid RD (2000) Improved multianalyte detection of organophosphates and carbamates with disposable multielectrode biosensors using recombinant mutants of Drosophila acetylcholinesterase and artificial neural networks. Biosens Bioelectron 15(3):193–201

Bahadır EB, Sezgintürk MK (2016) A review on impedimetric biosensors. Artif Cells Nanomed Biotechnol 44(1):248–262

Bala R, Sharma RK, Wangoo N (2016) Development of gold nanoparticles-based aptasensor for the colorimetric detection of organophosphorus pesticide phorate. Anal Bioanal Chem 408(1):333–338

Barceló D, Lacorte S, Marty J (1995) Validation of an enzymatic biosensor with liquid chromatography for pesticide monitoring. TrAC Trends Analyt Chem 14(7):334–340

Barrios CA (2009) Optical slot-waveguide based biochemical sensors. Sensors 9(6):4751–4765

Bassil K, Vakil C, Sanborn M, Cole D, Kaur JS, Kerr K (2007) Cancer health effects of pesticides Systematic review. Can Fam Physician 53(10):1704–1711

Bolognesi C (2003) Genotoxicity of pesticides: a review of human biomonitoring studies. Mutat Res, Rev Mutat Res 543(3):251–272

Boobis AR, Ossendorp BC, Banasiak U, Hamey PY, Sebestyen I, Moretto A (2008) Cumulative risk assessment of pesticide residues in food. Toxicol Lett 180(2):137–150

Bouchard MF, Bellinger DC, Wright RO, Weisskopf MG (2010) Attention-deficit/hyperactivity disorder and urinary metabolites of organophosphate pesticides. Pediatrics 125(6):e1270–e1277

Bülbül G, Hayat A, Andreescu S (2015) Portable nanoparticle-based sensors for food safety assessment. Sensors 15(12):30736–30758

Chaudhury N, Bhardwaj R, Murari B (2003) Fluorescence spectroscopic study to characterize and monitor TEOS based sol–gel process for development of optical biosensors. Curr Appl Phys 3(2):177–184

Choi J-W, Kim Y-K, Lee I-H, Min J, Lee WH (2001) Optical organophosphorus biosensor consisting of acetylcholinesterase/viologen hetero langmuir-blodgett film. Biosens Bioelectron 16(9):937–943

Choi S, Kim S, Shin JY, Kim M, Kim J-H (2015) Development and verification for analysis of pesticides in eggs and egg products using QuEChERS and LC–MS/MS. Food Chem 173:1236–1242

Chough SH, Mulchandani A, Mulchandani P, Chen W, Wang J, Rogers KR (2002) Organophosphorus hydrolase-based amperometric sensor: modulation of sensitivity and substrate selectivity. Electroanalysis 14(4):273

Chouteau C, Dzyadevych S, Durrieu C, Chovelon J-M (2005) A bienzymatic whole cell conductometric biosensor for heavy metal ions and pesticides detection in water samples. Biosens Bioelectron 21(2):273–281

Coscollà C, Hart E, Pastor A, Yusà V (2013) LC–MS characterization of contemporary pesticides in PM10 of Valencia Region, Spain. Atmos Environ 77:394–403

Dey D, Goswami T (2011) Optical biosensors: a revolution towards quantum nanoscale electronics device fabrication. Biomed Res Int 2011

Dong J, Gao N, Peng Y et al (2012) Surface plasmon resonance sensor for profenofos detection using molecularly imprinted thin film as recognition element. Food Control 25(2):543–549

Du D, Huang X, Cai J, Zhang A (2007) Amperometric detection of triazophos pesticide using acetylcholinesterase biosensor based on multiwall carbon nanotube–chitosan matrix. Sens Actuators B Chem 127(2):531–535

Du D, Ding J, Tao Y, Chen X (2008) Application of chemisorption/desorption process of thiocholine for pesticide detection based on acetylcholinesterase biosensor. Sens Actuators B Chem 134(2):908–912

Du D, Wang M, Cai J, Zhang A (2010) Sensitive acetylcholinesterase biosensor based on assembly of β-cyclodextrins onto multiwall carbon nanotubes for detection of organophosphates pesticide. Sens Actuators B Chem 146(1):337–341

Du G, Xiao Y, Yang HR, Wang L, Yl Song, Wang YT (2012) Rapid determination of pesticide residues in herbs using selective pressurized liquid extraction and fast gas chromatography coupled with mass spectrometry. J Sep Sci 35(15):1922–1932

Dvir H, Silman I, Harel M, Rosenberry TL, Sussman JL (2010) Acetylcholinesterase: from 3D structure to function. Chem Biol Interact 187(1):10–22

Dzyadevich S, Soldatkin A, Shul'ga A, Strikha V, El'Skaya A (1994) Conductometric biosensor for determination of organophosphorus pesticides. J Anal Chem 49(8):789–792

Dzyadevych SV, Soldatkin AP, Korpan YI et al (2003) Biosensors based on enzyme field-effect transistors for determination of some substrates and inhibitors. Anal Bioanal Chem 377(3):496–506

Dzyadevych SV, Soldatkin AP, Arkhypova VN et al (2005) Early-warning electrochemical biosensor system for environmental monitoring based on enzyme inhibition. Sens Actuators B Chem 105(1):81–87

Dzyadevych SV, Soldatkin AP, Anna V, Martelet C, Jaffrezic-Renault N (2006) Enzyme biosensors based on ion-selective field-effect transistors. Anal Chim Acta 568(1):248–258

Fei A, Liu Q, Huan J et al (2015) Label-free impedimetric aptasensor for detection of femtomole level acetamiprid using gold nanoparticles decorated multiwalled carbon nanotube-reduced graphene oxide nanoribbon composites. Biosens Bioelectron 70:122–129

Ferentinos K, Yialouris C, Blouchos P, Moschopoulou G, Tsourou V, Kintzios S (2012) The use of artificial neural networks as a component of a cell-based biosensor device for the detection of pesticides. Procedia Eng 47:989–992

Funari R, Della Ventura B, Schiavo L, Esposito R, Altucci C, Velotta R (2013) Detection of parathion pesticide by quartz crystal microbalance functionalized with uv-activated antibodies. Anal Chem 85(13):6392–6397

Gäberlein S, Spener F, Zaborosch C (2000) Microbial and cytoplasmic membrane-based potentiometric biosensors for direct determination of organophosphorus insecticides. Appl Microbiol Biotechnol 54(5):652–658

Gahlaut A, Gothwal A, Chhillar AK, Hooda V (2012) Electrochemical biosensors for determination of organophosphorus compounds: review. Open J Appl Biosens 1(01):1

García-Valcárcel AI, Tadeo JL (2009) A combination of ultrasonic assisted extraction with LC–MS/MS for the determination of organophosphorus pesticides in sludge. Anal Chim Acta 641(1):117–123

Ghasemi-Niri SF, Maqbool F, Baeeri M, Gholami M, Abdollahi M (2016) Phosalone induced inflammation and oxidative stress in the colon: evaluation and treatment. World J Gastroenterol 22:4999–5011

Grieshaber D, MacKenzie R, Voeroes J, Reimhult E (2008) Electrochemical biosensors–sensor principles and architectures. Sensors 8(3):1400–1458

Grimes CA, Roy SC, Rani S, Cai Q (2011) Theory, instrumentation and applications of magnetoelastic resonance sensors: a review. Sensors 11(3):2809–2844

Guler G, Cakmak Y, Dagli Z, Aktumsek A, Ozparlak H (2010) Organochlorine pesticide residues in wheat from Konya region, Turkey. Food Chem Toxicol 48(5):1218–1221

Guntupalli R, Hu J, Lakshmanan RS, Huang T, Barbaree JM, Chin BA (2007) A magnetoelastic resonance biosensor immobilized with polyclonal antibody for the detection of Salmonella typhimurium. Biosens Bioelectron 22(7):1474–1479

Halamek J, Přibyl J, Makower A, Skládal P, Scheller F (2005) Sensitive detection of organophosphates in river water by means of a piezoelectric biosensor. Anal Bioanal Chem 382(8):1904–1911

Hassani S, Sepand M, Jafari A et al (2014) Protective effects of curcumin and vitamin E against chlorpyrifos-induced lung oxidative damage. Hum Exp Toxicol 34(6):668–676

Haupt K (2001) Molecularly imprinted polymers in analytical chemistry. Analyst 126(6):747–756

Hayat A, Yang C, Rhouati A, Marty JL (2013) Recent advances and achievements in nanomaterial-based, and structure switchable aptasensing platforms for ochratoxin A detection. Sensors 13(11):15187–15208

He J, Song L, Chen S et al (2015) Novel restricted access materials combined to molecularly imprinted polymers for selective

solid-phase extraction of organophosphorus pesticides from honey. Food Chem 187:331–337
Hlavata L, Benikova K, Vyskocil V, Labuda J (2012) Evaluation of damage to DNA induced by UV-C radiation and chemical agents using electrochemical biosensor based on low molecular weight DNA and screen-printed carbon electrode. Electrochim Acta 71:134–139
Hobbiger F (1961) The inhibition of acetylcholinesterase by organophosphorus compounds and its reversal [abridged]. Proc R Soc Med 54(5):403
Hodjat M, Rezvanfar MA, Abdollahi M (2015) A systematic review on the role of environmental toxicants in stem cells aging. Food Chem Toxicol 86:298–308
Hu S-Q, Xie J-W, Xu Q-H, Rong K-T, Shen G-L, Yu R-Q (2003) A label-free electrochemical immunosensor based on gold nanoparticles for detection of paraoxon. Talanta 61(6):769–777
Hui-Li KT-FG (2005) Study of determination of organophosphorus pesticides using biosensors based on cobalt phthalocyanine polymer modified electrodes. Chem Sens 1:011
Istamboulie G, Cortina-Puig M, Marty J-L, Noguer T (2009) The use of artificial neural networks for the selective detection of two organophosphate insecticides: chlorpyrifos and chlorfenvinfos. Talanta 79(2):507–511
Ivanov A, Lukachova L, Evtugyn G et al (2002) Polyaniline-modified cholinesterase sensor for pesticide determination. Bioelectrochem 55(1):75–77
Jaffrezic-Renault N (2001) New trends in biosensors for organophosphorus pesticides. Sensors 1(2):60–74
Jaffrezic-Renault N, Dzyadevych SV (2008) Conductometric microbiosensors for environmental monitoring. Sensors 8(4):2569–2588
Jallouli M, Dhouib IEB, Dhouib H, Gharbi N, El Fazaa S (2015) Effects of dimethoate in male mice reproductive parameters. Regul Toxicol Pharmacol 73(3):853–858
Jenkins AL, Uy OM, Murray GM (1999) Polymer-based lanthanide luminescent sensor for detection of the hydrolysis product of the nerve agent soman in water. Anal Chem 71(2):373–378
Jenkins AL, Yin R, Jensen JL (2001) Molecularly imprinted polymer sensors for pesticide and insecticide detection in water. Analyst 126(6):798–802
Jiang X, Li D, Xu X et al (2008) Immunosensors for detection of pesticide residues. Biosens Bioelectron 23(11):1577–1587
Jin S, Xu Z, Chen J, Liang X, Wu Y, Qian X (2004) Determination of organophosphate and carbamate pesticides based on enzyme inhibition using a pH-sensitive fluorescence probe. Anal Chim Acta 523(1):117–123
Jokar M, Safaralizadeh MH, Hadizadeh F, Rahmani F, Kalani MR (2016a) Apta-nanosensor preparation and in vitro assay for rapid diazinon detection using a computational molecular approach. J Biomol Struct Dyn 1–11
Jokar M, Safaralizadeh MH, Hadizadeh F, Rahmani F, Kalani MR (2016b) Design and evaluation of an apta-nano-sensor to detect Acetamiprid in vitro and in silico. J Biomol Struct Dyn 1–13
Justino CI, Freitas AC, Pereira R, Duarte AC, Santos TAR (2015) Recent developments in recognition elements for chemical sensors and biosensors. TrAC Trends Analyt Chem 68:2–17
Kalender S, Ogutcu A, Uzunhisarcikli M et al (2005) Diazinon-induced hepatotoxicity and protective effect of vitamin E on some biochemical indices and ultrastructural changes. Toxicology 211(3):197–206
Kandimalla V, Neeta N, Karanth N et al (2004) Regeneration of ethyl parathion antibodies for repeated use in immunosensor: a study on dissociation of antigens from antibodies. Biosens Bioelectron 20(4):903–906
Karami-Mohajeri S, Hadian M, Fouladdel S et al (2013) Mechanisms of muscular electrophysiological and mitochondrial dysfunction following exposure to malathion, an organophosphorus pesticide. Hum Exp Toxicol 33(3):251–263
Karousos NG, Aouabdi S, Way AS, Reddy SM (2002) Quartz crystal microbalance determination of organophosphorus and carbamate pesticides. Anal Chim Acta 469(2):189–196
Khare SD, Kipnis Y, Takeuchi R et al (2012) Computational redesign of a mononuclear zinc metalloenzyme for organophosphate hydrolysis. Nat Chem Biol 8(3):294–300
Kim N, Park I-S, Kim D-K (2007) High-sensitivity detection for model organophosphorus and carbamate pesticide with quartz crystal microbalance-precipitation sensor. Biosens Bioelectron 22(8):1593–1599
Kissinger PT (2005) Biosensors—a perspective. Biosens Bioelectron 20(12):2512–2516
Kitchen DB, Decornez H, Furr JR, Bajorath J (2004) Docking and scoring in virtual screening for drug discovery: methods and applications. Nat Rev Drug Discov 3(11):935–949
Kolberg DI, Prestes OD, Adaime MB, Zanella R (2011) Development of a fast multiresidue method for the determination of pesticides in dry samples (wheat grains, flour and bran) using QuEChERS based method and GC–MS. Food Chem 125(4):1436–1442
Kolosova AY, Park J-H, Eremin SA, Kang S-J, Chung D-H (2003) Fluorescence polarization immunoassay based on a monoclonal antibody for the detection of the organophosphorus pesticide parathion-methyl. J Agric Food Chem 51(5):1107–1114
Kolosova AY, Park J-H, Eremin SA et al (2004) Comparative study of three immunoassays based on monoclonal antibodies for detection of the pesticide parathion-methyl in real samples. Anal Chim Acta 511(2):323–331
Koncki R (2007) Recent developments in potentiometric biosensors for biomedical analysis. Anal Chim Acta 599(1):7–15
K'Owino IO, Sadik OA (2005) Impedance spectroscopy: a powerful tool for rapid biomolecular screening and cell culture monitoring. Electroanalysis 17(23):2101–2113
Kumar P, Kim K-H, Deep A (2015) Recent advancements in sensing techniques based on functional materials for organophosphate pesticides. Biosens Bioelectron 70:469–481
Kwong TC (2002) Organophosphate pesticides: biochemistry and clinical toxicology. Ther Drug Monit 24(1):144–149
Laschi S, Bulukin E, Palchetti I, Cristea C, Mascini M (2008) Disposable electrodes modified with multi-wall carbon nanotubes for biosensor applications. Irbm 29(2):202–207
Lee S, Henthorn D (2012) Materials in biology and medicine. CRC press
Lee JH, Park JY, Min K, Cha HJ, Choi SS, Yoo YJ (2010) A novel organophosphorus hydrolase-based biosensor using mesoporous carbons and carbon black for the detection of organophosphate nerve agents. Biosens Bioelectron 25(7):1566–1570
Lei Y, Mulchandani P, Wang J, Chen W, Mulchandani A (2005) Highly sensitive and selective amperometric microbial biosensor for direct determination of p-nitrophenyl-substituted organophosphate nerve agents. Environ Sci Technol 39(22):8853–8857
Lerro CC, Koutros S, Andreotti G et al (2015) Organophosphate insecticide use and cancer incidence among spouses of pesticide applicators in the Agricultural Health Study. Occup Environ Med 72(10):736–744
Li A-F, Liu X-Y (2007) Determination of fenthion in tamatos by chemiluminescence assay [J]. Food Sci 6:069
Li B, He Y, Xu C (2007) Simultaneous determination of three organophosphorus pesticides residues in vegetables using continuous-flow chemiluminescence with artificial neural network calibration. Talanta 72(1):223–230
Li Y, Schluesener HJ, Xu S (2010) Gold nanoparticle-based biosensors. Gold Bull 43(1):29–41
Li X, Zhang S, Yu Z, Yang T (2014) Surface-enhanced Raman spectroscopic analysis of phorate and fenthion pesticide in apple skin using silver nanoparticles. Appl Spectrosc 68(4):483–487

Li S, Luo J, Yin G et al (2015) Selective determination of dimethoate via fluorescence resonance energy transfer between carbon dots and a dye-doped molecularly imprinted polymer. Sens Actuators B Chem 206:14–21

Lin Y, Lu F, Wang J (2004) Disposable carbon nanotube modified screen-printed biosensor for amperometric detection of organophosphorus pesticides and nerve agents. Electroanalysis 16(1–2):145–149

Lin T-J, Huang K-T, Liu C-Y (2006) Determination of organophosphorous pesticides by a novel biosensor based on localized surface plasmon resonance. Biosens Bioelectron 22(4):513–518

Liu G, Lin Y (2006) Biosensor based on self-assembling acetylcholinesterase on carbon nanotubes for flow injection/amperometric detection of organophosphate pesticides and nerve agents. Anal Chem 78(3):835–843

Liu G, Wang J, Barry R et al (2008) Nanoparticle-based electrochemical immunosensor for the detection of phosphorylated acetylcholinesterase: an exposure biomarker of organophosphate pesticides and nerve agents. Chem Eur J 14(32):9951–9959

Liu B, Zhou P, Liu X, Sun X, Li H, Lin M (2013) Detection of pesticides in fruits by surface-enhanced Raman spectroscopy coupled with gold nanostructures. Food Bioproc Tech 6(3):710–718

Long Q, Li H, Zhang Y, Yao S (2015) Upconversion nanoparticle-based fluorescence resonance energy transfer assay for organophosphorus pesticides. Biosens Bioelectron 68:168–174

Łozowicka B, Jankowska M, Rutkowska E, Hrynko I, Kaczyński P, Miciński J (2014) The evaluation of a fast and simple pesticide multiresidue method in various herbs by gas chromatography. J Nat Med 68(1):95–111

Lu C, Barr DB, Pearson MA, Waller LA (2008) Dietary intake and its contribution to longitudinal organophosphorus pesticide exposure in urban/suburban children. Environ Health Perspect 116(4):537

Lu D, Wang J, Wang L et al (2011) A novel nanoparticle-based disposable electrochemical immunosensor for diagnosis of exposure to toxic organophosphorus agents. Adv Funct Mater 21(22):4371–4378

Luzardo OP, Almeida-González M, Ruiz-Suárez N et al (2015) Validated analytical methodology for the simultaneous determination of a wide range of pesticides in human blood using GC–MS/MS and LC–ESI/MS/MS and its application in two poisoning cases. Sci Justice 55(5):307–315

Makaraviciute A, Ramanaviciene A (2013) Site-directed antibody immobilization techniques for immunosensors. Biosens Bioelectron 50:460–471

Mallat E, Barcelo D, Barzen C, Gauglitz G, Abuknesha R (2001) Immunosensors for pesticide determination in natural waters. TrAC Trends Analyt Chem 20(3):124–132

Marrazza G (2014) Piezoelectric biosensors for organophosphate and carbamate pesticides: a review. Biosensors 4(3):301–317

Martínez-Domínguez G, Nieto-García AJ, Romero-González R, Frenich AG (2015) Application of QuEChERS based method for the determination of pesticides in nutraceutical products (*Camellia sinensis*) by liquid chromatography coupled to triple quadrupole tandem mass spectrometry. Food Chem 177:182–190

Marty J-L, Mionetto N, Noguer T, Ortega F, Roux C (1993) Enzyme sensors for the detection of pesticides. Biosens Bioelectron 8(6):273–280

Marx S, Zaltsman A, Turyan I, Mandler D (2004) Parathion sensor based on molecularly imprinted sol-gel films. Anal Chem 76(1):120–126

Mauriz E, Calle A, Abad A et al (2006a) Determination of carbaryl in natural water samples by a surface plasmon resonance flow-through immunosensor. Biosens Bioelectron 21(11):2129–2136

Mauriz E, Calle A, Lechuga LM, Quintana J, Montoya A, Manclus J (2006b) Real-time detection of chlorpyrifos at part per trillion levels in ground, surface and drinking water samples by a portable surface plasmon resonance immunosensor. Anal Chim Acta 561(1):40–47

Mauriz E, Calle A, Manclus J et al (2006c) Single and multi-analyte surface plasmon resonance assays for simultaneous detection of cholinesterase inhibiting pesticides. Sens Actuators B Chem 118(1):399–407

Mauriz E, Calle A, Montoya A, Lechuga LM (2006d) Determination of environmental organic pollutants with a portable optical immunosensor. Talanta 69(2):359–364

Mauriz E, Calle A, Manclús J et al (2007) Optical immunosensor for fast and sensitive detection of DDT and related compounds in river water samples. Biosens Bioelectron 22(7):1410–1418

Mehrvar M, Abdi M (2004) Recent developments, characteristics, and potential applications of electrochemical biosensors. Anal Sci 20(8):1113–1126

Meng X, Wei J, Ren X, Ren J, Tang F (2013) A simple and sensitive fluorescence biosensor for detection of organophosphorus pesticides using H_2O_2-sensitive quantum dots/bi-enzyme. Biosens Bioelectron 47:402–407

Monošík R, Streďanský M, Šturdík E (2012) Biosensors-classification, characterization and new trends. Acta Chimica Slovaca 5(1):109–120

Mostafalou S, Abdollahi M (2013) Pesticides and human chronic diseases: evidences, mechanisms, and perspectives. Toxicol Appl Pharmacol 268(2):157–177

Mukundan H, Anderson AS, Grace WK et al (2009) Waveguide-based biosensors for pathogen detection. Sensors 9(7):5783–5809

Mulchandani A, Chen W, Mulchandani P, Wang J, Rogers KR (2001) Biosensors for direct determination of organophosphate pesticides. Biosens Bioelectron 16(4):225–230

Nougadère A, Reninger J-C, Volatier J-L, Leblanc J-C (2011) Chronic dietary risk characterization for pesticide residues: a ranking and scoring method integrating agricultural uses and food contamination data. Food Chem Toxicol 49(7):1484–1510

Nowicka AM, Kowalczyk A, Stojek Z, Hepel M (2010) Nanogravimetric and voltammetric DNA-hybridization biosensors for studies of DNA damage by common toxicants and pollutants. Biophys Chem 146(1):42–53

Obare SO, De C, Guo W et al (2010) Fluorescent chemosensors for toxic organophosphorus pesticides: a review. Sensors 10(7):7018–7043

Organization WH (2006) The impact of pesticides on health: preventing intentional and unintentional deaths from pesticide poisoning. WHO, Geneva

Özkütük EB, Diltemiz SE, Özalp E, Say R, Ersöz A (2013) Ligand exchange based paraoxon imprınted QCM sensor. Mater Sci Eng C Mater Biol Appl 33(2):938–942

Pacioni NL, Veglia AV (2003) Determination of carbaryl and carbofuran in fruits and tap water by β-cyclodextrin enhanced fluorimetric method. Anal Chim Acta 488(2):193–202

Pakzad M, Fouladdel S, Nili-Ahmadabadi A et al (2013) Sublethal exposures of diazinon alters glucose homostasis in Wistar rats: biochemical and molecular evidences of oxidative stress in adipose tissues. Pestic Biochem Physiol 105(1):57–61

Páleníková A, Martínez-Domínguez G, Arrebola FJ, Romero-González R, Hrouzková S, Frenich AG (2015) Multifamily determination of pesticide residues in soya-based nutraceutical products by GC/MS–MS. Food Chem 173:796–807

Paliwal S, Wales M, Good T, Grimsley J, Wild J, Simonian A (2007) Fluorescence-based sensing of p-nitrophenol and p-nitrophenyl substituent organophosphates. Anal Chim Acta 596(1):9–15

Patolsky F, Zheng G, Lieber CM (2006) Nanowire-based biosensors. Anal Chem 78(13):4260–4269

Pattnaik P (2005) Surface plasmon resonance. Appl Biochem Biotechnol 126(2):79–92

Paz M, Correia-Sá L, Becker H, Longhinotti E, Domingues VF, Delerue-Matos C (2015) Validation of QuEChERS method for organochlorine pesticides analysis in tamarind (*Tamarindus indica*) products: peel, fruit and commercial pulp. Food Control 54:374–382

Pogačnik L, Franko M (1999) Determination of organophosphate and carbamate pesticides in spiked samples of tap water and fruit juices by a biosensor with photothermal detection. Biosens Bioelectron 14(6):569–578

Pohanka M, Skládal P (2008) Electrochemical biosensors–principles and applications. J Appl Biomed 6(2):57–64

Pohanka M, Jun D, Kuca K (2008) Amperometric biosensors for real time assays of organophosphates. Sensors 8(9):5303–5312

Prabhakar N, Arora K, Singh SP, Pandey MK, Singh H, Malhotra BD (2007) Polypyrrole-polyvinyl sulphonate film based disposable nucleic acid biosensor. Anal Chim Acta 589(1):6–13

Quignot N, Tournier M, Pouech C, Cren-Olivé C, Barouki R, Lemazurier E (2012) Quantification of steroids and endocrine disrupting chemicals in rat ovaries by LC–MS/MS for reproductive toxicology assessment. Anal Bioanal Chem 403(6):1629–1640

Rahimi R, Nikfar S, Abdollahi M (2006) Increased morbidity and mortality in acute human organophosphate-poisoned patients treated by oximes: a meta-analysis of clinical trials. Hum Exp Toxicol 25(3):157–162

Ramadan KS, Sameoto D, Evoy S (2014) A review of piezoelectric polymers as functional materials for electromechanical transducers. Smart Mater Struct 23(3):033001

Ramnani P, Saucedo NM, Mulchandani A (2016) Carbon nanomaterial-based electrochemical biosensors for label-free sensing of environmental pollutants. Chemosphere 143:85–98

Rathnayake LK, Northrup SH (2016) Structure and mode of action of organophosphate pesticides: a computational study. Comput Theor Chem 1088:9–23

Razavi BM, Hosseinzadeh H, Movassaghi AR, Imenshahidi M, Abnous K (2013) Protective effect of crocin on diazinon induced cardiotoxicity in rats in subchronic exposure. Chem Biol Interact 203(3):547–555

Regueiro J, López-Fernández O, Rial-Otero R, Cancho-Grande B, Simal-Gándara J (2015) A review on the fermentation of foods and the residues of pesticides—biotransformation of pesticides and effects on fermentation and food quality. Crit Rev Food Sci Nutr 55(6):839–863

Rezvanfar MA, Hodjat M, Abdollahi M (2016) Growing knowledge of using embryonic stem cells as a novel tool in developmental risk assessment of environmental toxicants. Life Sci 158:137–160

Ristori C, Del Carlo C, Martini M, Barbaro A, Ancarani A (1996) Potentiometric detection of pesticides in water samples. Anal Chim Acta 325(3):151–160

Rodriguez-Mozaz S, de Alda MJL, Marco M-P, Barceló D (2005) Biosensors for environmental monitoring: a global perspective. Talanta 65(2):291–297

Rogers KR, Valdes JJ, Eldefrawi ME (1991) Effects of receptor concentration, media ph and storage on nicotinic receptor-transmitted signal in a fiber-optic biosensor. Biosens Bioelectron 6(1):1–8

Rowland CE, Brown CW, Delehanty JB, Medintz IL (2016) Nanomaterial-based sensors for the detection of biological threat agents. Mater Today

Sassolas A, Prieto-Simón B, Marty J-L (2012) Biosensors for pesticide detection: new trends. Am J Analyt Chem 3(3):210

Schäferling M (2006) Fluorescence-based biosensors. Encyclopedia of analytical chemistry

Schöning MJ, Krause R, Block K, Musahmeh M, Mulchandani A, Wang J (2003) A dual amperometric/potentiometric FIA-based biosensor for the distinctive detection of organophosphorus pesticides. Sens Actuators B Chem 95(1):291–296

Schuhmann W (1995) Electron-transfer pathways in amperometric biosensors. Ferrocene-modified enzymes entrapped in conducting-polymer layers. Biosens Bioelectron 10(1):181–193

Schulze H, Vorlová S, Villatte F, Bachmann TT, Schmid RD (2003) Design of acetylcholinesterases for biosensor applications. Biosens Bioelectron 18(2):201–209

Shang Z-j Xu, Y-l Wang Y, D-x Wei, L-l Zhan (2011) A rapid detection of pesticide residue based on piezoelectric biosensor. Procedia Eng 15:4480–4485

Sharma AK, Gaur K, Tiwari RK, Gaur MS (2011) Computational interaction analysis of organophosphorus pesticides with different metabolic proteins in humans. J Biomed Res 25(5):335–347

Simoneschi D, Simoneschi F, Todd NE (2014) Assessment of cardiotoxicity and effects of malathion on the early development of zebrafish (*Danio rerio*) using computer vision for heart rate quantification. Zebrafish 11(3):275–280

Simonian A, Good T, Wang S-S, Wild J (2005) Nanoparticle-based optical biosensors for the direct detection of organophosphate chemical warfare agents and pesticides. Anal Chim Acta 534(1):69–77

Song S, Wang L, Li J, Fan C, Zhao J (2008) Aptamer-based biosensors. TrAC Trends Analyt Chem 27(2):108–117

Stadtherr K, Wolf H, Lindner P (2005) An aptamer-based protein biochip. Anal Chem 77(11):3437–3443

Strehlitz B, Nikolaus N, Stoltenburg R (2008) Protein detection with aptamer biosensors. Sensors 8(7):4296–4307

Suri CR, Raje M, Varshney GC (2002) Immunosensors for pesticide analysis: antibody production and sensor development. Crit Rev Biotechnol 22(1):15–32

Taranekar P, Baba A, Park JY, Fulghum TM, Advincula R (2006) Dendrimer precursors for nanomolar and picomolar real-time surface plasmon resonance/potentiometric chemical nerve agent sensing using electrochemically crosslinked ultrathin films. Adv Funct Mater 16(15):2000–2007

Teles F, Fonseca L (2008) Trends in DNA biosensors. Talanta 77(2):606–623

Thrasher JD, Heuser G, Broughton A (2002) Immunological abnormalities in humans chronically exposed to chlorpyrifos. Arch Environ Health An Int J 57(3):181–187

Uygun ZO, Dilgin Y (2013) A novel impedimetric sensor based on molecularly imprinted polypyrrole modified pencil graphite electrode for trace level determination of chlorpyrifos. Sens Actuators B Chem 188:78–84

Vakurov A, Simpson C, Daly C, Gibson T, Millner P (2004) Acetylcholinesterase-based biosensor electrodes for organophosphate pesticide detection: I. Modification of carbon surface for immobilization of acetylcholinesterase. Biosens Bioelectron 20(6):1118–1125

Velasco-Garcia MN, Mottram T (2003) Biosensor technology addressing agricultural problems. Biosyst Eng 84(1):1–12

Velusamy V, Arshak K, Korostynska O, Oliwa K, Adley C (2010) An overview of foodborne pathogen detection: in the perspective of biosensors. Biotechnol Adv 28(2):232–254

Vercoutere W, Akeson M (2002) Biosensors for DNA sequence detection. Curr Opin Chem Biol 6(6):816–822

Verma N, Bhardwaj A (2015) Biosensor technology for pesticides—a review. Appl Biochem Biotechnol 175(6):3093–3119

Viveros L, Paliwal S, McCrae D, Wild J, Simonian A (2006) A fluorescence-based biosensor for the detection of organophosphate pesticides and chemical warfare agents. Sens Actuators B Chem 115(1):150–157

Vuković G, Shtereva D, Bursić V, Mladenova R, Lazić S (2012) Application of GC–MSD and LC–MS/MS for the determination of priority pesticides in baby foods in Serbian market. LWT-Food Sci Technol 49(2):312–319

Wang J (2000) Survey and summary from DNA biosensors to gene chips. Nucleic Acids Res 28(16):3011–3016

Wang J, Krause R, Block K et al (2002) Dual amperometric–potentiometric biosensor detection system for monitoring organophosphorus neurotoxins. Anal Chim Acta 469(2):197–203

Wang X, Xing H, Li X, Xu S, Wang X (2011a) Effects of atrazine and chlorpyrifos on the mRNA levels of IL-1 and IFN-γ2b in immune organs of common carp. Fish Shellfish Immunol 31(1):126–133

Wang Y, Jin H-Y, Ma S-C, Lu J, Lin R-C (2011b) Determination of 195 pesticide residues in Chinese herbs by gas chromatography–mass spectrometry using analyte protectants. J Chromatogr A 1218(2):334–342

Wang L, Liu X, Zhang Q et al (2012) Selection of DNA aptamers that bind to four organophosphorus pesticides. Biotechnol Lett 34(5):869–874

Weerathunge P, Ramanathan R, Shukla R, Sharma TK, Bansal V (2014) Aptamer-controlled reversible inhibition of gold nanozyme activity for pesticide sensing. Anal Chem 86(24):11937–11941

Wu JC, Hseu YC, Tsai JS et al (2011) Fenthion and terbufos induce DNA damage, the expression of tumor-related genes, and apoptosis in HEPG2 cells. Environ Mol Mutagen 52(7):529–537

Xiao F, Wang L, Duan H (2016) Nanomaterial based electrochemical sensors for in vitro detection of small molecule metabolites. Biotechnol Adv 34(3):234–249

Xu Z-L, Wang Q, Lei H-T et al (2011) A simple, rapid and high-throughput fluorescence polarization immunoassay for simultaneous detection of organophosphorus pesticides in vegetable and environmental water samples. Anal Chim Acta 708(1):123–129

Yadav SS, Singh MK, Yadav RS (2016) Organophosphates Induced Alzheimer's disease: An Epigenetic Aspect. J Clin Epigenet

Yan F, Wang F, Chen Z (2011) Aptamer-based electrochemical biosensor for label-free voltammetric detection of thrombin and adenosine. Sens Actuators B Chem 160(1):1380–1385

Yang Q, Sun Q, Zhou T, Shi G, Jin L (2009) Determination of parathion in vegetables by electrochemical sensor based on molecularly imprinted polyethyleneimine/silica gel films. J Agric Food Chem 57(15):6558–6563

Zehani N, Dzyadevych SV, Kherrat R, Jaffrezic-Renault NJ (2014) Sensitive impedimetric biosensor for direct detection of diazinon based on lipases. Front Chem 2:44

Zhang W, Ge X, Tang Y, Du D, Liu D, Lin Y (2013a) Nanoparticle-based immunochromatographic test strip with fluorescent detector for quantification of phosphorylated acetylcholinesterase: an exposure biomarker of organophosphorus agents. Analyst 138(18):5431–5436

Zhang X, Wang H, Yang C, Du D, Lin Y (2013b) Preparation, characterization of Fe_3O_4 at TiO_2 magnetic nanoparticles and their application for immunoassay of biomarker of exposure to organophosphorus pesticides. Biosens Bioelectron 41:669–674

Zhang C, Wang L, Tu Z et al (2014a) Organophosphorus pesticides detection using broad-specific single-stranded DNA based fluorescence polarization aptamer assay. Biosens Bioelectron 55:216–219

Zhang W, Asiri AM, Liu D, Du D, Lin Y (2014b) Nanomaterial-based biosensors for environmental and biological monitoring of organophosphorus pesticides and nerve agents. TrAC Trends Analyt Chem 54:1–10

Zhao L, Zhao F, Zeng B (2013) Electrochemical determination of methyl parathion using a molecularly imprinted polymer–ionic liquid–graphene composite film coated electrode. Sens Actuators B Chem 176:818–824

Zhao G, Sun X, Guo Y, Wang X, Jia Y (2014) A portable instrument based on acetylcholinesterase biosensor for the rapid detection of pesticides residues. Sens Transducers 182(11):1

Zhao G, Guo Y, Sun X, Wang X (2015a) A system for pesticide residues detection and agricultural products traceability based on acetylcholinesterase biosensor and internet of things. Int J Electrochem Sci 10:3387–3399

Zhao G, Wang H, Liu G (2015b) Advances in biosensor-based instruments for pesticide residues rapid detection. Int J Electrochem Sci 10(12):9790–9807

Zhi-tao C, Yan Z, Xiang-ping Z, Jin-hu Z, Wen-fan W, Jian-hui Z (2010) Determination of the phosalone by flow-injection chemiluminescent. Fujian Anal Test 4:007

Zhu X, Yang J, Su Q, Cai J, Gao Y (2005) Selective solid-phase extraction using molecularly imprinted polymer for the analysis of polar organophosphorus pesticides in water and soil samples. J Chromatogr A 1092(2):161–169

Zourob M, Ong KG, Zeng K, Mouffouk F, Grimes CA (2007) A wireless magnetoelastic biosensor for the direct detection of organophosphorus pesticides. Analyst 132(4):338–343